Table of Contents

1 Fundamental Physical and Technical Terms

1.1 Units of physical quantities

1.1.1 The International System of Units (SI)

The statutory units of measurement are[1]

1. the basic units of the International System of Units (Sl units) for the basic quantities length, mass, time, electric current, thermodynamic temperature and luminous intensity,
2. the units defined for the atomic quantities of quantity of substance, atomic mass and energy,
3. the derived units obtained as products of powers of the basic units and atomic units through multiplication with a defined numerical factor,
4. the decimal multiples and sub-multiples of the units stated under 1-3.

Table 1-1

Basic SI units

Quantity	Units Symbol	Units Name
Length	m	metre
Mass	kg	kilogramme
Time	s	second
Electric current	A	ampere
Thermodynamic temperature	K	kelvin
Luminous intensity	cd	candela
Atomic units		
Quantity of substance	mol	mole

Table 1-2

Decimals

Multiples and sub-multiples of units

Decimal power	Prefix	Symbol			
10^{12}	Tera	T	10^{-2}	Zenti	c
10^{9}	Giga	G	10^{-3}	Milli	m
10^{6}	Mega	M	10^{-6}	Mikro	µ
10^{3}	Kilo	k	10^{-9}	Nano	n
10^{2}	Hekto	h	10^{-12}	Piko	p
10^{1}	Deka	da	10^{-15}	Femto	f
10^{-1}	Dezi	d	10^{-18}	Atto	a

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[1] DIN 1301

Table 1-3

List of units

1	*2*	*3*	*4*	*5*	*6*	*7*	*8*
No.	Quantity	SI unit1)		Other units		Relationship1)	Remarks
		Name	Symbol	Name	Symbol		
1	**Length, area, volume**						
1.1	Length	metre	m				see Note to No. 1.1
1.2	Area	square metre	m^2				
				are	a	$1\ a = 10^2\ m^2$	for land measurement only
				hectare	ha	$1\ ha = 10^4\ m^2$	
1.3	Volume	cubic metre	m^3				
				litre	l	$1\ l = 1\ dm^3 = 10^{-3}\ m^3$	
1.4	Reciprocal length	reciprocal metre	1/m				
				dioptre	dpt	1 dpt = 1/m	only for refractive index of optical systems
1.5	Elongation	metre per metre	m/m				Numerical value of elongation often expressed in per cent

1) See also notes to columns 3 and 4 and to column 7 on page 15.

(*continued)*

Table 1-3 (continued)

List of units

1	2	3	4	5	6	7	8
No.	Quantity	SI unit[1]		Other units		Relationship[1]	Remarks
		Name	Symbol	Name	Symbol		
2 Angle							
2.1	Plane angle (angle)	radian	rad			1 rad = 1 m/m	see DIN 1315 In calculation the unit rad as a factor can be replaced by numerical 1.
				full angle		1 full angle = 2 π rad	
				right angle	V	1 V $= \frac{\pi}{2}$ rad	
				degree	°	1 ° $= \frac{\pi}{180}$ rad	
				minute	'	1' = 1°/60	
				second	"	1" = 1'/60	
				gon	gon	1 gon $= \frac{\pi}{200}$ rad	
2.2	Solid angle	steradian	sr			1 sr $= 1 m^2/m^2$	see DIN 1315

[1] See also notes to columns 3 and 4 and to column 7 on page 15.

(continued)

Table 1-3 (continued)

List of units

1	2	3	4	5	6	7	8
No.	Quantity	SI unit1)		Other units		Relationship1)	Remarks
		Name	Symbol	Name	Symbol		
3	**Mass**						
3.1	Mass	kilogramme	kg				Units of weight used as terms for mass in expressing quantities of goods are the units of mass, see DIN 1305
				gramme	g	1 g = 10^{-3} kg	At the present state of measuring technology the 3-fold standard deviation for the relationship for u given in col. 7 is ± 3 · 10^{-32} kg.
				tonne	t	1 t = 10^{3} kg	
				atomic mass unit	u	1 u = 1.66053 · 10^{-27} kg	
				metric carat	Kt	1 Kt = 0.2 · 10^{-3} kg	only for gems
3.2	Mass per unit length	kilogramme per metre	kg/m				
				Tex	tex	1 tex = 10^{-6} kg/m = 1 g/km	only for textile fibres and yarns, see DIN 60905 Sheet 1

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1) See also notes to columns 3 and 4 and to column 7 on page 15.

(continued)

Table 1-3 (continued)

List of units

1	*2*	*3*	*4*	*5*	*6*	*7*	*8*
No.	Quantity	SI unit1)		Other units		Relationship1)	Remarks
		Name	Symbol	Name	Symbol		
3.3	Density	kilogramme per cubic metre	kg/m^3				see DIN 1306
3.4	Specific volume	cubic metre per kilogramme	m^3/kg				see DIN 1306
3.5	Moment of inertia	kilogramme-square metre	kg m^2				see DIN 5497 and Note to No. 3.5

1) See also notes to columns 3 and 4 and to column 7 on page 15.

(*continued)*

Table 1-3 (continued)

List of units

1	*2*	*3*	*4*	*5*	*6*	*7*	*8*
No.	Quantity	SI unit[1]		Other units		Relationship[1]	Remarks
		Name	Symbol	Name	Symbol		
4	**Time**						
4.1	Time	second	s	minute	min	1 min = 60 s	see DIN 1355
				hour	h	1 h = 60 min	
				day	d	1 d = 24 h	
				year	a		In the power industry a year is taken as 8760 hours. See also Note to No. 4.1.
4.2	Frequency	hertz	Hz			1 Hz = 1/s	1 hertz is equal to the frequency of a periodic event having a duration of 1 s.
4.3	Revolutions per second	reciprocal second	1/s	reciprocal minute	1/min	1/min = 1/(60 s)	If it is defined as the reciprocal of the time of revolution, see DIN 1355.

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[1] See also notes to columns 3 and 4 and to column 7 on page 15.

(continued)

Table 1-3 (continued)

List of units

1	2	3	4	5	6	7	8
No.	Quantity	SI unit[1]		Other units		Relationship[1]	Remarks
		Name	Symbol	Name	Symbol		
4.4	Cyclic frequency	reciprocal second	1/s				
4.5	Velocity	metre per second	m/s				
				kilometre per hour	km/h	$1\ \text{km/h} = \frac{1}{3.6}\ \text{m/s}$	
4.6	Acceleration	metre per second squared	m/s^2				
4.7	Angular velocity	radian per second	rad/s				
4.8	Angular acceleration	radian per second squared	rad/s^2				

[1] See also notes to columns 3 and 4 and to column 7 on page 15.

(continued)

Table 1-3 (continued)

List of units

1	*2*	*3*	*4*	*5*	*6*	*7*	*8*
No.	Quantity	SI unit[1)]		Other units		Relationship[1)]	Remarks
		Name	Symbol	Name	Symbol		
5	**Force, energy, power**						Units of weight as a quantity of force are the units of force, see DIN 1305.
5.1	Force	newton	N			1 N = 1 kg m/s^2	
5.2	Momentum	newton-second	Ns			1 Ns = 1 kg m/s	
5.3	Pressure	pascal	Pa			1 Pa = 1 N/m^2	see Note to columns 3 and 4
				bar	bar	1 bar = 10^5 Pa	see DIN 1314

1) See also notes to columns 3 and 4 and to column 7 on page 15.

(*continued)*

Table 1-3 (continued)

List of units

1	*2*	*3*	*4*	*5*	*6*	*7*	*8*
No.	Quantity	SI unit[1]		Other units		Relationship[1]	Remarks
		Name	Symbol	Name	Symbol		
5.4	Mechanical stress	newton per square metre, pascal	N/m^2, Pa			1 Pa = 1 N/m^2	In many technical fields it has been agreed to express mechanical stress and strength in N/mm^2. 1 N/mm^2 = 1 MPa.
5.5	Energy, work, quantity of heat	joule	J			1 J = 1 Nm = 1 Ws = 1 kg m^2/s^2	see DIN 1345
				kilowatt-hour electron volt	kWh eV	1 kWh = 3.6 MJ 1 eV = $1.60219 \cdot 10^{-19}$ J	At the present state of measuring technology the 3-fold standard deviation for the relationship given in col. 7 is $\pm 2 \cdot 10^{-24}$ J.
5.6	Torque	newton-metre	Nm			1 Nm = 1 J = 1 Ws	
5.7	Angular momentum	newton-second-metre	Nsm			1 Nsm = 1 kg m^2/s	

[1] See also notes to columns 3 and 4 and to column 7 on page 15.

(continued)

Table 1-3 (continued)

List of units

1	2	3	4	5	6	7	8
No.	Quantity	SI unit[1]		Other units		Relationship[1]	Remarks
		Name	Symbol	Name	Symbol		
5.8	Power energy flow, heat flow	watt	W			1 W = 1 J/s =1 N m/s = 1 VA	The watt is also termed volt-ampere (standard symbol VA) when expressing electrical apparent power, and Var (standard symbol var) when expressing electrical reactive power, see DIN 40110.
6	**Viscometric quantities**						
6.1	Dynamic viscosity	pascal-second	Pas			1 Pas = 1 Ns/m^2 = 1 kg/(sm)	see DIN 1342
6.2	Kinematic viscosity	square metre per second	m^2/s				see DIN 1342

[1] See also notes to columns 3 and 4 and to column 7 on page 15.

(*continued)*

Table 1-3 (continued)

List of units

1	*2*	*3*	*4*	*5*	*6*	*7*	*8*
No.	Quantity	SI unit[1]		Other units		Relationship[1]	Remarks
		Name	Symbol	Name	Symbol		
7	**Temperature and heat**						
7.1	Temperature	kelvin	K				Thermodynamic temperature; see Note to No. 7.1 and DIN 1345. Kelvin is also the unit for temperature differences and intervals.
				degree Celsius (centigrade)	° C	The degree Celsius is the special name for kelvin when expressing Celsius temperatures.	Expression of Celsius temperatures and Celsius temperature differences, see Note to No 7.1.
7.2	Thermal diffusivity	square metre per second	m^2/s				see DIN 1341
7.3	Entropy, thermal capacity	joule per kelvin	J/K				see DIN 1345
7.4	Thermal conductivity	watt per kelvin-metre	W/(K m)				see DIN 1341

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[1] See also notes to columns 3 and 4 and to column 7 on page 15.

(*continued)*

Table 1-3 (continued)

List of units

1	*2*	*3*	*4*	*5*	*6*	*7*	*8*
No.	Quantity	SI unit[1]		Other units		Relationship[1]	Remarks
		Name	Symbol	Name	Symbol		
7.5	Heat transfer coefficient	watt per kelvin-square metre	$W/(Km^2)$				see DIN 1341
8	**Electrical and magnetic quantities**						
8.1	Electric current, magnetic potential difference	ampere	A				see DIN 1324 and DIN 1325
8.2	Electric voltage, electric potential difference	volt	V			1 V =1 W/A	see DIN 1323
8 3	Electric conductance	siemens	S			1 S = A/V	see Note to columns 3 and 4 and also DIN 1324
8.4	Electric resistance	ohm	Ω			1 Ω = 1/S	see DIN 1324

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[1] See also notes to columns 3 and 4 and to column 7 on page 15.

(continued)

Table 1-3 (continued)

List of units

1	*2*	*3*	*4*	*5*	*6*	*7*	*8*
No.	Quantity	SI unit[1]		Other units		Relationship[1]	Remarks
		Name	Symbol	Name	Symbol		
8.5	Quantity of electricity, electric charge	coulomb	C	 ampere-hour	 Ah	1 C = 1 As 1 Ah = 3600 As	see DIN 1324
8.6	Electric capacitance	farad	F			1 F = 1 C/V	see DIN 1357
8.7	Electric flux density	coulomb per square metre	C/m^2				see DIN 1324
8.8	Electric field strength	volt per metre	V/m				see DIN 1324
8.9	Magnetic flux	weber, volt-second	Wb, Vs			1 Wb = 1 Vs	see DIN 1325
8.10	Magnetic flux density, (induction)	tesla	T			$1\ T = 1\ Wb/m^2$	see DIN 1325
8.11	Inductance (permeance)	henry	H			1 H = 1 Wb/A	see DIN 1325

[1] See also notes to columns 3 and 4 and to column 7 on page 15.

(*continued)*

Table 1-3 (continued)

List of units

1	*2*	*3*	*4*	*5*	*6*	*7*	*8*
No.	Quantity	SI unit[1)]		Other units		Relationship[1)]	Remarks
		Name	Symbol	Name	Symbol		
8.12	Magnetic field intensity	ampere per metre	A/m				see DIN 1325
9	**Photometric quantities**						
9.1	Luminous intensity	candela	cd				see DIN 5031 Part 3. The word candela is stressed on the 2nd syllable.
9.2	Luminance	candela per square metre	cd/m^2				see DIN 5031 Part 3
9.3	Luminous flux	lumen	lm			1 lm = 1 cd · sr	see DIN 5031 Part 3
9.4	Illumination	lux	lx			$1\ lx = 1\ lm/m^2$	see DIN 5031 Part 3

1) See also notes to columns 3 and 4 and to column 7 on page 15.

Notes to Table 1-3

To column 7:

A number having the last digit in bold type denotes that this number is defined by agreement (see DIN 1333).

To No. 1.1:

The nautical mile is still used for marine navigation (1 nm = 1852 m). For conversion from inches to millimetres see DIN 4890, DIN 4892, DIN 4893.

To No. 3.5:

When converting the so-called “flywheel inertia GD^2” into a mass moment of inertia J, note that the numerical value of GD^2 in kp m^2 is equal to four times the numerical value of the mass moment of inertia J in kg m^2.

To No. 4.1:

Since the year is defined in different ways, the particular year in question should be specified where appropriate.

3 h always denotes a time span (3 hours), but 3^h a moment in time (3 o’clock). When moments in time are stated in mixed form, e.g. $2^h25^m3^s$, the abbreviation min may be shortened to m (see DIN 1355).

To No. 7.1:

The (thermodynamic) temperature *(T)*, also known as “absolute temperature”, is the physical quantity on which the laws of thermodynamics are based. For this reason, only this temperature should be used in physical equations. The unit kelvin can also be used to express temperature differences.

Celsius (centigrade) temperature *(t)* is the special difference between a given thermodynamic temperature T and a temperature of $T_0 = 273.15$ K.

Thus,

$$t = T - T_0 = T - 273.15 \text{ K}. \qquad (1)$$

When expressing Celsius temperatures, the standard symbol °C is to be used.

The difference Δ t between two Celsius temperatures, e. g. the temperatures $t_1 = T_1 - T_0$ and $t_2 = T_2 - T_0$, is

$$\Delta t = t_1 - t_2 = T_1 - T_2 = \Delta T \qquad (2)$$

A temperature difference of this nature is no longer referred to the thermodynamic temperature T_0, and hence is not a Celsius temperature according to the definition of Eq. (1).

However, the difference between two Celsius temperatures may be expressed either in kelvin or in degrees Celsius, in particular when stating a range of temperatures, e. g. (20 ± 2) °C

Thermodynamic temperatures are often expressed as the sum of T_0 and a Celsius temperature t, i. e. following Eq. (1)

$$T = T_0 + t \qquad (3)$$

and so the relevant Celsius temperatures can be put in the equation straight away. In this case the kelvin unit should also be used for the Celsius temperature (i. e. for the “special thermodynamic temperature difference”). For a Celsius temperature of 20 °C, therefore, one should write the sum temperature as

$$T = T_0 + t = 273.15 \text{ K} + 20 \text{ K} = 293.15 \text{ K} \qquad (4)$$

1.1.2 Other units still in common use; metric, British and US measures

Some of the units listed below may be used for a limited transition period and in certain exceptional cases. The statutory requirements vary from country to country.

ångström	Å	length	1 Å = 0.1 nm = 10^{-10}m
atmosphere physical	atm	pressure	1 atm = 101 325 Pa
atmosphere technical	at, ata	pressure	1 at = 98 066.5 Pa
British thermal unit	Btu	quantity of heat	1 Btu ≈ 1055.056 J
calorie	cal	quantity of heat	1 cal = 4.1868 J
centigon	c	plane angle	1 c = 1 cgon = $5 \pi \cdot 10^{-5}$ rad
degree	deg, grd	temperature difference	1 deg = 1 K
degree fahrenheit	°F	temperature	$T_K = 273.15 + (5/9) \cdot (t_F - 32)$
dyn	dyn	force	1 dyn = 10^{-5} N
erg	erg	energy	1 erg = 10^{-7} J
foot	ft	length	1 ft = 0.3048 m
gallon (UK)	gal (UK)	volume	1 gal (UK) ≈ $4.54609 \cdot 10^{-3}$ m^3
gallon (US)	gal (US)	liquid volume	1 gal (US) ≈ $3.78541 \cdot 10^{-3}$ m^3
gauss	G.Gs	magnetic flux density	1 G = 10^{-4}T
gilbert	Gb	magnetic potential difference	1 Gb = $(10/4\ \pi)$ A
gon	g	plane angle	1 g = 1 gon = $5 \pi \cdot 10^{-3}$ rad
horsepower	hp	power	1 hp ≈ 745.700 W
hundredweight (long)	cwt	mass	1 cwt ≈ 50.8023 kg
inch (inches)	in, ″	length	1 in = 25.4 mm = $254 \cdot 10^{-4}$ m
international ampere	A_{int}	electric current	1 A_{int} ≈ 0.99985 A
international farad	F_{int}	electrical capacitance	1 F_{int} = (1/1.00049) F
international henry	H_{int}	inductance	1 H_{int} = 1.00049 H
international ohm	Ω_{int}	electrical resistance	1 Ω_{int} = 1.00049 Ω
international volt	V_{int}	electrical potential	1 V_{int} = 1.00034 V
international watt	W_{int}	power	1 W_{int} ≈ 1.00019 W
kilogramme-force, kilopond	kp, kgf	force	1 kp = 9.80665 N ≈ 10 N

Unit of mass	ME	mass	1 ME = 9.80665 kg
maxwell	M, Mx	magnetic flux	1 M = 10 nWb = 10^{-8} Wb
metre water column	mWS	pressure	1 mWS = 9806.65 PA ≈ 0,1 bar
micron	µ	length	1 µ = 1 µm = 10^{-6} m
millimetres of mercury	mm Hg	pressure	1 mm Hg ≈ 133.322 Pa
milligon	cc	plane angle	1 cc = 0.1 mgon = $5 \pi \cdot 10^{-7}$ rad
oersted	Oe	magnetic field strength	10e = (250/π) A/m
Pferdestärke, cheval-vapeur	PS, CV	power	1 PS = 735.49875 W
Pfund	Pfd	mass	1 Pfd = 0.5 kg
pieze	pz	pressure	1 pz = 1 mPa = 10^{-3} Pa
poise	P	dynamic viscosity	1 P = 0.1 Pa · s
pond, gram -force	p, gf	force	1 p = $9.80665 \cdot 10^{-3}$ N ≈ 10 mN
pound[1]	Ib	mass	1 Ib ≈ 0.453592 kg
poundal	pdl	force	1 pdl ≈ 0.138255 N
poundforce	Ibf	force	1 Ibf ≈ 4.44822 N
sea mile, international	n mile	length (marine)	1 n mile = 1852 m
short hundredweight	sh cwt	mass	1 sh cwt ≈ 45.3592 kg
stokes	St	kinematic viscosity	1 St = 1 cm^2/s = 10^{-4} m^2/s
torr	Torr	pressure	1 Torr ≈ 133.322 Pa
typographical point	p	length (printing)	1 p = (1.00333/2660) m ≈ 0.4 mm
yard	yd	length	1 yd = 0.9144 m
Zentner	z	mass	1 z = 50 kg

[1] UK and US pounds avoirdupois differ only after the sixth decimal place.

Table 1-4

Metric, British and US linear measure

Metric units of length					British and US units of length				
Kilometre	Metre	Decimetre	Centimetre	Millimetre	Mile	Yard	Foot	Inch	Mil
km	m	dm	cm	mm	mile	yd	ft	in or "	mil
1	1 000	10 000	100 000	1 000 000	0.6213	1 093.7	3 281	39 370	$3\ 937 \cdot 10^4$
0.001	1	10	100	1 000	$0.6213 \cdot 10^{-3}$	1.0937	3.281	39.370	39 370
0.0001	0.1	1	10	100	$0.6213 \cdot 10^{-4}$	0.1094	0.3281	3.937	3 937.0
0.00001	0.01	0.1	1	10	$0.6213 \cdot 10^{-5}$	0.01094	0.03281	0.3937	393.70
0.000001	0.001	0.01	0.1	1	$0.6213 \cdot 10^{-6}$	0.001094	0.003281	0.03937	39.37
1.60953	1 609.53	16 095.3	160 953	1 609 528	1	1 760	5 280	63 360	$6\ 336 \cdot 10^4$
0.000914	0.9143	9.1432	91.432	914.32	$0.5682 \cdot 10^{-3}$	1	3	36	36 000
$0.305 \cdot 10^{-3}$	0.30479	3.0479	30.479	304.79	$0.1894 \cdot 10^{-3}$	0.3333	1	12	12 000
$0.254 \cdot 10^{-4}$	0.02539	0.25399	2.53997	25.3997	$0.158 \cdot 10^{-4}$	0.02777	0.0833	1	1 000
$0.254 \cdot 10^{-7}$	$0.254 \cdot 10^{-4}$	$0.254 \cdot 10^{-3}$	0.00254	0.02539	$0.158 \cdot 10^{-7}$	$0.0277 \cdot 10^{-3}$	$0.0833 \cdot 10^{-3}$	0.001	1

Special measures: 1 metric nautical mile = 1852 m
1 metric land mile = 7500 m
1 Brit. or US nautical mile = 1855 m
1 micron (μ) = 1/1000 mm = 10 000 Å

Table 1-5

Metric, British and US square measure

Metric units of area					British and US units of area				
Square kilometres km^2	Square metre m^2	Square decim. dm^2	Square centim. cm^2	Square millim. mm^2	Square mile sq.mile	Square yard sq.yd	Square foot sq.ft	Square inch sq.in	Circular mils cir.mils
1	$1 \cdot 10^{6}$	$100 \cdot 10^{6}$	$100 \cdot 10^{8}$	$100 \cdot 10^{10}$	0.386013	$1\,196 \cdot 10^{3}$	$1076 \cdot 10^{4}$	$1\,550 \cdot 10^{6}$	$197.3 \cdot 10^{13}$
$1 \cdot 10^{-6}$	1	100	10 000	1 000 000	$0.386 \cdot 10^{-6}$	1.1959	10.764	1 550	$197.3 \cdot 10^{7}$
$1 \cdot 10^{-8}$	$1 \cdot 10^{-2}$	1	100	10 000	$0.386 \cdot 10^{-8}$	0.01196	0.10764	15.50	$197.3 \cdot 10^{5}$
$1 \cdot 10^{-10}$	$1 \cdot 10^{-4}$	$1 \cdot 10^{-2}$	1	100	$0.386 \cdot 10^{-10}$	$0.1196 \cdot 10^{-3}$	$0.1076 \cdot 10^{-2}$	0.1550	$197.3 \cdot 10^{3}$
$1 \cdot 10^{-12}$	$1 \cdot 10^{-6}$	$1 \cdot 10^{-4}$	$1 \cdot 10^{-2}$	1	$0.386 \cdot 10^{-12}$	$0.1196 \cdot 10^{-5}$	$0.1076 \cdot 10^{-4}$	0.00155	1 973
2.58999	2 589 999	$259 \cdot 10^{6}$	$259 \cdot 10^{8}$	$259 \cdot 10^{10}$	1	$30\,976 \cdot 10^{2}$	$27\,878 \cdot 10^{3}$	$40\,145 \cdot 10^{5}$	$5\,098 \cdot 10^{12}$
$0.8361 \cdot 10^{-6}$	0.836130	83.6130	8 361.307	836 130.7	$0.3228 \cdot 10^{-6}$	1	9	1296	$1\,646 \cdot 10^{6}$
$9.290 \cdot 10^{-8}$	$9.290 \cdot 10^{-2}$	9.29034	929.034	92 903.4	$0.0358 \cdot 10^{-6}$	0.11111	1	144	$183 \cdot 10^{6}$
$6.452 \cdot 10^{-10}$	$6.452 \cdot 10^{-4}$	$6.452 \cdot 10^{-2}$	6.45162	645.162	$0.2396 \cdot 10^{-9}$	$0.7716 \cdot 10^{-3}$	0.006940	1	$1.27 \cdot 10^{6}$
$506.7 \cdot 10^{-18}$	$506.7 \cdot 10^{-12}$	$506.7 \cdot 10^{-10}$	$506.7 \cdot 10^{-8}$	$506.7 \cdot 10^{-6}$	$0.196 \cdot 10^{-15}$	$0.607 \cdot 10^{-9}$	$0.00547 \cdot 10^{-6}$	$0.785 \cdot 10^{-6}$	1

Special measures:
1 hectare (ha) = 100 are (a)
1 are (a) = 100 m^2
1 Bad. morgen = 56 a = 1.38 acre
1 Prussian morgen = 25.53 a = 0.63 acre
1 Württemberg morgen = 31.52 a = 0.78 acre
1 Hesse morgen = 25.0 a = 0.62 acre
1 Tagwerk (Bavaria) = 34.07 a = 0.84 acre
1 sheet of paper = 86 x 61 cm
gives 8 pieces size A4 or 16 pieces A5
or 32 pieces A6

1 section (sq.mile) = 64 acres = 2,589 km^2
1 acre = 4840 sq.yds = 40.468 a
1 sq. pole = 30.25 sq.yds = 25.29 m^2
} USA

1 acre = 160 sq.poles = 4840 sq.yds = 40.468 a
1 yard of land = 30 acres = 1214.05 a
1 mile of land = 640 acres = 2.589 km^2
} Brit.

Table 1-6

Metric, British and US cubic measures

Metric units of volume				British and US units of volume			US liquid measure		
Cubic metre	Cubic decimetre	Cubic centimetre	Cubic millimetre	Cubic yard	Cubic foot	Cubic inch	Gallon	Quart	Pint
m^3	dm^3	cm^3	mm^3	cu.yd	cu.ft	cu.in	gal	quart	pint
1	1 000	$1\,000 \cdot 10^3$	$1\,000 \cdot 10^6$	1.3079	35.32	$61 \cdot 10^3$	264.2	1 056.8	2 113.6
$1 \cdot 10^{-3}$	1	1 000	$1\,000 \cdot 10^3$	$1.3079 \cdot 10^{-3}$	0.03532	61.023	0.2642	1.0568	2.1136
$1 \cdot 10^{-6}$	$1 \cdot 10^{-3}$	1	1 000	$1.3079 \cdot 10^{-6}$	$0.3532 \cdot 10^{-4}$	0.061023	$0.2642 \cdot 10^{-3}$	$1.0568 \cdot 10^{-3}$	$2.1136 \cdot 10^{-3}$
$1 \cdot 10^{-9}$	$1 \cdot 10^{-6}$	$1 \cdot 10^{-3}$	1	$1.3079 \cdot 10^{-9}$	$0.3532 \cdot 10^{-7}$	$0.610 \cdot 10^{-4}$	$0.2642 \cdot 10^{-6}$	$1.0568 \cdot 10^{-6}$	$2.1136 \cdot 10^{-6}$
0.764573	764.573	764 573	$764\,573 \cdot 10^3$	1	27	46 656	202	808	1 616
0.0283170	28.31701	28 317.01	28 317 013	0.037037	1	1 728	7.48224	29.92896	59.85792
$0.1638 \cdot 10^{-4}$	0.0163871	16.38716	16387.16	$0.2143 \cdot 10^{-4}$	$0.5787 \cdot 10^{-3}$	1	0.00433	0.01732	0.03464
$3.785 \cdot 10^{-3}$	3.785442	3 785.442	3 785 442	0.0049457	0.1336797	231	1	4	8
$0.9463 \cdot 10^{-3}$	0.9463605	946.3605	946 360.5	0.0012364	0.0334199	57.75	0.250	1	2
$0.4732 \cdot 10^{-3}$	0.4731802	473.1802	473 180.2	0.0006182	0.0167099	28.875	0.125	0.500	1

Table 1-7

Conversion tables

Millimetres to inches, formula: mm x 0.03937 = inch

mm	0	1	2	3	4	5	6	7	8	9
0		0.03937	0.07874	0.11811	0.15748	0.19685	0.23622	0.27559	0.31496	0.35433
10	0.39370	0.43307	0.47244	0.51181	0.55118	0.59055	0.62992	0.66929	0.70866	0.74803
20	0.78740	0.82677	0.86614	0.90551	0.94488	0.98425	1.02362	1.06299	1.10236	1.14173
30	1.18110	1.22047	1.25984	1.29921	1.33858	1.37795	1.41732	1.45669	1.49606	1.53543
40	1.57480	1.61417	1.65354	1.69291	1.73228	1.77165	1.81102	1.85039	1.88976	1.92913
50	1.96850	2.00787	2.04724	2.08661	2.12598	2.16535	2.20472	2.24409	2.28346	2.32283

Inches to millimetres, formula: inches x 25.4 = mm

inch	0	1	2	3	4	5	6	7	8	9
0		25.4	50.8	76.2	101.6	127.0	152.4	177.8	203.2	228.6
10	254.0	279.4	304.8	330.2	355.6	381.0	406.4	431.8	457.2	482.6
20	508.0	533.4	558.8	584.2	609.6	635.0	660.4	685.8	711.2	736.6
30	762.0	787.4	812.8	838.2	863.6	889.0	914.4	939.8	965.2	990.8
40	1 016.0	1 041.4	1 066.8	1 092.2	1 117.6	1 143.0	1 168.4	1 193.8	1 219.2	1 244.6
50	1 270.0	1 295.4	1 320.8	1 246.2	1 371.6	1 397.0	1 422.4	1 447.8	1 473.2	1 498.6

Fractions of inch to millimetres

inch	mm	inch	mm	inch	mm	inch	mm	inch	mm
1/64	0.397	7/32	5.556	27/64	10.716	5/8	15.875	53/64	21.034
1/32	0.794	15/64	5.953	7/16	11.112	41/64	16.272	27/32	21.431
3/64	1.191	1/4	6.350	29/64	11.509	21/32	16.669	55/64	21.828
1/16	1.587	17/64	6.747	15/32	11.906	43/64	17.066	7/8	22.225
5/64	1.984	9/32	7.144	31/64	12.303	11/16	17.462	57/64	22.622
3/32	2.381	19/64	7.541	1/2	12.700	45/64	17.859	29/32	23.019
7/64	2.778	5/6	7.937	33/64	13.097	23/32	18.256	59/64	23.416
1/8	3.175	21/64	8.334	17/32	13.494	47/64	18.653	15/16	23.812
9/64	3.572	11/32	8.731	35/64	13.891	3/4	19.050	61/64	24.209
5/32	3.969	23/64	9.128	9/16	14.287	49/64	19.447	31/32	24.606
11/64	4.366	3/8	9.525	37/64	14.684	25/32	19.844	63/64	25.003
3/16	4.762	25/64	9.922	19/32	15.081	51/64	20.241	1	25.400
13/64	5.159	13/32	10.319	39/64	15.478	13/16	20.637	2	50.800

1.1.3 Fundamental physical constants

General gas constant: $R = 8.3166\ J\ K^{-1}\ mol^{-1}$
is the work done by one mole of an ideal gas under constant pressure (1013 hPa) when its temperature rises from 0 °C to 1 °C.

Avogadro's constant: N_A (Loschmidt's number N_L): $N_A = 6.0225 \cdot 10^{23}\ mol^{-1}$
number of molecules of an ideal gas in one mole.
When $V_m = 2.2414 \cdot 10^4\ cm^3 \cdot mol^{-1}$: $N_A/V_m = 2.686\ 10^{19}\ cm^{-3}$.

Atomic weight of the carbon atom: $^{12}C = 12.0000$
is the reference quantity for the relative atomic weights of fundamental substances.

Base of natural logarithms: $e = 2.718282$

Bohr's radius: $r_1 = 0.529 \cdot 10^{-8}$ cm
radius of the innermost electron orbit in Bohr's atomic model

Boltzmann's constant: $k = \frac{R}{N_A} = 1.38 \cdot 10^{-23}\ J \cdot K^{-1}$

is the mean energy gain of a molecule or atom when heated by 1 K.

Elementary charge: $e_o = F/N_A = 1.602 \cdot 10^{-19}$ As
is the smallest possible charge a charge carrier (e.g. electron or proton) can have.

Electron-volt: $eV = 1.602 \cdot 10^{-19}$ J

Energy mass equivalent: $8.987 \cdot 10^{13}\ J \cdot g^{-1} = 1.78 \cdot 10^{-27}\ g\ (MeV)^{-1}$
according to Einstein, following $E = m \cdot c^2$, the mathematical basis for all observed transformation processes in sub-atomic ranges.

Faraday's constant: $F = 96\,480\ As \cdot mol^{-1}$
is the quantity of current transported by one mole of univalent ions.

Field constant, electrical: $\varepsilon_o = 0.885419 \cdot 10^{-11}\ F \cdot m^{-1}$.
a proportionality factor relating charge density to electric field strength.

Field constant, magnetic: $\mu_0 = 4 \cdot \pi \cdot 10^{-7}\ H \cdot m^{-1}$
a proportionality factor relating magnetic flux density to magnetic field strength.

Gravitational constant: $\gamma = 6.670 \cdot 10^{-11}\ m^4 \cdot N^{-1} \cdot s^{-4}$
is the attractive force in N acting between two masses each of 1 kg weight separated by a distance of 1 m.

Velocity of light in vacuo: $c = 2.99792 \cdot 10^8\ m \cdot s^{-1}$
maximum possible velocity. Speed of propagation of electro-magnetic waves.

Mole volume: $V_m = 22\,414\ cm^3 \cdot mol^{-1}$
the volume occupied by one mole of an ideal gas at 0 °C and 1013 mbar. A mole is that quantity (mass) of a substance which is numerically equal in grammes to the molecular weight (1 mol H_2 = 2 g H_2)

Planck's constant: $h = 6.625 \cdot 10^{-34}\ J \cdot s$
a proportionality factor relating energy and frequency of a light quantum (photon).

Stefan Boltzmann's radiation constant: $\delta = 5.6697 \cdot 10^{-8}\ W \cdot m^{-2}\ K^{-4}$ relates radiant energy to the temperature of a radiant body. Radiation coefficient of a black body.

Temperature of absolute zero: $T_0 = -273.16$ °C = 0 K.

Wave impedance of space: $\Gamma_0 = 376.73\ \Omega$
coefficient for the H/E distribution with electromagnetic wave propagation.

$$\Gamma_0 = \sqrt{\mu_0/\varepsilon_0} = \mu_0 \cdot c = 1/(\varepsilon_0 \cdot c)$$

Weston standard cadmium cell: $E_0 = 1.0186$ V at 20 °C.

Wien's displacement constant: $A = 0.28978\ cm \cdot K$
enables the temperature of a light source to be calculated from its spectrum.

1.2 Physical, chemical and technical values

1.2.1 Electrochemical series

If different metals are joined together in a manner permitting conduction, and both are wetted by a liquid such as water, acids, etc., an electrolytic cell is formed which gives rise to corrosion. The amount of corrosion increases with the differences in potential. If such conducting joints cannot be avoided, the two metals must be insulated from each other by protective coatings or by constructional means. In outdoor installations, therefore, aluminium/copper connectors or washers of copper-plated aluminium sheet are used to join aluminium and copper, while in dry indoor installations aluminium and copper may be joined without the need for special protective measures.

Table 1-8

Electrochemical series, normal potentials against hydrogen, in volts.

1. Lithium	approx. – 3.02	10. Zinc	approx. – 0.77	19. Hydrogen	approx. 0.0
2. Potassium	approx. – 2.95	11. Chromium	approx. – 0.56	20. Antimony	approx. + 0.2
3. Barium	approx. – 2.8	12. Iron	approx. – 0.43	21. Bismuth	approx. + 0.2
4. Sodium	approx. – 2.72	13. Cadmium	approx. – 0.42	22. Arsenic	approx. + 0.3
5. Strontium	approx. – 2.7	14. Thallium	approx. – 0.34	23. Copper	approx. + 0.35
6. Calcium	approx. – 2.5	15. Cobalt	approx. – 0.26	24. Silver	approx. + 0.80
7. Magnesium	approx. – 1.8	16. Nickel	approx. – 0.20	25. Mercury	approx. + 0.86
8. Aluminium	approx. – 1.45	17. Tin	approx. – 0.146	26. Platinum	approx. + 0.87
9. Manganese	approx. – 1.1	18. Lead	approx. – 0.132	27. Gold	approx. + 1.5

If two metals included in this table come into contact, the metal mentioned first will corrode.

The less noble metal becomes the anode and the more noble acts as the cathode. As a result, the less noble metal corrodes and the more noble metal is protected.

Metallic oxides are always less strongly electronegative, i. e. nobler in the electrolytic sense, than the pure metals. Electrolytic potential differences can therefore also occur between metal surfaces which to the engineer appear very little different. Even though the potential differences for cast iron and steel, for example, with clean and rusty surfaces are small, as shown in Table 1-9, under suitable circumstances these small differences can nevertheless give rise to significant direct currents, and hence corrosive attack.

Table 1-9

Standard potentials of different types of iron against hydrogen, in volts

SM steel, clean surface	approx. – 0.40	cast iron, rusty	approx. – 0.30
cast iron, clean surface	approx. – 0.38	SM steel, rusty	approx. – 0.25

1.2.2 Faraday's law

1. The amount m (mass) of the substances deposited or converted at an electrode is proportional to the quantity of electricity $Q = I \cdot t$.

   $m \sim I \cdot t$

2. The amounts m (masses) of the substances converted from different electrolytes by equal quantities of electricity $Q = I \cdot t$ behave as their electrochemical equivalent masses M^*. The equivalent mass M^* is the molar mass M divided by the electrochemical valency n (a number). The quantities M and M^* can be stated in g/mol.

$$m = \frac{M^*}{F} I \cdot t$$

If during electroysis the current I is not constant, the product $I \cdot$ t must be represented by the integral $\int_{t_1}^{t_2} I\,\mathrm{d}t$.

The quantity of electricity per mole necessary to deposit or convert the equivalent mass of 1 g/mol of a substance (both by oxidation at the anode and by reduction at the cathode) is equal in magnitude to Faraday's constant (F = 96480 As/mol).

Table 1-10

Electrochemical equivalents[1)]

	Valency n	Equivalent mass[2)] g/mol	Quantity precipitated, theoretical g/Ah	Approximate optimum current efficiency %
Aluminium	3	8.9935	0.33558	85 … 98
Cadmium	2	56.20	2.0970	95 … 95
Caustic potash	1	56.10937	2.0036	95
Caustic soda	1	30.09717	1.49243	95
Chlorine	1	35.453	1.32287	95
Chromium	3	17.332	0.64672	—
Chromium	6	8.666	0.32336	10 … 18
Copper	1	63.54	2.37090	65 … 98
Copper	2	31.77	1.18545	97 … 100
Gold	3	65.6376	2.44884	—
Hydrogen	1	1.00797	0.037610	100
Iron	2	27.9235	1.04190	95 … 100
Iron	3	18.6156	0.69461	—
Lead	2	103.595	3.80543	95 … 100
Magnesium	2	12.156	0.45358	—
Nickel	2	29.355	1.09534	95 … 98
Nickel	3	19.57	0.73022	—
Oxygen	2	7.9997	0.29850	100
Silver	1	107.870	4.02500	98 … 100
Tin	2	59.345	2.21437	70 … 95
Tin	4	29.6725	1.10718	70 … 95
Zinc	2	32.685	1.21959	85 … 93

1) Relative to the carbon-12 isotope = 12.000.

2) Chemical equivalent mass is molar mass/valency in g/mol.

Example:

Copper and iron earthing electrodes connected to each other by way of the neutral conductor form a galvanic cell with a potential difference of about 0.7 V (see Table 1-8). These cells are short-circuited via the neutral conductor. Their internal resistance is determined by the earth resistance of the two earth electrodes. Let us say the sum of all these resistances is 10 Ω. Thus, if the drop in “short-circuit emf” relative to the “open-circuit emf” is estimated to be 50 % approximately, a continuous corrosion current of 35 mA will flow, causing the iron electrode to decompose. In a year this will give an electrolytically active quantity of electricity of

$$35\ \mathrm{mA} \cdot 8760\ \frac{\mathrm{h}}{\mathrm{a}} = 306\ \frac{\mathrm{Ah}}{\mathrm{a}}\,.$$

Since the equivalent mass of bivalent iron is 27.93 g/mol, the annual loss of weight from the iron electrode will be

$$m = \frac{27.93\ \mathrm{g/mol}}{96480\ \mathrm{As/mol}} \cdot 306\ \mathrm{Ah/a} \cdot \frac{3600\ \mathrm{s}}{\mathrm{h}} = 320\ \mathrm{g/a}.$$

1.2.3 Thermoelectric series

If two wires of two different metals or semiconductors are joined together at their ends and the two junctions are exposed to different temperatures, a thermoelectric current flows in the wire loop (Seebeck effect, thermocouple). Conversely, a temperature difference between the two junctions occurs if an electric current is passed through the wire loop (Peltier effect).

The thermoelectric voltage is the difference between the values, in millivolts, stated in Table 1-11. These relate to a reference wire of platinum and a temperature difference of 100 K.

Table 1-11

Thermoelectric series, values in mV, for platinum as reference and temperature difference of 100 K

Bismut ll axis	−7.7	Rhodium	0.65
Bismut ⊥ axis	−5.2	Silver	0.67 … 0.79
Constantan	−3.37 … −3.4	Copper	0.72 … 0.77
Cobalt	−1.99 … −1.52	Steel (V2A)	0.77
Nickel	−1.94 … −1.2	Zinc	0.6 … 0.79
Mercury	−0.07 … +0.04	Manganin	0.57 … 0.82
Platinum	± 0	Irdium	0.65 … 0.68
Graphite	0.22	Gold	0.56 … 0.8
Carbon	0.25 … 0.30	Cadmium	0.85 … 0.92
Tantalum	0.34 … 0.51	Molybdenum	1.16 … 1.31
Tin	0.4 … 0.44	Iron	1.87 … 1.89
Lead	0.41 … 0.46	Chrome nickel	2.2
Magnesium	0.4 … 0.43	Antimony	4.7 … 4.86
Aluminium	0.37 … 0.41	Silicon	44.8
Tungsten	0.65 … 0.9	Tellurium	50
Common thermocouples			
Copper/constantan (Cu/const)	up to 500 °C	Nickel chromium/nickel (NiCr/Ni)	up to 1 000 °C
Iron/constantan (Fe/const)	up to 700 °C	Platinum rhodium/ platinum	up to 1 600 °C
Nickel chromium/ constantan	up to 800 °C	Platinum rhodium/ platinum rhodium	up to 1 800 °C

1.2.4 pH value

The pH value is a measure of the “acidity” of aqueous solutions. It is defined as the logarithm to base 10 of the reciprocal of the hydrogen ion concentration CH_3O1).

$$pH \equiv -\log CH_3O.$$

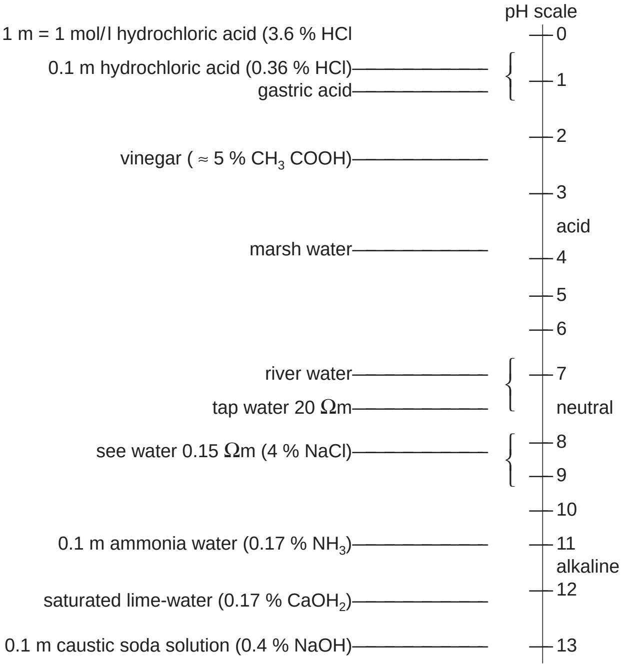


Fig. 1-1

pH value of some solutions

1) CH_3O = Hydrogen ion concentration in mol/l.

1.2.5 Heat transfer

Heat content (enthalpy) of a body: $Q = V \cdot \rho \cdot c \cdot \Delta\vartheta$
V volume, ρ density, c specific heat, $\Delta\vartheta$ temperature difference

Heat flow is equal to enthalpy per unit time:

$$\Phi = Q/t$$

Heat flow is therefore measured in watts (1 W = 1 J/s).

Specific heat (specific thermal capacity) of a substance is the quantity of heat required to raise the temperature of 1 kg of this substance by 1 °C. Mean specific heat relates to a temperature range, which must be stated. For values of c and λ, see Section 1.2.7.

Thermal conductivity is the quantity of heat flowing per unit time through a wall 1 m^2 in area and 1 m thick when the temperatures of the two surfaces differ by 1 °C. With many materials it increases with rising temperature, with magnetic materials (iron, nickel) it first falls to the Curie point, and only then rises (Curie point = temperature at which a ferro-magnetic material becomes non-magnetic, e. g. about 800 °C for Alnico). With solids, thermal conductivity generally does not vary much (invariable only with pure metals); in the case of liquids and gases, on the other hand, it is often strongly influenced by temperature.

Heat can be transferred from a place of higher temperature to a place of lower temperature by

- conduction (heat transmission between touching particles in solid, liquid or gaseous bodies).
- convection (circulation of warm and cool liquid or gas particles).
- radiation (heat transmission by electromagnetic waves, even if there is no matter between the bodies).

The three forms of heat transfer usually occur together.

Heat flow with conduction through a wall:

$$\Phi = \frac{\lambda}{s} \cdot A \cdot \Delta\vartheta$$

A transfer area, λ thermal conductivity, s wall thickness, $\Delta\vartheta$ temperature difference.

Heat flow in the case of transfer by convection between a solid wall and a flowing medium:

$$\Phi = \alpha \cdot A \cdot \Delta\vartheta$$

α heat transfer coefficient, A transfer area, $\Delta\vartheta$ temperature difference.

Heat flow between two flowing media of constant temperature separated by a solid wall:

$$\Phi = k \cdot A \cdot \Delta\vartheta$$

k thermal conductance, A transfer area, $\Delta\vartheta$ temperature difference.

In the case of plane layered walls perpendicular to the heat flow, the thermal conductance coefficient k is obtained from the equation

$$\frac{1}{k} = \frac{1}{\alpha_1} + \sum \frac{s_n}{\lambda_n} + \frac{1}{\alpha_2}$$

Here, α_1 and α_2 are the heat transfer coefficients at either side of a wall consisting of n layers of thicknesses s_n and thermal conductivities λ_n.

For two parallel black surfaces of equal size the heat flow exchanged by radiation is

$$\Phi_{12} = \sigma \cdot A(T_1^4 - T_2^4)$$

With grey radiating surfaces having emissivities of ε_1 and ε_2, it is

$$\Phi_{12} = C_{12} \cdot A\,(T_1^4 - T_2^4)$$

$\sigma = 5.6697 \cdot 10^{-8}\ \mathrm{W \cdot m^{-2} \cdot K^{-4}}$ radiation coefficient of a black body (Stefan Boltzmann's constant), A radiating area, T absolute temperature.

Index 1 refers to the radiating surface, Index 2 to the radiated surface.

C_{12} is the effective radiation transfer coefficient. It is determined by the geometry and emissivity ε of the surface.

Special cases: $A_1 \ll A_2$ $\qquad C_{12} = \sigma \cdot \varepsilon_1$

$A_1 \approx A_2$ $\qquad$ $$C_{12} = \frac{\sigma}{\frac{1}{\varepsilon_1} + \frac{1}{\varepsilon_2} - 1}$$

A_2 includes A_1 $\qquad$ $$C_{12} = \frac{\sigma}{\frac{1}{\varepsilon_1} + \frac{A_1}{A_2} \cdot \left(\frac{1}{\varepsilon_2} - 1\right)}$$

Table 1-12

Emissivity ε (average values $\vartheta < 200$ °C)

Black body	1	Oil	0.82
Aluminium, bright	0.04	Paper	0.85
Aluminium, oxidized	0.5	Porcelain, glazed	0.92
Copper, bright	0.05	Ice	0.96
Copper, oxidized	0.6	Wood (beech)	0.92
Brass, bright	0.05	Roofing felt	0.93
Brass, dull	0.22	Paints	0.8-0.95
Steel, dull, oxidized	0.8	Red lead oxide	0.9
Steel, polished	0.06	Soot	0.94

Table 1-13

Heat transfer coefficients α in $W/(m^2 \cdot K)$ (average values)

Natural air movement in a closed space		
Wall surfaces		10
Floors, ceilings:	in upward direction	7
	in downward direction	5
Force-circulated air		
Mean air velocity w = 2 m/s		20
Mean air velocity w > 5 m/s		$6.4 \cdot w^{0.75}$

1.2.6 Acoustics, noise measurement, noise abatement

Perceived sound comprises the mechanical oscillations and waves of an elastic medium in the frequency range of the human ear of between 16 Hz and 20 000 Hz. Oscillations below 16 Hz are termed infrasound and above 20 000 Hz ultrasound. Sound waves can occur not only in air but also in liquids (water-borne sound) and in solid bodies (solid-borne sound). Solid-borne sound is partly converted into audible air-borne sound at the bounding surfaces of the oscillating body. The frequency of oscillation determines the pitch of the sound. The sound generally propagates spherically from the sound source, as longitudinal waves in gases and liquids and as longitudinal and transverse waves in solids.

Sound propagation gives rise to an alternating pressure, the root-mean-square value of which is termed the sound pressure p. It decreases approximately as the square of the distance from the sound source. The sound power P is the sound energy flowing through an area in unit time. Its unit of measurement is the watt.

Since the sensitivity of the human ear is proportional to the logarithm of the sound pressure, a logarithmic scale is used to represent the sound pressure level as loudness.

The *sound pressure level* L is measured with a sound level metre as the logarithm of the ratio of sound pressure to the reference pressure p_o, see DIN 35 632

$$L = 20 \lg \frac{p}{p_o} \text{ in dB.}$$

Here: p_o reference pressure, roughly the audible threshold at 1000 Hz.

$p_o = 2 \cdot 10^{-5} \text{ N/m}^2 = 2 \cdot 10^{-4}\ \mu\text{bar}$

p = the root-mean-square sound pressure

Example:

$p = 2 \cdot 10^{-3} \text{ N/m}^2$ measured with a sound level metre, then

$$\text{sound level } L = 20 \lg \frac{2 \cdot 10^{-3}}{2 \cdot 10^{-5}} = 40 \text{ dB.}$$

The *loudness* of a sound can be measured as DIN loudness (DIN 5045) or as the weighted sound pressure level. DIN loudness (λ DIN) is expressed in units of DIN phon.

The weighted sound pressure levels L_A, L_B, L_C, which are obtained by switching in defined weighting networks A, B, C in the sound level metre, are stated in the unit dB (decibel). The letters A, B and C must be added to the units in order to distinguish the different values, e. g. dB (A). According to an ISO proposal, the weighted sound pressure L_A in dB (A) is recommended for expressing the loudness of machinery noise. DIN loudness and the weighted sound pressure level, e.g. as recommended in IEC publication 123, are related as follows: for all numerical values above 60 the DIN loudness in DIN phon corresponds to the sound pressure level LB in dB (B), for all numerical values between 30 and 60 to the sound pressure level LA in dB (A). All noise level values are referred to a sound pressure of $2 \cdot 10^{-5}$ N/m^2.

According to VDI guideline 2058, the acceptable loudness of noises must on average not exceed the following values at the point of origin:

Area	Daytime (6–22 hrs) dB (A)	Night-time (22–6 hrs) dB (A)
Industrial	70	70
Commercial	65	50
Composite	60	45
Generally residential	55	40
Purely residential	50	35
Therapy (hospitals, etc.)	45	35

Short-lived, isolated noise peaks can be disregarded.

Disturbing noise is propagated as air- and solid-borne sound. When these sound waves strike a wall, some is thrown back by reflection and some is absorbed by the wall. Air-borne noise striking a wall causes it to vibrate and so the sound is transmitted into the adjacent space. Solid-borne sound is converted into audible air-borne sound by radiation from the bounding surfaces. Ducts, air-shafts, piping systems and the like can transmit sound waves to other rooms. Special attention must therefore be paid to this at the design stage.

There is a logarithmic relationship between the sound pressure of several sound sources and their total loudness.

Total loudness of several sound sources:

A doubling of equally loud sound sources raises the sound level by 3 dB (example: 3 sound sources of 85 dB produce 88 dB together). Several sound sources of different loudness produce together roughly the loudness of the loudest sound source. (Example: 2 sound sources of 80 and 86 dB have a total loudness of 87 dB). In consequence: with 2 equally loud sound sources attenuate both of them, with sound sources of different loudness attentuate only the louder.

An increase in level of 10 dB signifies a doubling, a reduction of 10 dB a halving of the perceived loudness.

In general, noises must be kept as low as possible at their point of origin. This can often be achieved by enclosing the noise sources.

Sound can be reduced by natural means. The most commonly used sound-absorbent materials are porous substances, plastics, cork, glass fibre and mineral wool, etc. The main aim should be to reduce the higher-frequency noise components. This is also generally easier to achieve than eliminating the lower-frequency noise.

When testing walls and ceilings for their behaviour regarding air-borne sound, one determines the difference "D" in sound level "L" for the frequency range from 100 Hz to 3200 Hz.

$$D = L1 - L2 \text{ in dB where } L = 20 \lg \frac{p}{p_o} \text{ dB}$$

L_1 = sound level in room containing sound source

L_2 = sound level in room receiving the sound

Table 1-14

Attenuation figures for some building materials in the range 100 to 3200 Hz

Structural component	Attenuation dB	Structural component	Attenuation dB
Brickwork rendered, 12 cm thick	45	Single door without extra sealing	to 20
Brickwork rendered, 25 cm thick	50	Single door with good seal	30
Concrete wall, 10 cm thick	42	Double door without seal	30
Concrete wall, 20 cm thick	48	Double door with extra sealing	40
Wood wool mat, 8 cm thick	50	Single window without sealing	15
Straw mat, 5 cm thick	38	Spaced double window with seal	30

The reduction in level ΔL obtainable in a room by means of sound-absorbing materials or structures is:

$$\Delta L = 10 \lg \frac{A_2}{A_1} = 10 \lg \frac{T_1}{T_2} \text{ dB}$$

In the formula:

$$A = 0.163 \frac{V}{T} \text{ in } m^2$$

V = volume of room in m^3

T = reverberation time in s in which the sound level L falls by 60 dB after sound emission ceases.

Index 1 relates to the state of the untreated room, Index 2 to a room treated with noise-reduction measures.

1.2.7 Technical values of solids, liquids and gases

Table 1-15

Technical values of solids

Material	Density ρ kg/dm³	Melting or freezing point °C	Boiling point °C	Linear thermal expansion α mm/K x 10^{-6} [1]	Thermal conducti-vity λ at 20 °C W/(m · K)	Mean spec. heat c at 0 . . 100 °C J/(kg · K)	Specific electrical resistance ρ at 20 °C Ω mm²/m	Temperature coefficient α of electrical resistance at 20 °C 1/K
E-aluminium F9	2.70	658	2270	23.8	220	920	0.02874	0.0042
Alu alloy AlMgSi 1 F20	2.70	≈ 645		23	190	920	0.0407	0.0036
Lead	11.34	327	1730	28	34	130	0.21	0.0043
Bronze CuSnPb	8.6 . . 9	≈ 900		≈ 17.5	42	360	≈ 0.027	0.004
Cadmium	8.64	321	767	31.6	92	234	0.762	0.0042
Chromium	6.92	1800	2 400	8.5		452	0.028	
Iron, pure	7.88	1530	2 500	12.3	71	464	0.10	0.0058
Iron, steel	≈ 7.8	≈ 1350		≈ 11.5	46	485	0.25 . . 0.10	≈ 0.005
Iron, cast	≈ 7.25	≈ 1200		≈ 11	46	540	0.6 . . 1	0.0045
Gold	19.29	1063	2 700	14.2	309	130	0.022	0 0038
Constantan Cu + Ni	8 . . 8.9	1600		16.8	22	410	0.48 . . 0.50	≈ 0.00005
Carbon diamond	3.51	≈ 3 600	4 200	1.3		502		
Carbon graphite	2.25			7.86	5	711		
E-copper F30	8.92	1083	2 330	16.5	385	393	0.01786	0.00392
E-copper F20	8.92	1083	2 330	16.5	385	393	0.01754	0.00392
Magnesium	1.74	650	1110	25.0	167	1034	0.0455	0.004

[1] between 0 °C and 100 °C

(continued)

Table 1-15 (continued)

Technical values of solids

Material	Density ρ kg/dm^3	Melting or freezing point °C	Boiling point °C	Linear thermal expansion α mm/K x 10^{-6} [1]	Thermal conducti-vity λ at 20 °C W/(m · K)	Mean spec. heat c at 0. . 100 °C J/(kg · K)	Specific electrical resistance ρ at 20 °C Ω mm^2/m	Temperature coefficient α of electrical resistance at 20 °C 1/K
Brass (Ms 58)	8.5	912		17	110	397	≈ 0.0555	0.0024
Nickel	8.9	1455	3 000	13	83	452	≈ 0.12	0.0046
Platinum	21.45	1773	3 800	8.99	71	134	≈ 0.11	0.0039
Mercury	13.546	38.83	357	61	8.3	139	0.698	0.0008
Sulphur (rhombic)	2.07	113	445	90	0.2	720		
Selenium (metallic)	4.26	220	688	66		351		
Silver	10.50	960	1950	19.5	421	233	0.0165	0.0036
Tungsten	19.3	3 380	6 000	4.50	167	134	0.06	0.0046
Zinc	7.23	419	907	16.50	121	387	0.0645	0.0037
Tin	7.28	232	2 300	26.7	67	230	0.119	0.004

[1] between 0 °C and 100 °C

Table 1-16

Technical values of liquids

Material	Chemical formula	Density ρ kg/dm³	Melting or freezing point °C	Boiling point at 760 Torr °C	Expansion coefficient x 10^{-3} at 18 °C	Thermal conductivity λ at 20 °C W/(m · K)	Specific heat c_p at 0 °C J/(kg · K)	Relative dielectric constant ε_r at 180 °C
Acetone	C_3H_6O	0.791	— 95	56.3	1.43		2 160	21.5
Ethyl alcohol	C_2H_6O	0.789	— 114	78.0	1.10	0.2	2 554	25.8
Ethyl ether	$C_4H_{10}O$	0.713	— 124	35.0	1.62	0.14	2 328	4.3
Ammonia	NH_3	0.771	— 77.8	— 33.5		0.022	4 187	14.9
Aniline	C_6H_7N	1.022	— 6.2	184.4	0.84		2 064	7.0
Benzole	C_6H_6	0.879	+ 5.5	80.1	1.16	0.14	1 758	2.24
Acetic acid	$C_2H_4O_2$	1.049	+ 16.65	117.8	1.07		2 030	6.29
Glycerine	$C_3H_8O_3$	1.26	— 20	290	0.50	0.29	2 428	56.2
Linseed oil		0.94	— 20	316		0.15		2.2
Methyl alcohol	CH_4O	0.793	— 97.1	64.7	1.19	0.21	2 595	31.2
Petroleum		0.80			0.99	0.16	2 093	2.1
Castor oil		0.97			0.69		1 926	4.6
Sulphuric acid	$H_2S\ O_4$	1.834	— 10.5	338	0.57	0.46	1 385	> 84
Turpentine	$C_{10}H_{16}$	0.855	— 10	161	9.7	0.1	1 800	2.3
Water	H_2O	1.00[1]	0	106	0.18	0.58	4 187	88

[1] at 4 °C

Table 1- 17

Technical values of gases

Material	Chemical formula	Density ρ[1] kg/m^3	Melting point °C	Boiling point °C	Thermal conductivity λ 10^{-2} W/(m · K)	Specific heat c_p at 0 °C J/(kg · K)	Relative[1] dielectric constant ε_r
Ammonia	NH_3	0.771	— 77.7	— 33.4	2.17	2 060	1.0072
Ethylene	C_2H_4	1.260	— 169.4	— 103.5	1.67	1 611	1.001456
Argon	Ar	1.784	— 189.3	— 185.9	1.75	523	1.00056
Acetylene	C_2H_2	1.171	— 81	— 83.6	1.84	1 511	
Butane	C_4H_{10}	2.703	— 135	— 0.5	0.15		
Chlorine	Cl_2	3.220	— 109	— 35.0	0.08	502	1.97
Helium	He	0.178	— 272	— 268.9	1.51	5 233	1.000074
Carbon monoxide	CO	1.250	— 205	— 191.5	0.22	1 042	1.0007
Carbon dioxide	CO_2	1.977	— 56	— 78.5	1.42	819	1.00095
Krypton	Kr	3.743	— 157.2	— 153.2	0.88		
Air	CO_2 free	1.293		— 194.0	2.41	1 004	1.000576
Methane	CH_4	0.717	— 182.5	— 161.7	3.3	2 160	1.000953
Neon	Ne	0.8999	— 248.6	— 246.1	4.6		
Ozone	O_3	2.22	— 252	— 112			
Propane	C_2H_8	2.019	— 189.9	— 42.6			
Oxygen	O_2	1.429	— 218.83	— 192.97	2.46	1 038	1.000547
Sulphur hexafluoride	SF_6	6.07[2]	— 50.8[3]	— 63	1.28[2]	670	1.0021[2]
Nitrogen	N_2	1.250	— 210	— 195.81	2.38	1042	1.000606
Hydrogen	H_2	0.0898	— 259.2	— 252.78	17.54	14 235	1.000264

[1] at 0 °C and 1013 mbar
[2] at 20 °C and 1013 mbar
[3] at 2.26 bar

1.3 Strength of materials

1.3.1 Fundamentals and definitions

External forces *F* acting on a cross-section A of a structural element can give rise to tensile stresses (σ_z), compressive stresses (σ_d), bending stresses (σ_b), shear stresses (τ_s) or torsional stresses (τ_t). If a number of stresses are applied simultaneously to a component, i. e. compound stresses, this component must be designed according to the formulae for compound strength. In this case the following rule must be observed:

Normal stresses σ_z. σ_d. σ_b,
Tangential stresses (shear and torsional stresses) τ_s, τ_t.

are to be added arithmetically;

Normal stresses σ_b with shear stresses τ_s,
Normal stresses σ_b with torsional stresses τ_t,

are to be added geometrically.

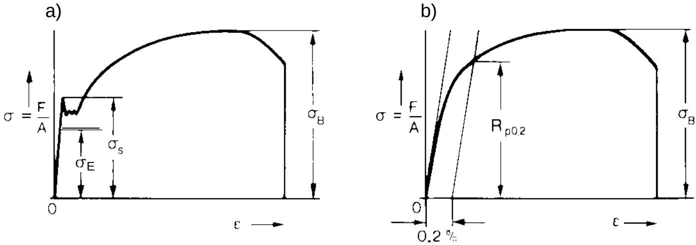


Fig. 1-2

Stress-strain diagram, a) Tensile test with pronounced yield point, material = structural steel; b) Tensile test without pronounced yield point, material = Cu/Al, ε Elongation, σ Tensile stress, σ_s Stress at yield point, σ_E Stress at proportionality limit, R_{p02} Stress with permanent elongation less than 0.2 %, σ_B Breaking stress.

Elongation $\varepsilon = \Delta l / l_0$ (or compression in the case of the compression test) is found from the measured length l_0 of a bar test specimen and its change in length $\Delta l = l - l_0$ in relation to the tensile stress σ_z, applied by an external force F. With stresses below the proportionality limit σ_E elongation increases in direct proportion to the stress σ (Hooke's law).

The ratio $\frac{\text{Stress } \sigma}{\text{Elongation } \varepsilon} = \frac{\sigma_E}{\varepsilon_E} = E$ is termed the elasticity modulus.

E is an imagined stress serving as a measure of the resistance of a material to deformation due to tensile or compressive stresses; it is valid only for the elastic region.

According to DIN 1602/2 and DIN 50143, *E* is determined in terms of the load $\sigma_{0.01}$, i.e. the stress at which the permanent elongation is 0.01 % of the measured length of the test specimen.

If the stresses exceed the yield point σ_s, materials such as steel undergo permanent elongation. The ultimate strength, or breaking stress, is denoted by σ_B, although a bar does not break until the stress is again being reduced. Breaking stress σ_B is related to the elongation on fracture δ of a test bar. Materials having no marked proportional limit or elastic limit, such as copper and aluminium, are defined in terms of the so-called $R_{p0.2}$-limit, which is that stress at which the permanent elongation is 0.2 % after the external force has been withdrawn, cf. DIN 50144.

For reasons of safety, the maximum permissible stresses, σ_{max} or τ_{max} in the material must be below the proportional limit so that no permanent deformation, such as elongation or deflection, persists in the structural component after the external force ceases to be applied.

Table 1-18

Material	Elasticity modulus *E* N/mm² [1]
Structural steel in general, spring steel (unhardened), cast steel	210 000
Grey cast iron	100 000
Electro copper, Al bronze with 5 % Al, rolled	110 000
Red brass	90 000
E-AlMgSi 0.5	75 000
E-Al	65 000
Magnesium alloy	45 000
Wood	10 000

[1] Typical values.

Fatigue strength (endurance limit) is present when the maximum variation of a stress oscillating about a mean stress is applied “infinitely often” to a loaded material (at least 10^7 load reversals in the case of steel) without giving rise to excessive deformation or fracture.

Cyclic stresses can occur in the form of a stress varying between positive and negative values of equal amplitude, or as a stress varying between zero and a certain maximum value. Cyclic loading of the latter kind can occur only in compression or only in tension.

Depending on the manner of loading, fatigue strength can be considered as bending fatigue strength, tension-compression fatigue strength or torsional fatigue strength. Structural elements which have to withstand only a limited number of load reversals can be subjected to correspondingly higher loads. The resulting stress is termed the fatigue limit.

One speaks of creep strength when a steady load with uniform stress is applied, usually at elevated temperatures.

1.3.2 Tensile and compressive strength

If the line of application of a force *F* coincides with the centroidal axis of a prismatic bar of cross section *A* (Fig.1-3), the normal stress uniformly distributed over the cross-section area and acting perpendicular to it is

$$\sigma = \frac{F}{A} .$$

With the maximum permissible stress σ_{max} for a given material and a given loading, the required cross section or the maximum permissible force, is therefore:

$$A = \frac{F}{\sigma_{max}} \text{ or } F = \sigma_{max} \cdot A.$$

Example:

A drawbar is to be stressed with a steady load of F = 180 000 N.

The chosen material is structural steel St 37 with $\sigma_{max} = 120\ \text{N/mm}^2$.

Required cross section of bar:

$$A = \frac{E}{\sigma_{max}} = \frac{180\,000\ N}{120\ N/mm^2} = 1500\ mm^2.$$

Round bar of d = 45 mm *chosen.*

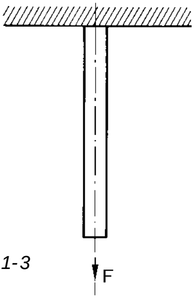


Fig. 1-3

1.3.3 Bending strength

The greatest bending action of an external force, or its greatest bending moment *M,* occurs at the point of fixing *a* in the case of a simple cantilever, and at point *c* in the case of a centrally loaded beam on two supports.

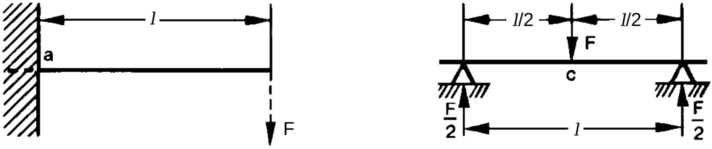


Fig. 1-4

Maximum bending moment at a: $M = Fl$; *at c:* $M = Fl/4$

In position *a* and *c*, assuming the beams to be of constant cross section, the bending stresses σ_b are greatest in the filaments furthermost from the neutral axis. *M* may be greater, the greater is σ_{max} and the "more resistant" is the cross-section. The following cross sections have moments of resistance *W* in cm, if *a, b, h* and *d* are stated in cm.

The maximum permissible bending moment is $M = W \cdot \sigma_{max}$ and the required moment of resistance

$$W = \frac{M}{\sigma_{max}} .$$

Example:

A mild-steel stud $\left(\sigma_{max} = 70\ \text{N/mm}^2\right)$ with an unsupported length of $l = 60$ mm is to be loaded in the middle with a force $F = 30\,000$ N. Required moment of resistance is:

$$W = \frac{M}{\sigma_{max}} = \frac{F \cdot l}{4 \cdot \sigma_{max}} = \frac{30\,000\ \text{N} \cdot 60\ \text{mm}}{4 \cdot 70\ \text{N/mm}^2} = 6.4 \cdot 10^3\ \text{mm}^3.$$

According to Table 1-22, the moment of resistance W with bending is $W \approx 0.1 \cdot d^3$.

The diameter of the stud will be: $d = \sqrt[3]{10\ W}$, $d = \sqrt[3]{64\,000} = \sqrt[3]{64} \cdot 10 = 40$ mm.

1.3.4 Loadings on beams

Table 1-19

Bending load

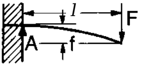
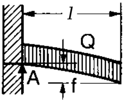
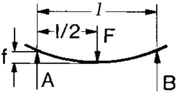
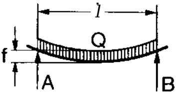
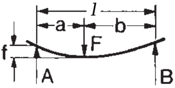
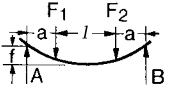
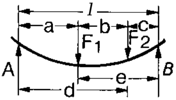
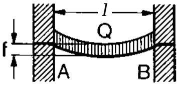
Case	Reaction force Bending moment	Required moment of resistance, max. permissible load	Deflection
	$A = F$	$W = \frac{F\,l}{\sigma_{max}}$	$f = \frac{F\,l^3}{3\,E\,J}$
	$M_{max} = F\,l$	$F = \frac{\sigma_{max}\,W}{l}$	
	$A = Q$	$W = \frac{Q\,l}{2\,\sigma_{max}}$	$f = \frac{Q\,l^3}{8\,E\,J}$
	$M_{max} = \frac{Q\,l}{2}$	$Q = \frac{2\,\sigma_{max}\,W}{l}$	
	$A = B = \frac{F}{2}$	$W = \frac{F\,l}{4\,\sigma_{max}}$	$f = \frac{F\,l^3}{48\,E\,J}$
	$M_{max} = \frac{F\,l}{4}$	$F = \frac{4\,\sigma_{max}\,W}{l}$	
	$A = B = \frac{Q}{2}$	$W = \frac{Q\,l}{8\,\sigma_{max}}$	$f = \frac{5}{384} \cdot \frac{Q\,l^3}{E\,J}$
	$M_{max} = \frac{Q\,l}{8}$	$Q = \frac{8\,\sigma_{max}\,W}{l}$	(continued)

Table 1-19 (continued)

Bending load

Case	Reaction force Bending moment	Required moment of resistance, max. permissible load	Deflection
	$A = \frac{F b}{l}$ $B = \frac{F a}{l}$ $M_{max} = A a = B b$	$W = \frac{F a b}{l \sigma_{max}}$ $F = \frac{\sigma_{max} W l}{a b}$	$f = \frac{F a^2 b^2}{3 E J l}$
	for $F_1 = F_2 = F$ 1) $A = B = F$ $M_{max} = F a$	$W = \frac{F a}{\sigma_{max}}$ $F = \frac{\sigma_{max} W}{a}$	$f = \frac{F a}{24 E J}$ $[3 (l + 2 a)^2 - 4 a^2]$
	$A = \frac{F_1 e + F_2 c}{l}$ $B = \frac{F_1 a + F_2 d}{l}$	$W_1 = \frac{A a}{\sigma_{max}}$ $W_2 = \frac{B c}{\sigma_{max}}$ Determine beam for greatest *“W”*	$f = \frac{F_1 a^2 e^2 + F_2 l^2 d^2}{3 E J l}$
	$A = B = \frac{Q}{l}$ $M_{max} = \frac{Q l}{12}$	$W = \frac{Q l}{12 \sigma_{zul}}$ $Q = \frac{12 \sigma_{zul} W}{l}$	$f = \frac{Q}{E J} \cdot \frac{l^3}{384}$

A and *B* = Section at risk.

F = Single point load, *Q* = Uniformly distributed load.

1) If F_1 und F_2 are not equal, calculate with the third diagram.

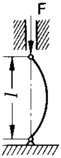
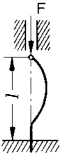
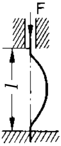
1.3.5 Buckling strength

Thin bars loaded in compression are liable to buckle. Such bars must be checked both for compression and for buckling strength, cf. DIN 4114.

Buckling strength is calculated with Euler's formula, a distinction being drawn between four cases.

Table 1-20

Buckling

	Case I One end fixed, other end free	$F = \frac{10\,E\,J}{4\,s\,l^2}$ $J = \frac{4\,s\,F\,l^2}{10\,E}$
	Case II Both ends free to move along bar axis	$F = \frac{10\,E\,J}{s\,l^2}$ $J = \frac{s\,F\,l^2}{10\,E}$
	Case III One end fixed, other end free to move along bar axis	$F = \frac{20\,E\,J}{s\,l^2}$ $J = \frac{s\,F\,l^2}{20\,E}$
	Case IV Both ends fixed, movement along bar axis	$F = \frac{40\,E\,J}{s\,l^2}$ $J = \frac{s\,F\,l^2}{40\,E}$

E = Elasticity modulus of material
J = Minimum axial moment of inertia
F = Maximum permissible force
l = Length of bar

s = Factor of safety:
for cast iron = 8,
for mild carbon steel = 5,
for wood = 10.

1.3.6 Maximum permissible buckling and tensile stress for tubular rods

Threaded steel tube (gas pipe) DIN 2440, Table 1[1]
or seamless steel tube DIN 2448[2].

$$F_{\text{buck}} = \frac{10\,E}{s\,l^2} \cdot J = \frac{10\,E}{s\,l^2} \cdot \frac{D^4 - d^4}{20} \quad \text{where } J \approx \frac{D^4 - d^4}{20} \text{ from Table 1-22}$$

$$F_{\text{ten}} = A \cdot \sigma_{\max}$$

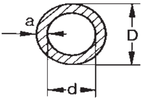


Fig. 1-5

in which

F	Force
E	Elasticity modulus = 210 000 N/mm^2
J	Moment of inertia in cm^4
s	Factor of safety = 5
$\sigma_{\max}$	Max. permissible stress
A	Cross-section area
D	Outside diameter
d	Inside diameter
l	Length

Table 1-21

Nominal diameter	Dimensions			Cross-sections	Moment of inertia	Weight of tube	F_{buck} for tube length $l \approx$						F_{ten}
	D inch	D mm	a mm	A mm^2	J cm^4	kg/m	0.5 m N	1 m N	1.5 m N	2 m N	2.5 m N	3 m N	N
10	⅜	17.2	2.35	109.6	0.32	0.85	5400	1350	600	340	220	150	6600
15	½	21.3	2.65	155.3	0.70	1.22	11800	2950	1310	740	470	330	9300
20	¾	26.9	2.65	201.9	1.53	1.58	25700	6420	2850	1610	1030	710	12100
25	1	33.7	3.25	310.9	3.71	2.44	62300	15600	6920	3900	2490	1730	18650
	0.8	25	2	144.5	0.98	1.13	16500	4100	1830	1030	660	460	17350
	0.104	31.8	2.6	238.5	2.61	1.88	43900	11000	4880	2740	1760	1220	28600

---

[1] No test values specified for steel ST 00.

[2] $\sigma_{\max}$ = 350 N/mm^2 for steel ST 35 DIN 1629 seamless steel tube, cf. max. permissible buckling stress for structural steel, DIN 1050 Table 3.

1.3.7 Shear strength[1]

Two equal and opposite forces F acting perpendicular to the axis of a bar stress this section of the bar in shear. The stress is

$\tau_s = \frac{F}{A}$ or for given values of F and $\tau_{s\,max}$, the required cross section is

$$A = \frac{F}{\tau_{s\,max}}$$

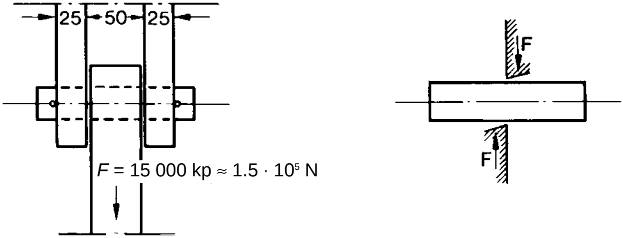


Fig. 1-6

Pull-rod coupling

Stresses in shear are always combined with a bending stress, and therefore the bending stress σ_b has to be calculated subsequently in accordance with the following example.

Rivets, short bolts and the like need only be calculated for shear stress.

Example:

Calculate the cross section of a shackle pin of structural steel ST 50-1[2], with $R_{p\,0.2\,min} = 300\ \text{N/mm}^2$ and $\tau_{s\,max} = 0.8\ R_{p\,0.2\,min}$, for the pull-rod coupling shown in Fig. 1-6.

1. Calculation for shear force:

$$A = \frac{F}{2\ \tau_{s\,max}} = \frac{150\ 000\ \text{N}}{2 \cdot (0.8 \cdot 300)\ \text{N/mm}^2} = 312\ \text{mm}^2$$

yields a pin diameter of $d \approx 20$ mm, with $W = 0.8 \cdot 10^3\ \text{mm}^3$ (from $W \approx 0.1 \cdot d^3$, see Table 1-22).

---

[1] For maximum permissible stresses on steel structural components of transmission towers and structures for outdoor switchgear installations, see VDE 0210.

[2] Yield point of steel ST 50-1 $\sigma_{0.2\,min} = 300\ \text{N/mm}^2$, DIN 17100 Table 1 (Fe 50-1).

2. Verification of bending stress:

The bending moment for the pin if $F\,l/4$ with a singlepoint load, and $F\,l/8$ for a uniformly distributed load. The average value is

$$M_b = \frac{\frac{F\,l}{4} + \frac{F\,l}{8}}{2} = \frac{3}{16} F\,l$$

when F = $1.5 \cdot 10^5$ N, l = 75 mm becomes:

$$M_b = \frac{3}{16} \cdot 1.5 \cdot 10^5 \text{ N} \cdot 75 \text{ mm} \approx 21 \cdot 10^5 \text{ N} \cdot \text{mm};$$

$$\sigma_B = \frac{M_b}{W} = \frac{21 \cdot 10^5 \text{ N} \cdot \text{mm}}{0.8 \cdot 10^3 \text{ mm}^3} \approx 262 \cdot 10^3 \frac{\text{N}}{\text{mm}^2} = 2.6 \cdot 10^5 \frac{\text{N}}{\text{mm}^2}$$

i. e. a pin calculated in terms of shear with $d = 20$ mm will be too weak. The required pin diameter d calculated in terms of bending is

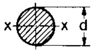
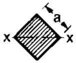
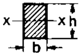
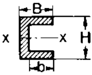
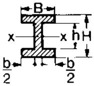
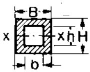
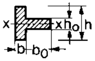
$$W = \frac{M_b}{\sigma_{max}} = \frac{21 \cdot 10^5 \text{ N} \cdot \text{mm}}{300 \text{ N/mm}^2} = 7 \cdot 10^3 \text{ mm}^2 = 0.7 \text{ cm}^3$$

$$d \approx \sqrt[3]{10 \cdot W} = \sqrt[3]{10 \cdot 7 \cdot 10^3 \text{ mm}^3} = \sqrt[3]{70} = 41.4 \text{ mm} \approx 42 \text{ mm}.$$

i. e. in view of the bending stress, the pin must have a diameter of 42 mm instead of 20 mm.

1.3.8 Moments of resistance and moments of inertia

Table 1-22

Cross-section	Moment of resistance torsion W 4) cm^3	 bending1) W 4) cm^3	Moment of inertia polar1) J_p cm^4	 axial2) J cm^4
	$0.196\,d^3$ $\approx 0.2\,d^3$	$0.098\,d^3$ $\approx 0.1\,d^3$	$0.098\,d^4$ $\approx\ 0.1\,d^4$	$0.049\,d^4$ $\approx 0.05\,d^4$
	$0.196\ \frac{D^4-d^4}{D}$	$0.098\,\frac{D^4-d^4}{D}$	$0.098\,(D^4-d^4)$	$0.049\,(D^4-d^4)$ $\approx\ \frac{D^4-d^4}{20}$
	$0.208\,a^3$	$0.018\,a^3$	$0.167\,a^4$	$0.083\,a^4$
	$0.208\,k\,b^2\,h$ 3)	$\frac{b\,h^2}{6} =\ 0.167\,b\,h^2$	$\frac{b\,h}{12}\ (b^2+h^2)$	$\frac{b\,h^3}{12} = 0.083\,b\,h^3$
		$\frac{B\,H^3-b\,h^3}{6\,H}$		$\frac{B\,H^3-b\,h^3}{12}$
		$\frac{B\,H^3-b\,h^3}{6\,H}$		$\frac{B\,H^3-b\,h^3}{12}$
		$\frac{B\,H^3-b\,h^3}{6\,H}$		$\frac{B\,H^3-b\,h^3}{12}$
		$\frac{b\,h^3+b_\mathrm{o}\,h_\mathrm{o}^3}{6\,h}$		$\frac{b\,h^3+b_\mathrm{o}\,h_\mathrm{o}^3}{12}$

---

1) Referred to CG of area.

2) Referred to plotted axis.

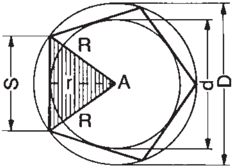
3) Values for *k:*

if $h : b$ =	1	1.5	2	3	4
then k =	1	1.11	1.18	1.27	1.36

4) Symbol Z is also applicable, see DIN VDE 0103

1.4 Geometry, calculation of areas and solid bodies

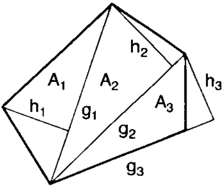
1.4.1 Area of polygons



Regular polygons (n angles)
The area A, length of sides S and radii of the outer and inner circles can be taken from Table 1-23 below.

Table 1-23

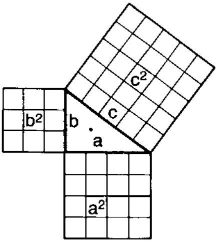
Number of sides	Area A			Side S		Outer radius		Inner radius	
						R		r	
n	$S^2 \times$	$R^2 \times$	$r^2 \times$	$R \times$	$r \times$	$S \times$	$r \times$	$R \times$	$S \times$
3	0.4330	1.2990	5.1962	1.7321	3.4641	0.5774	2.0000	0.5000	0.2887
4	1.0000	2.0000	4.0000	1.4142	2.0000	0.7071	1.4142	0.7071	0.5000
5	1.7205	2.3776	3.6327	1.1756	1.4531	0.8507	1.2361	0.8090	0.6882
6	2.5981	2.5981	3.4641	1.0000	1.1547	1.0000	1.1547	0.8660	0.8660
8	4.8284	2.8284	3.3137	0.7654	0.8284	1.3066	1.0824	0.9239	1.2071
10	7.6942	2.9389	3.2492	0.6180	0.6498	1.6180	1.0515	0.9511	1.5388
12	11.196	3.0000	3.2154	0.5176	0.5359	1.9319	1.0353	0.9659	1.8660



Irregular polygons

$$A = \frac{g_1 h_1}{2} + \frac{g_2 h_2}{2} + \ldots$$

$$= \frac{1}{2}(g_1 h_1 + g_2 h_2 + \ldots)$$

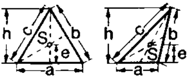
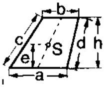
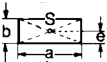
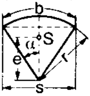
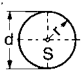
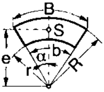
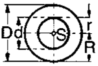
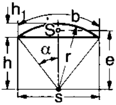
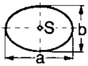


Pythagoras theorem

$$c^2 = a^2 + b^2; \qquad c = \sqrt{a^2 + b^2}$$
$$a^2 = c^2 - b^2; \qquad a = \sqrt{c^2 - b^2}$$
$$b^2 = c^2 - a^2; \qquad b = \sqrt{c^2 - a^2}$$

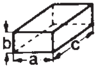
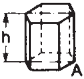
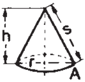
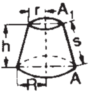
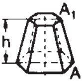
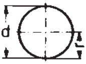
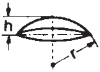
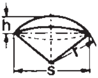
1.4.2 Areas and centres of gravity

Table 1-24

Shape of surface		A = area	U = perimeter S = centre of gravity (cg) e = distance of cg
Triangle		$A = \frac{1}{2} a h$	$U = a + b + c$ $e = \frac{1}{3} h$
Trapezium		$A = \frac{a + b}{2} \cdot h$	$U = a + b + c + d$ $e = \frac{h}{3} \cdot \frac{a + 2 b}{a + b}$
Rectangle		$A = a b$	$U = 2 (a + b)$
Circle segment		$A = \frac{b r}{2} = \frac{\alpha^0}{180} r \pi$ $b = r \pi \frac{\alpha^0}{180}$	$U = 2 r + b$ $e = \frac{2}{3} r \frac{\sin \alpha}{\alpha^0} \cdot \frac{180}{\pi}$
Semicircle		$A = \frac{1}{2} \pi r^2$	$U = r (2 + \pi) = 5.14 r$ $e = \frac{1}{3} \cdot \frac{r}{\pi} = 0.425 r$
Circle		$A = r^2 \pi = \pi \frac{d^2}{4}$	$U = 2 \pi r = \pi d$
Annular segment		$A = \frac{\pi}{180} \alpha^0 (R^2 - r^2)$	$U = 2 (R - r) + B + b$ $e = \frac{2}{3} \cdot \frac{R^2 - r^2}{R^2 - r^2} \cdot \frac{\sin \alpha}{\alpha^0} \cdot \frac{180}{\pi}$
Semi-annulus		$A = \frac{\pi}{2} \alpha^0 (R^2 - r^2)$	if $b < 0.2 R$, then $e \approx 0.32 (R + r)$
Annulus		$A = \pi (R^2 - r^2)$	$U = 2 \pi (R + r)$
Circular segment		$A = \frac{\alpha^0}{180} r^2 \pi - \frac{s h}{2}$ $s = 2 \sqrt{r^2 - h^2}$	$U = 2 \sqrt{r^2 - h^2} + \frac{\pi r \alpha^0}{90}$ $e = \frac{s^2}{12 \cdot A}$
Ellipse		$A = \frac{a b}{4} \pi$	$U = \frac{\pi}{2} \left[1.5 (a + b) - \sqrt{ab} \right]$

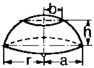
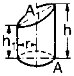
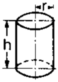
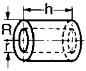
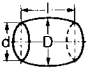
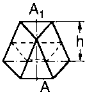
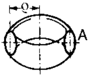
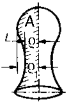
1.4.3 Volumes and surface areas of solid bodies

Table 1-25

Shape of body		V = volume	O = Surface A = Area
Solid rectangle		$V = a\,b\,c$	$O = 2\,(a\,b + a\,c + b\,c)$
Cube		$V = a^3 = \frac{d^3}{2.828}$	$O = 6\,a^2 = 3\,d^2$
Prism		$V = A\,h$	$O = U\,h + 2\,A$ A = base surface
Pyramid		$V = \frac{1}{3}\,A\,h$	O = A + Nappe
Cone		$V = \frac{1}{3}\,A\,h$	$O = \pi\,r\,s + \pi\,r^2$ $s = \sqrt{h^2 + r^2}$
Truncated cone		$V = (R^2 + r^2 + R\,r) \cdot \frac{\pi\,h}{3}$	$O = (R + r)\,\pi\,s + \pi\,(R^2 + r^2)$ $s = \sqrt{h^2 + (R - r)^2}$
Truncated pyramid		$V = \frac{1}{3}\,h\,(A + A_1 + \sqrt{AA_1})$	$O = A + A_1$ + Nappe
Sphere		$V = \frac{4}{3}\,\pi\,r^3$	$O = 4\,\pi\,r^2$
Hemisphere		$V = \frac{2}{3}\,\pi\,r^3$	$O = 3\,\pi\,r^2$
Spherical segment		$V = \pi\,h^2 \left(r - \frac{1}{3}\,h\right)$	$O = 2\,\pi\,r\,h + \pi\,(2\,r\,h - h^2) =$ $\pi\,h\,(4\,r - h)$
Spherical sector		$V = \frac{2}{3}\,\pi\,r^2\,h$	$O = \frac{\pi\,r}{2}\,(4\,h + s)$

(*continued*)

Table 1-25 (continued)

Shape of body		V = Volume	O = Surface A = Area
Zone of sphere		$V = \frac{\pi h}{3}(3a^2 + 3b^2 + h^2)$	$O = \pi(2rh + a^2 + b^2)$
Obliquely cut cylinder		$V = \pi r^2 \frac{h + h_1}{2}$	$O = \pi r(h + h_1) + A + A_1$
Cylindrical wedge		$V = \frac{2}{3} r^2 h$	$0 = 2rh + \frac{\pi}{2} r^2 + A$
Cylinder		$V = \pi r^2 h$	$O = 2\pi r h + 2\pi r^2$
Hollow cylinder		$V = \pi\, h(R^2 - r^2)$	$O = 2\pi\, h(R + r) + 2\pi(R^2 - r^2)$
Barrel		$V = \frac{\pi}{15} l \cdot$ $(2D^2 + Dd + 0.75\, d^2)$	$O = \frac{D + d}{2} \pi d + \frac{\pi}{2} d^2$ (approximate)
Frustum		$V = \left(\frac{A - A_1}{2} + A_1\right) h$	$O = A + A_1$ + areas of sides
Body of rotation (ring)		$V = 2\pi \varrho A$ A = cross-section	O = circumference of cross-section x $2\pi\varrho$
Pappus' theorem for bodies of revolution		Volume of turned surface (hatched) x path of its centre of gravity $V = A\, 2\pi\varrho$	Length of turned line x path of its centre of gravity $O = L\, 2\pi\varrho_1$

2 General Electrotechnical Formulae

2.1 Electrotechnical symbols as per DIN 1304 Part 1

Table 2-1

Mathematical symbols for electrical quantities (general)

Symbol	Quantity	SI unit
Q	quantity of electricity, electric charge	C
E	electric field strength	V/m
D	electric flux density, electric displacement	C/m^2
U	electric potential difference	V
φ	electric potential	V
ε	permittivity, dielectric constant	F/m
ε_o	electric field constant, $\varepsilon_o = 0.885419 \cdot 10^{-11}$ F/m	F/m
ε_r	relative permittivity	1
C	electric capacitance	F
I	electric current	A
J	electric current density	A/m^2
x, γ, σ	specific electric conductivity	S/m
ρ	specific electric resistance	Ωm
G	electric conductance	S
R	electric resistance	Ω
θ	electromotive force	A

Table 2-2

Mathematical symbols for magnetic quantities (general)

Symbol	Quantity -	SI unit
Φ	magnetic flux	Wb
B	magnetic induction	T
H	magnetic field strength	A/m
V	magnetomotive force	A
φ	magnetic potential	A
μ	permeability	H/m
μ_o	absolute permeability, $\mu_o = 4\,\pi \cdot 10^{-7} \cdot$ H/m	H/m
μ_r	relative permeability	1
L	inductance	H
L_{mn}	mutual inductance	H

Table 2-3

Mathematical symbols for alternating-current quantities and network quantities

Symbol	Quantity	SI unit
S	apparent power	W, VA
P	active power	W
Q	reactive power	W, Var
D	distortion power	W
φ	phase displacement	rad
ϑ	load angle	rad
λ	power factor, $\lambda = P/S$, λ cos φ 1)	1
δ	loss angle	rad
d	loss factor, $d = \tan \delta$	1
Z	impedance	Ω
Y	admittance	S
R	resistance	Ω
G	conductance	S
X	reactance	Ω
B	susceptance	S
γ	impedance angle, $\gamma = \arctan X/R$	rad

Table 2-4

Numerical and proportional relationships

Symbol	Quantity	SI unit
η	efficiency	1
s	slip	1
p	number of pole-pairs	1
w, N	number of turns	1
$ü$	transformation ratio	1
m	number of phases and conductors	1
γ	amplitude factor	1
k	overvoltage factor	1
ν	ordinal number of a periodic component	1
s	wave content	1
g	fundamental wave content	1
k	harmonic content, distortion factor	1
ζ	increase in resistance due to skin effect, $\zeta = R_{\sim} / R_{—}$	1

---

1) Valid only for sinusoidal voltage and current.

2.2 Alternating-current quantities

With an alternating current, the instantaneous value of the current changes its direction as a function of time $i = f(t)$. If this process takes place periodically with a period of duration T, this is a periodic alternating current. If the variation of the current with respect to time is then sinusoidal, one speaks of a sinusoidal alternating current.

The frequency f and the angular frequency ω are calculated from the periodic time T with

$$f = \frac{1}{T} \text{ and } \omega = 2\,\pi\, f = \frac{2\pi}{T}.$$

The *equivalent d. c. value* of an alternating current is the average, taken over one period, of the value:

$$|\bar{i}| = \frac{1}{T}\int_0^T |i|\,\mathrm{d}t = \frac{1}{2\pi}\int_0^{2\pi} |i|\,\mathrm{d}\omega t.$$

This occurs in rectifier circuits and is indicated by a moving-coil instrument, for example.

The root-mean-square value (rms value) of an alternating current is the square root of the average of the square of the value of the function with respect to time.

$$I = \sqrt{\frac{1}{T}\cdot\int_0^T i^2\mathrm{d}t} = \sqrt{\frac{1}{2\pi}\cdot\int_0^{2\pi} i^2\mathrm{d}\omega t}.$$

As regards the generation of heat, the root-mean-square value of the current in a resistance achieves the same effect as a direct current of the same magnitude.

The root-mean-square value can be measured not only with moving-coil instruments, but also with hot-wire instruments, thermal converters and electrostatic voltmeters.

A non-sinusoidal current can be resolved into the fundamental oscillation with the fundamental frequency f and into harmonics having whole-numbered multiples of the fundamental frequency. If I_1 is the rms value of the fundamental oscillation of an alternating current, and I_2, I_3 etc. are the rms values of the harmonics having frequencies 2 f, 3 f, etc., the rms value of the alternating current is

$$I = \sqrt{I_1^2 + I_2^2 + I_3^2 + \ldots}$$

If the alternating current also includes a direct-current component i_-, this is termed an undulatory current. The rms value of the undulatory current is

$$I = \sqrt{I_-^2 + I_1^2 + I_2^2 + I_3^2 + \ldots}$$

The fundamental oscillation content g is the ratio of the rms value of the fundamental oscillation to the rms value of the alternating current

$$g = \frac{I_1}{I}.$$

The harmonic content k (distortion factor) is the ratio of the rms value of the harmonics to the rms value of the alternating current.

$$k = \frac{\sqrt{I_2^2 + I_3^2 + \ldots}}{I} = \sqrt{1 - g^2}$$

The fundamental oscillation content and the harmonic content cannot exceed 1.

In the case of a sinusoidal oscillation

the fundamental oscillation content	$g = 1$,
the harmonic content	$k = 0$.

Forms of power in an alternating-current circuit

The following terms and definitions are in accordance with DIN 40110 for the sinusoidal wave-forms of voltage and current in an alternating-current circuit.

apparent power	$S = UI = \sqrt{P^2 + Q^2}$,
active power	$P = UI \cdot \cos\varphi = S \cdot \cos\varphi$,
reactive power	$Q = UI \cdot \sin\varphi = S \cdot \sin\varphi$,
power factor	$\cos\varphi = \frac{P}{S}$,
reactive factor	$\sin\varphi = \frac{Q}{S}$.

When a three-phase system is loaded symmetrically, the apparent power is

$$S = 3\,U_1 I_1 = \sqrt{3} \cdot U \cdot I_1,$$

where I_1 is the rms phase current, U_1 the rms value of the phase to neutral voltage and U the rms value of the phase to phase voltage. Also

active power	$P = 3\,U_1 I_1 \cos\varphi = \sqrt{3} \cdot U \cdot I_1 \cdot \cos\varphi$,
reactive power	$Q = 3\,U_1 I_1 \sin\varphi = \sqrt{3} \cdot U \cdot I_1 \cdot \sin\varphi$.

The unit for all forms of power is the watt (W). The unit watt is also termed volt-ampere (symbol VA) when stating electric apparent power, and Var (symbol var) when stating electric reactive power.

Resistances and conductances in an alternating-current circuit

impedance	$Z = \frac{U}{I} = \frac{S}{I^2} = \sqrt{R^2 + X^2}$
resistance	$R = \frac{U\cos\varphi}{I} = \frac{P}{I^2} = Z\cos\varphi = \sqrt{Z^2 - X^2}$
reactance	$X = \frac{U\sin\varphi}{I} = \frac{Q}{I^2} = Z\sin\varphi = \sqrt{Z^2 - R^2}$
inductive reactance	$X_i = \omega L$
capacitive reactance	$X_c = \frac{1}{\omega C}$
admittance	$Y = \frac{I}{U} = \frac{S}{U^2} = \sqrt{G^2 + B^2} = \frac{1}{Z}$
conductance	$G = \frac{I\cos\varphi}{U} = \frac{P}{U^2} = Y\cos\varphi = \sqrt{Y^2 - B^2} = \frac{R}{Z^2}$
conductance	$B = \frac{I\sin\varphi}{U} = \frac{Q}{U^2} = Y\sin\varphi = \sqrt{Y^2 - G^2} = \frac{X}{Z^2}$
inductive susceptance	$B_i = \frac{1}{\omega L}$
capacitive susceptance	$B_c = \omega C$

$\omega = 2\,\pi\,f$ is the angular frequency and φ the phase displacement angle of the voltage with respect to the current. U, I and Z are the numerical values of the alternating-current quantities $\underline{U}$, $\underline{I}$ and $\underline{Z}$.

Complex presentation of sinusoidal time-dependent a. c. quantities

Expressed in terms of the load vector system:

$\underline{U} = \underline{I} \cdot \underline{Z}$, $\underline{I} = \underline{U} \cdot \underline{Y}$

The symbols are underlined to denote that they are complex quantities (DIN 1304).

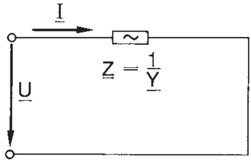


Fig. 2- 1
Equivalent circuit diagram

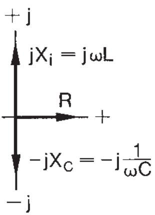


Fig. 2-2
Vector diagram of resistances

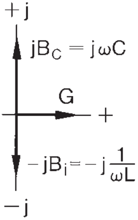


Fig. 2-3
Vector diagram of conductances

If the voltage vector $\underline{U}$ is laid on the real reference axis of the plane of complex numbers, for the equivalent circuit in Fig. 2-1 with $\underline{Z} = R + \mathrm{j}\,X_i$: we have

$$\underline{U} = U,$$

$$\underline{I} = I_w - \mathrm{j}\,I_b = I\,(\cos\varphi - \mathrm{j}\sin\varphi),$$

$$I_w = \frac{P}{U};\ I_b = \frac{Q}{U};$$

$$\underline{S}^{1)} = U\,\underline{I}^* = U\,I\,(\cos\varphi + \mathrm{j}\sin\varphi) = P + \mathrm{j}\,Q,$$

$$S = |\underline{S}| = U\,I = \sqrt{P^2 + Q^2},$$

$$\underline{Z} = R + \mathrm{j}\,X_i = \frac{U}{\underline{I}} = \frac{U}{I\,(\cos\varphi - \mathrm{j}\sin\varphi)} = \frac{U}{I}\,(\cos\varphi + \mathrm{j}\sin\varphi),$$

where $R = \frac{U}{I}\cos\varphi$ and $X_i = \frac{U}{I}\sin\varphi$,

$$\underline{Y} = \mathrm{G} - \mathrm{j}B = \frac{\underline{I}}{U} = \frac{I}{U}\,(\cos\varphi - \mathrm{j}\sin\varphi)$$

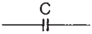
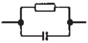
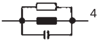
where $\mathrm{G} = \frac{I}{U}\cos\varphi$ and $B_i = \frac{I}{U}\sin\varphi$.

---

[1] $\underline{S}$: See DIN 40110
$\underline{I}^*$ = conjugated complex current vector

Table 2-5

Alternating-current quantities of basic circuits

	Circuit	$\underline{Z}$	$\lvert\underline{Z}\rvert$
1.		R	R
2.		$j\,\omega L$	ωL
3.		$-j/(\omega C)$	$1/\omega C$
4.		$R + j\,\omega L$ 1)	$\sqrt{R^2 + (\omega L)^2}$
5.		$R - j/(\omega C)$	$\sqrt{R^2 + 1/(\omega C)^2}$
6.		$j\,(\omega L - 1/(\omega C))$ 2)	$\sqrt{(\omega L - 1/(\omega C))^2}$
7.		$R + j(\omega L - 1/(\omega C))$ 2)	$\sqrt{R^2 + (\omega L - 1/(\omega C))^2}$
8.		$\dfrac{R\,\omega L}{\omega L - j R}$	$\dfrac{R\,\omega L}{\sqrt{R^2 + (\omega L)^2}}$
9.		$\dfrac{R - j\,\omega C R^2}{1 + (\omega C)^2 R^2}$ 3)	$\dfrac{R}{\sqrt{1 + (\omega C)^2 R^2}}$
10.		$\dfrac{j}{1/(\omega L) - \omega C}$	$\dfrac{1}{\sqrt{(1/\omega L)^2 - (\omega C)^2}}$
11.	 4)	$\dfrac{1}{1/R + j\,(\omega C - 1/(\omega L))}$ $[\underline{Y} = 1/R^2 + j\,(\omega C - 1/(\omega L))]$	$\dfrac{1}{\sqrt{1/R^2 + (\omega C - 1/(\omega L))^2}}$
12.	 5)	$\dfrac{R + j\,(L\,(1 - \omega^2 LC) - R^2 C)}{(1 - \omega^2 L C)^2 + (R\,\omega C)^2}$	$\dfrac{\sqrt{R^2 + [L\,(1 - \omega^2 LC) - R^2 C]^2}}{(1 - \omega^2 L C)^2 + (R\,\omega C)^2}$

1) With small loss angle δ (= $1/\varphi$) ≈ tan δ (error at 4° about 1 ‰): $\underline{Z} \approx \omega L\,(\delta + j)$.

2) Series resonance (voltage resonance) for $\omega L = 1/(\omega C)$:

$$X_{res} = |X_L| = |X_c| = \sqrt{L/C} \qquad f_{res} = \frac{1}{2\pi\sqrt{LC}} \qquad \underline{Z}_{res} = R.$$

Close to resonance ($|\Delta f| < 0.1\, f_{res}$) is $Z \approx R + j\,X_{res} \cdot 2\,\Delta f / f_{res}$ with $\Delta f = f - f_{res}$

3) With small loss angle δ (= $1/\varphi$) ≈ tan $\delta = -1/(\omega C R)$:

$$\underline{Z} = \frac{\delta + j}{\omega C} \qquad B_{res} = \sqrt{C/L}: \; f_{res} = \frac{1}{2\pi\sqrt{LC}} \qquad \underline{Y}_{res} = G.$$

4) Close to resonance ($|\Delta f| < 0.1\, f_{res}$):
$\underline{Y} = G + j\,B_{res} \cdot 2\,\Delta f$ with $\Delta f = f - f_{res}$

5) e. g. coil with winding capacitance.

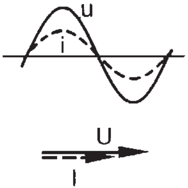
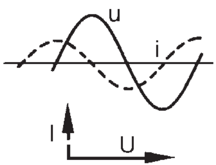
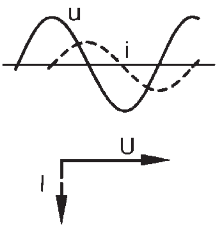
Table 2-6

Current / voltage relationships

		Ohmic resistance R	Capacitance (capacitor) C	Inductance (choke coil) L
General law	$u =$	$i\,R$	$\frac{1}{C}\int i\,\mathrm{d}t$	$L \cdot \frac{\mathrm{d}i}{\mathrm{d}t}$
	$i =$	$\frac{u}{R}$	$C \cdot \frac{\mathrm{d}u}{\mathrm{d}t}$	$\frac{1}{L}\int u\,\mathrm{d}t$
Time law	$u =$	$\hat{u} \sin \omega t$	$\hat{u} \sin \omega t$	$\hat{u} \sin \omega t$
hence	$u =$	$\hat{\imath}\,R \sin \omega t = \hat{u} \sin \omega t$	$-\frac{1}{\omega C}\,\hat{\imath} \cos \omega t = -\hat{u} \cos \omega t$	$\omega L\,\hat{\imath} \cos \omega t = \hat{u} \cos \omega t$
	$i =$	$\frac{\hat{u}}{R} \sin \omega t = \hat{\imath} \sin \omega t$	$\omega C\,\hat{u} \cos \omega t = \hat{\imath} \cos \omega t$	$-\frac{1}{\omega L}\,\hat{u} \cos \omega t = -\hat{\imath} \cos \omega t$
Elements of calculation	$\hat{\imath} =$	$\hat{u} / R$	$\omega C\,\hat{u}$	$\hat{u} / (\omega L)$
	$\hat{u} =$	$\hat{\imath}\,R$	$\hat{\imath} / (\omega C)$	$\hat{\imath}\,\omega L$
	$\varphi =$	0 *u* and *i* in phase	$\arctan \frac{1}{\omega C \cdot 0} = -\frac{\pi}{2}$ *i* leads *u* by 90 °	$\arctan \frac{\omega L}{0} = \frac{\pi}{2}$ *i* lags *u* by 90 °
	$f =$	$\frac{\omega}{2\pi}$	$\frac{\omega}{2\pi}$	$\frac{\omega}{2\pi}$

(continued)

Table 2-6 (continued)

		Ohmic resistance *R*	Capacitance (capacitor) *C*	Inductance (choke coil) *L*
Alternating current impedance	$\underline{Z}$ =	R	$\frac{-\mathrm{j}}{\omega C}$	$\mathrm{j}\,\omega L$
	$\lvert\underline{Z}\rvert$ =	R	$\frac{1}{\omega C}$	ωL
Diagrams				

2.3 Electrical resistances

2.3.1 Definitions and specific values

An ohmic resistance is present if the instantaneous values of the voltage are proportional to the instantaneous values of the current, even in the event of time-dependent variation of the voltage or current. Any conductor exhibiting this proportionality within a defined range (e. g. of temperature, frequency or current) behaves within this range as an ohmic resistance. Active power is converted in an ohmic resistance. For a resistance of this kind is

$$R = \frac{P}{I^2}\,.$$

The resistance measured with direct current is termed the *d. c. resistance* R_{-}. If the resistance of a conductor differs from the d. c. resistance only as a result of skin effect, we then speak of the a. c. resistance $R_{\sim}$ of the conductor. The ratio expressing the increase in resistance is

$$\zeta = \frac{R_{\sim}}{R_{-}} = \frac{\textit{a. c.}\text{ resistance}}{\text{d. c. resistance}}\,.$$

Specific values for major materials are shown in Table 2-7.

Table 2-7

Numerical values for major materials

Conductor	Specific electric resistance ρ ($\mathrm{mm^2\,\Omega/m}$)	Electric conductivity $x = 1/\rho$ ($\mathrm{m/mm^2\,\Omega}$)	Temperature coefficient α ($\mathrm{K^{-1}}$)	Density ($\mathrm{kg/dm^3}$)
Aluminium, 99.5 % Al, soft	0.0278	36	$4 \cdot 20^{-3}$	2.7
Al-Mg-Si	0.03…0.033	33…30	$3.6 \cdot 10^{-3}$	2.7
Al-Mg	0.06…0.07	17…14	$2.0 \cdot 10^{-3}$	2.7
Al bronze, 90 % Cu, 10 % Al	0.13	7.7	$3.2 \cdot 10^{-3}$	8.5
Bismuth	1.2	0.83	$4.5 \cdot 10^{-3}$	9.8
Brass	0.07	14.3	$1.3…1.9 \cdot 10^{-3}$	8.5
Bronze, 88 % Cu, 12 % Sn	0.18	5.56	$0.5 \cdot 10^{-3}$	8.6…9
Cast iron	0.60…1.60	1.67…0.625	$1.9 \cdot 10^{-3}$	7.86…7.2
Conductor copper, soft	0.01754	57	$4.0 \cdot 10^{-3}$	8.92
Conductor copper, hard	0.01786	56	$3.92 \cdot 10^{-3}$	8.92
Constantan	0.49…0.51	2.04…1.96	$-0.05 \cdot 10^{-3}$	8.8
CrAl 20 5	1.37	0.73	$0.05 \cdot 10^{-3}$	—
CrAl 30 5	1.44	0.69	$0.01 \cdot 10^{-3}$	—
Dynamo sheet	0.13	7.7	$4.5 \cdot 10^{-3}$	7.8
Dynamo sheet alloy (1 to 5 % Si)	0.27…0.67	3.7…1.5	—	7.8
Graphite and retort carbon	13…100	0.077…0.01	$-0.8…-0.2 \cdot 10^{-3}$	2.5…1.5
Lead	0.208	4.8	$4.0 \cdot 10^{-3}$	11.35
Magnesium	0.046	21.6	$3.8 \cdot 10^{-3}$	1.74
Manganin	0.43	2.33	$0.01 \cdot 10^{-3}$	8.4
Mercury	0.958	1.04	$0.90 \cdot 10^{-3}$	13.55
Molybdenum	0.054	18.5	$4.3 \cdot 10^{-3}$	10.2
Monel metal	0.42	2.8	$0.19 \cdot 10^{-3}$	—
Nickel silver	0.33	3.03	$0.4 \cdot 10^{-3}$	8.5

(continued)

Table 2-7 (continued)

Numerical values for major materials

Conductor	Specific electric resistance ρ ($mm^2\ \Omega/m$)	Electric conductivity $x = 1/\rho$ ($m/mm^2\ \Omega$)	Temperature coefficient α (K^{-1})	Density (kg/dm^3)
Ni Cr 30 20	1.04	0.96	$0.24 \cdot 10^{-3}$	8.3
Ni Cr 6015	1.11	0.90	$0.13 \cdot 10^{-3}$	8.3
Ni Cr 80 20	1.09	0.92	$0.04 \cdot 10^{-3}$	8.3
Nickel	0.09	11.1	$6.0 \cdot 10^{-3}$	8.9
Nickeline	0.4	2.5	$0.18…0.21 \cdot 10^{-3}$	8.3
Platinum	0.1	10	$3.8…3.9 \cdot 10^{-3}$	21.45
Red brass	0.05	20	—	8.65
Silver	0.0165	60.5	$41 \cdot 10^{-3}$	10.5
Steel, 0.1% C, 0.5 % Mn	0.13…0.15	7.7…6.7	$4…5 \cdot 10^{-3}$	7.86
Steel, 0.25 % C, 0.3 % Si	0.18	5.5	$4…5 \cdot 10^{-3}$	7.86
Steel, spring, 0.8 % C	0.20	5	$4…5 \cdot 10^{-3}$	7.86
Tantalum	0.16	6.25	$3.5…10^{-3}$	16.6
Tin	0.12	8.33	$4.4 \cdot 10^{-3}$	7.14
Tungsten	0.055	18.2	$4.6 \cdot 10^{-3}$	19.3
Zinc	0.063	15.9	$3.7 \cdot 10^{-3}$	7.23

Resistance varies with temperature, cf. Section 2.3.3

2.3.2 Resistances in different circuit configurations

Connected in series (Fig. 2-4)

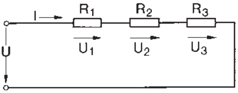


Fig. 2-4

Total resistance = Sum of individual resistances

$$R = R_1 + R_2 + R_3 + \dots$$

The component voltages behave in accordance with the resistances $U_1 = I\,R_1$ etc.

The current at all resistances is of equal magnitude $I = \dfrac{U}{R}$.

Connected in parallel (Fig. 2-5)

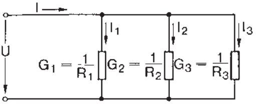


Fig. 2-5

Total conductance = Sum of the individual conductances

$$\frac{1}{R} = G = G_1 + G_2 + G_3 + \dots \qquad R = \frac{1}{G}.$$

In the case of n equal resistances the total resistance is the nth part of the individual resistances. The voltage at all the resistances is the same. Total current

$$I = \frac{U}{R} = \text{Sum of components } I_1 = \frac{U}{R_1} \text{ etc.}$$

The currents behave inversely to the resistances

$$I_1 = I\frac{R}{R_1};\ I_2 = I\frac{R}{R_2};\ I_3 = I\frac{R}{R_3}.$$

Transformation delta-star and star-delta (Fig. 2-6)

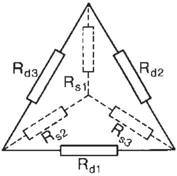


Fig. 2-6

Conversion from delta to star connection with the same total resistance:

$$R_{S1} = \frac{R_{d2} R_{d3}}{R_{d1} + R_{d2} + R_{d3}}$$

$$R_{S2} = \frac{R_{d3} R_{d1}}{R_{d1} + R_{d2} + R_{d3}}$$

$$R_{S3} = \frac{R_{d1} R_{d2}}{R_{d1} + R_{d2} + R_{d3}}$$

Conversion from star to delta connection with the same total resistance:

$$R_{d1} = \frac{R_{S1} R_{S2} + R_{S2} R_{S3} + R_{S3} R_{S1}}{R_{S1}}$$

$$R_{d2} = \frac{R_{S1} R_{S2} + R_{S2} R_{S3} + R_{S3} R_{S1}}{R_{S2}}$$

$$R_{d3} = \frac{R_{S1} R_{S2} + R_{S2} R_{S3} + R_{S3} R_{S1}}{R_{S3}}$$

Calculation of a bridge between points A and B (Fig. 2-7)

To be found:

1. the total resistance R_{tot} between points A and B,
2. the total current I_{tot} between points A and B,
3. the component currents in R_1 to R_5.

Given:

voltage $U = 220$ V.
resistance $R_1 = 10\ \Omega$,
$R_2 = 20\ \Omega$,
$R_3 = 30\ \Omega$,
$R_4 = 40\ \Omega$,
$R_5 = 50\ \Omega$.

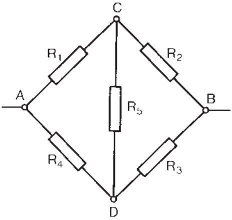


Fig. 2-7

First delta connection CDB is converted to star connection CSDB (Fig. 2-8):

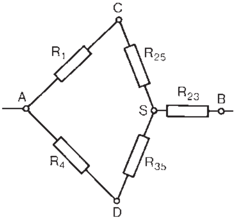


Fig. 2-8

$$R_{25} = \frac{R_2\,R_5}{R_2 + R_3 + R_5} = \frac{20 \cdot 50}{20 + 30 + 50} = 10\ \Omega,$$

$$R_{35} = \frac{R_3\,R_5}{R_2 + R_3 + R_5} = \frac{30 \cdot 50}{20 + 30 + 50} = 15\ \Omega,$$

$$R_{23} = \frac{R_2\,R_3}{R_2 + R_3 + R_5} = \frac{20 \cdot 30}{20 + 30 + 50} = 6\ \Omega,$$

$$R_{\text{tot}} = \frac{(R_1 + R_{25})\,(R_4 + R_{35})}{R_1 + R_{25} + R_4 + R_{35}} + R_{23} =$$

$$= \frac{(10 + 10)\,(40 + 15)}{10 + 10 + 40 + 15} + 6 = 20.67\ \Omega.$$

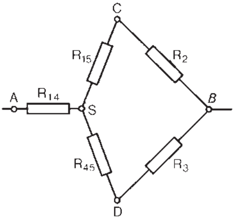


Fig. 2-9

$$I_{\text{tot}} = \frac{U}{R_{\text{tot}}} = \frac{220}{20.67} = 10.65\ \text{A}.$$

$$I_{\text{R1}} = I_{\text{tot}}\ \frac{R_{\text{tot}} - R_{23}}{R_1 + R_{25}} = 10.65 \cdot \frac{20.67 - 6}{10 + 10} = 7.82\ \text{A},$$

$$I_{\text{R4}} = I_{\text{tot}}\ \frac{R_{\text{tot}} - R_{23}}{R_4 + R_{35}} = 10.65 \cdot \frac{20.67 - 6}{40 + 15} = 2.83\ \text{A},$$

By converting the delta connection CDA to star connection CSDA, we obtain the following values (Fig. 2-9): $R_{15} = 5\,\Omega$; $R_{45} = 20\,\Omega$; $R_{14} = 4\,\Omega$; $I_{\text{R2}} = 7.1\,\text{A}$; $I_{\text{R3}} = 3.55\,\text{A}$.

With alternating current the calculations are somewhat more complicated and are carried out with the aid of resistance operators. Using the symbolic method of calculation, however, it is basically the same as above.

2.3.3 The influence of temperature on resistance

The resistance of a conductor is

$$R = \frac{l \cdot \rho}{A} = \frac{l}{x \cdot A}$$

where

l = Total length of conductor
A = Cross-sectional area of conductor
ρ = Specific resistance (at 20 °C)
$x = \frac{1}{\rho}$ Conductance
α = Temperature coefficient.

Values for ρ, x and α are given in Table 2-7 for a temperature of 20 °C.

For other temperatures ϑ[1] (ϑ in °C)

$$\rho_{\vartheta} = \rho_{20}\,[1 + \alpha\,(\vartheta - 20)]$$

---

[1] Valid for temperatures from – 50 to + 200 °C.

and hence for the conductor resistance

$$\mathrm{R}_{\vartheta} = \frac{l}{A} \cdot \rho_{20}\,[1 + \alpha\,(\vartheta - 20)].$$

Similarly for the conductivity

$$x_{\vartheta} = x_{20}\,[1 + \alpha\,(\vartheta - 20)]^{-1}$$

The temperature rise of a conductor or a resistance is calculated as

$$\Delta\,\vartheta = \frac{R_{\mathrm{w}}/R_{\mathrm{k}} - 1}{\alpha}\,.$$

The values R_{k} and R_{w} are found by measuring the resistance of the conductor or resistance in the cold and hot conditions, respectively.

Example:

The resistance of a copper conductor of $l = 100$ m and $A = 10\ \mathrm{mm}^2$ at 20 °C is

$$R_{20} = \frac{100 \cdot 0.0175}{10} = 0.175\ \Omega.$$

If the temperature of the conductor rises to $\vartheta = 50$ °C, the resistance becomes

$$R_{50} = \frac{100}{10} \cdot 0.0175\,[1 + 0.004\,(50 - 20)] \approx 0.196\ \Omega.$$

2.4 Relationships between voltage drop, power loss and conductor cross section

Especially in low-voltage networks is it necessary to check that the conductor cross-section, chosen with respect to the current-carrying capacity, is adequate as regards the voltage drop. It is also advisable to carry out this check in the case of very long connections in medium-voltage networks. (See also Sections 6.1.6 and 13.2.3).

Direct current

voltage drop

$$\Delta\,U = R'_{\mathrm{L}} \cdot 2 \cdot l \cdot I = \frac{2 \cdot l \cdot I}{x \cdot A} = \frac{2 \cdot l \cdot P}{x \cdot A \cdot U}$$

percentage voltage drop

$$\Delta\,u = \frac{\Delta\,U}{U_{\mathrm{n}}}\ 100\ \% = \frac{R'_{\mathrm{L}} \cdot 2 \cdot l \cdot I}{U_{\mathrm{n}}}\ 100\ \%$$

power loss

$$\Delta\,P = I^2\,R'_{\mathrm{L}}\,2 \cdot l = \frac{2 \cdot l \cdot P^2}{x \cdot A \cdot U^2}$$

percentage power loss

$$\Delta\,p = \frac{\Delta\,P}{P_{\mathrm{n}}}\ 100\ \% = \frac{I^2\,R'_{\mathrm{L}} \cdot 2 \cdot l}{P_{\mathrm{n}}}\ 100\ \%$$

conductor cross section

$$A = \frac{2 \cdot l \cdot I}{x \cdot \Delta\,U} = \frac{2 \cdot l \cdot I}{x \cdot \Delta\,u \cdot U}\ 100\ \% = \frac{2 \cdot l \cdot P}{\Delta\,p \cdot U^2 \cdot x}\ 100\ \%$$

Single-phase alternating current

voltage drop[2]

$$\Delta U = I \cdot 2 \cdot l\,(R'_L \cdot \cos\varphi + X'_L \cdot \sin\varphi)$$

percentage voltage drop[2]

$$\Delta u = \frac{\Delta U}{U_n}\,100\,\% = \frac{I \cdot 2 \cdot l\,(R'_L \cdot \cos\varphi + X'_L \cdot \sin\varphi)}{U_n}$$

power loss

$$\Delta P = I^2 R'_L \cdot 2 \cdot l = \frac{2 \cdot l \cdot P^2}{x \cdot A \cdot U^2 \cdot \cos^2\varphi}$$

percentage power loss

$$\Delta p = \frac{\Delta P}{P_n}\,100\,\% = \frac{I^2 \cdot R'_L \cdot 2 \cdot l}{P_n}\,100\,\%$$

conductor cross-section[1]

$$A = \frac{2 \cdot l \cos\varphi}{x\left(\dfrac{\Delta U}{I} - X'_L \cdot 2 \cdot l \cdot \sin\varphi\right)}$$

$$= \frac{2 \cdot l \cos\varphi}{x\left(\dfrac{\Delta u \cdot U_n}{I \cdot 100\,\%} - X'_L \cdot 2 \cdot l \cdot \sin\varphi\right)}$$

Three-phase current

voltage drop[2]

$$\Delta U = \sqrt{3} \cdot I \cdot l\,(R'_L \cdot \cos\varphi + X'_L \cdot \sin\varphi)$$

percentage voltage drop[2]

$$\Delta u = \frac{\Delta U}{U_n}\,100\,\% = \frac{\sqrt{3} \cdot I \cdot l\,(R'_L \cdot \cos\varphi + X'_L \cdot \sin\varphi)}{U_n}\,100\,\%$$

power loss

$$\Delta P = 3 \cdot I^2 R'_L \cdot l = \frac{l \cdot P^2}{x \cdot A \cdot U^2 \cdot \cos^2\varphi}$$

percentage power loss

$$\Delta p = \frac{\Delta P}{P_n}\,100\,\% = \frac{3\,I^2 \cdot R'_L \cdot l}{P_n}\,100\,\%$$

conductor cross-section[1]

$$A = \frac{l \cdot \cos\varphi}{x\left(\dfrac{\Delta U}{\sqrt{3} \cdot I} - X'_L \cdot l \cdot \sin\varphi\right)}$$

$$= \frac{l \cdot \cos\varphi}{x\left(\dfrac{\Delta u \cdot U}{\sqrt{3} \cdot I \cdot 100\,\%} - X'_L \cdot l \cdot \sin\varphi\right)}$$

l = one-way length of conductor

R'_L = Resistance per km

P = Active power to be transmitted ($P = P_n$)

U = phase-to-phase voltage

X'_L = Reactance per km

I = phase-to-phase current

In single-phase and three-phase a.c. systems with cables and lines of less than 16 mm² the inductive reactance can usually be disregarded. It is sufficient in such cases to calculate only with the d.c. resistance.

[1] Reactance is slightly dependent on conductor cross section.

[2] Longitudinal voltage drop becomes effectively apparent.

Table 2-8

Effective resistances per unit length of PVC-insulated cables with copper conductors as per DIN VDE 0271 for 0.6/1 kV

Number of conductors and cross-section	D. C. resistance at 70 °C	Ohmic resistance at 70 °C	Inductive reactance	Effective resistance per unit length $R'_L \cdot \cos\varphi + X'_L \cdot \sin\varphi$ at cos φ				
				0.95	0.9	0.8	0.7	0.6
	R'_{L-}	$R'_{L\sim}$	X'_L					
mm²	Ω/km	Ω/km	Ω/km	Ω/km	Ω/km	Ω/km	Ω/km	Ω/km
4 × 1.5	14.47	14.47	0.115	13.8	13.1	11.65	10.2	8.77
4 × 2.5	8.71	8.71	0.110	8.31	7.89	7.03	6.18	5.31
4 × 4	5.45	5.45	0.107	5.21	4.95	4.42	3.89	3.36
4 × 6	3.62	3.62	0.100	3.47	3.30	2.96	2.61	2.25
4 × 10	2.16	2.16	0.094	2.08	1.99	1.78	1.58	1.37
4 × 16	1.36	1.36	0.090	1.32	1.26	1.14	1.020	0.888
4 × 25	0.863	0.863	0.086	0.847	0.814	0.742	0.666	0.587
4 × 35	0.627	0.627	0.083	0.622	0.60	0.55	0.498	0.443
4 × 50	0.463	0.463	0.083	0.466	0.453	0.42	0.38	0.344
4 × 70	0.321	0.321	0.082	0.331	0.326	0.306	0.283	0.258
4 × 95	0.231	0.232	0.082	0.246	0.245	0.235	0.221	0.205
4 × 120	0.183	0.184	0.080	0.2	0.2	0.195	0.186	0.174
4 × 150	0.149	0.150	0.080	0.168	0.17	0.168	0.162	0.154
4 × 185	0.118	0.1202	0.080	0.139	0.143	0.144	0.141	0.136
4 × 240	0.0901	0.0922	0.079	0.112	0.117	0.121	0.121	0.119
4 × 300	0.0718	0.0745	0.079	0.0954	0.101	0.107	0.109	0.108

Example:

A three-phase power of 50 kW with cos $\varphi = 0.8$ is to be transmitted at 400 V over a line 100 m long. The voltage drop must not exceed 2 %. What is the required cross section of the line?

The percentage voltage drop of 2 % is equivalent to

$$\Delta U = \frac{\Delta u}{100\ \%} U_n = \frac{2\ \%}{100\ \%} 400\ \text{V} = 8.0\ \text{V}.$$

The current is

$$I = \frac{P}{\sqrt{3} \cdot U \cdot \cos\varphi} = \frac{50\ \text{kW}}{\sqrt{3} \cdot 400\ \text{V} \cdot 0.8} = 90\ \text{A}.$$

Calculation is made easier by Table 2-8, which lists the effective resistance per unit length $R'_L \cdot \cos\varphi + X'_L \cdot \sin\varphi$ for the most common cables and conductors. Rearranging the formula for the voltage drop yields

$$R'_L \cdot \cos\varphi + X'_L \cdot \sin\varphi = \frac{\Delta \text{U}}{\sqrt{3} \cdot I \cdot l} = \frac{8.0}{\sqrt{3} \cdot 90\ \text{A} \cdot 0.1\ \text{km}} = 0.513\ \Omega/\text{km}.$$

According to Table 2-8 a cable of 50 mm² with an effective resistance per unit length of 0.42 Ω/km should be used. The actual voltage drop will then be

$$\begin{aligned}\Delta U &= \sqrt{3}\cdot I\cdot l\,(R'_{\mathrm{L}}\cdot\cos\varphi + X'_{\mathrm{L}}\cdot\sin\varphi)\\ &= \sqrt{3}\cdot 90\ \mathrm{A}\cdot 0.1\ \mathrm{km}\cdot 0.42\ \Omega/\mathrm{km} \;=\; 6.55\ \mathrm{V}.\end{aligned}$$

This is equivalent to $\Delta u = \dfrac{\Delta U}{U_{\mathrm{n}}}\,100\,\% = \dfrac{6.55\ \mathrm{V}}{400\ \mathrm{V}}\,100\,\% = 1.6\,\%.$

2.5 Current input of electrical machines and transformers

Direct current

Motors:

$$I = \frac{P_{mech}}{U\cdot\eta}$$

Generators:

$$I = \frac{P}{U}$$

Single-phase alternating current

Motors:

$$I = \frac{P_{mech}}{U\cdot\eta\cdot\cos\varphi}$$

Transformers and synchronous generators:

$$I = \frac{S}{U}$$

Three-phase current

Induction motors:

$$I = \frac{P_{mech}}{\sqrt{3}\cdot U\cdot\eta\cdot\cos\varphi}$$

Transformers and synchronous generators:

$$I = \frac{S}{\sqrt{3}\cdot U}$$

Synchronous motors:

$$I \approx \frac{P_{mech}}{\sqrt{3}\cdot U\cdot\eta\cdot\cos\varphi}\cdot\sqrt{1+\tan^2\varphi}$$

In the formulae for three-phase current, *U* is the phase voltage.

Table 2-9

Motor current ratings for three-phase motors (typical values for squirrel-cage type)

Smallest possible short-circuit fuse (Service category gG[1)]) for three-phase motors. The maximum value is governed by the switching device or motor relay.

Motor output data			Rated currents at							
			230 V		400 V		500 V		600 V	
			Motor	Fuse	Motor	Fuse	Motor	Fuse	Motor	Fuse
kW	$\cos\varphi$	η %	A	A	A	A	A	A	A	A
0.25	0.7	62	1.4	4	0.8	2	0.6	2	—	—
0.37	0.72	64	2.0	4	1.2	4	0.9	2	0.7	2
0.55	0.75	69	2.7	4	1.5	4	1.2	4	0.9	2
0.75	0.8	74	3.2	6	1.8	4	1.5	4	1.1	2
1.1	0.83	77	4.3	6	2.5	4	2	4	1.5	2
1.5	0.83	78	5.8	16	3.3	6	2.6	4	2	4
2.2	0.83	81	8.2	20	4.7	10	3.7	10	2.9	6
3	0.84	81	11.1	20	6.4	16	5	10	3.5	6

(continued)

Table 2-9 (continued)

Motor current ratings for three-phase motors (typical values for squirrel-cage type)

Smallest possible short-circuit fuse (Service category gG[1]) for three-phase motors. The maximum value is governed by the switching device or motor relay.

Motor output data			Rated currents at							
			230 V		400 V		500 V		660 V	
			Motor	Fuse	Motor	Fuse	Motor	Fuse	Motor	Fuse
kW	cos φ	η %	A	A	A	A	A	A	A	A
4	0.84	82	14.6	25	8.4	20	6.4	16	4.9	10
5.5	0.85	83	19.6	35	11.3	25	8.6	20	6.7	16
7.5	0.86	85	25.8	50	14.8	35	11.5	25	9	16
11	0.86	87	36.9	63	21.2	35	17	35	13	25
15	0.86	87	50	80	29	50	22.5	35	17.5	25
18.5	0.86	88	61	100	35	63	27	50	21	35
22	0.87	89	71	100	41	63	32	63	25	35
30	0.87	90	96	125	55	80	43	63	33	50
37	0.87	90	119	200	68	100	54	80	42	63
45	0.88	91	141	225	81	125	64	100	49	63
55	0.88	91	172	250	99	160	78	125	60	100
75	0.88	91	235	350	135	200	106	160	82	125
90	0.88	92	279	355	160	225	127	200	98	125
110	0.88	92	341	425	196	250	154	225	118	160
132	0.88	92	409	600	235	300	182	250	140	200
160	0.88	93	491	600	282	355	220	300	170	224
200	0.88	93	613	800	353	425	283	355	214	300
250	0.88	93	—	—	441	500	355	425	270	355
315	0.88	93	—	—	556	630	444	500	337	400
400	0.89	96	—	—	—	—	534	630	410	500
500	0.89	96	—	—	—	—	—	—	515	630

---

[1] see 7.1.2 for definitions

The motor current ratings relate to normal internally cooled and surface-cooled threephase motors with synchronous speeds of 1500 min^{-1}.

The fuses relate to the stated motor current ratings and to direct starting:
starting current max. 6 × rated motor current,
starting time max. 5 s.

In the case of slipring motors and also squirrel-cage motors with star-delta starting ($t_{\text{start}} \leqq 15$ *s*, $I_{\text{start}} = 2 \cdot I_{\text{n}}$) it is sufficient to size the fuses for the rated current of the motor concerned.

Motor relay in phase current: set to 0.58 × motor rated current.

With higher rated current, starting current and/or longer starting time, use larger fuses. Note comments on protection of lines and cables against overcurrents (Section 13.2.3).

2.6 Attenuation constant *a* of transmission systems

The transmission properties of transmission systems, e. g. of lines and two-terminal pair networks, are denoted in logarithmic terms for the ratio of the output quantity to the input quantity of the same dimension. When several transmission elements are arranged in series the total attenuation or gain is then obtained, again in logarithmic terms, by simply adding together the individual partial quantities.

The natural logarithm for the ratio of two quantities, e. g. two voltages, yields the voltage gain in Neper (Np):

$$\frac{a}{\mathrm{Np}} = \ln U_2/U_1.$$

If $P = U^2/R$, the power gain, provided $R_1 = R_2$ is

$$\frac{a}{\mathrm{Np}} = \frac{1}{2} \ln P_2/P_1.$$

The conversion between logarithmic ratios of voltage, current and power when $R_1 \neq R_2$ is

$$\ln U_2/U_1 = \ln I_2/I_1 + \ln R_2/R_1 = \frac{1}{2} \ln P_2/P_1 + \frac{1}{2} \ln R_2/R_1.$$

The common logarithm of the power ratio is the power gain in Bel. It is customary to calculate with the decibel (dB), one tenth of a Bel:

$$\frac{a}{\mathrm{dB}} = 10 \lg P_2/P_1.$$

If $R_1 = R_2$, for the conversion we have

$$\frac{a}{\mathrm{dB}} = 20 \lg U_2/U_1 \text{ respectively } \frac{a}{\mathrm{dB}} = 20 \lg I_2/I_1.$$

If $R_1 \neq R_2$, then

$$10 \lg P_2/P_1 = 20 \lg U_2/U_1, - 10 \lg R_2/R_1, = 20 \lg I_2/I_1, + 10 \lg R_2/R_1.$$

Relationship between Neper and decibel:

1 dB = 0.1151 Np
1 Np = 8.6881 dB

In the case of absolute levels one refers to the internationally specified values P_0 = 1 mW at 600 Ω, equivalent to $U_0 \cdot 0.775$ V, $I_0 \cdot 1.29$ mA (0 Np or 0 dB).

For example, 0.36 Np signifies a voltage ratio of $U/U_0 = e^{0.35} = 1.42$.

This corresponds to an absolute voltage level of $U = 0.776 \text{ V} \cdot 1.42 = 1.1$ V. Also 0.35 Np = 0.35 · 8.6881 = 3.04 dB.

3 Calculation of Short-Circuit Currents in Three-Phase Systems

3.1 Terms and definitions

3.1.1 Terms as per DIN VDE 0102 / IEC 909

Short circuit: the accidental or deliberate connection across a comparatively low resistance or impedance between two or more points of a circuit which usually have differing voltage.

Short-circuit current: the current in an electrical circuit in which a short circuit occurs.

Prospective (available) short-circuit current: the short-circuit current which would arise if the short circuit were replaced by an ideal connection having negligible impedance without alteration of the incoming supply.

Symmetrical short-circuit current: root-mean-square (r.m.s.) value of the symmetrical alternating-current (a.c.) component of a prospective short-circuit current, taking no account of the direct-current (d.c.) component, if any.

Initial symmetrical short-circuit current I_k''*:* the r.m.s. value of the symmetrical a.c. component of a prospective short-circuit current at the instant the short circuit occurs if the short-circuit impedance retains its value at time zero.

Initial symmetrical (apparent) short-circuit power S_k''*:* a fictitious quantity calculated as the product of initial symmetrical short-circuit current I_k'', nominal system voltage U_n and the factor $\sqrt{3}$.

D.C. (aperiodic) component i_{DC} *of short-circuit current:* the mean value between the upper and lower envelope curve of a short-circuit current decaying from an initial value to zero.

Peak short-circuit current i_p*:* the maximum possible instantaneous value of a prospective short-circuit current.

Symmetrical short-circuit breaking current I_a*:* the r.m.s. value of the symmetrical a.c. component of a prospective short-circuit current at the instant of contact separation by the first phase to clear of a switching device.

Steady-state short-circuit current I_k*:* the r.m.s. value of the symmetrical a.c. component of a prospective short-circuit current persisting after all transient phenomena have died away.

(Independent) Voltage source: an active element which can be simulated by an ideal voltage source in series with a passive element independently of currents and other voltages in the network.

Nominal system voltage U_n*:* the (line-to-line) voltage by which a system is specified and to which certain operating characteristics are referred.

Equivalent voltage source $cU_n / \sqrt{3}$*:* the voltage of an ideal source applied at the short-circuit location in the positive-sequence system as the network's only effective voltage in order to calculate the short-circuit currents by the equivalent voltage source method.

Voltage factor c: the relationship between the voltage of the equivalent voltage source and $U_n / \sqrt{3}$.

Subtransient voltage E" of a synchronous machine: the r.m.s. value of the symmetrical interior voltages of a synchronous machine which is effective behind the subtransient reactance X_d'' at the instant the short circuit occurs.

Far-from-generator short circuit: a short circuit whereupon the magnitude of the symmetrical component of the prospective short-circuit current remains essentially constant.

Near-to-generator short circuit: a short circuit whereupon at least one synchronous machine delivers an initial symmetrical short-circuit current greater than twice the synchronous machine's rated current, or a short circuit where synchronous or induction motors contribute more than 5 % of the initial symmetrical short-circuit current I_k'' without motors.

Positive-sequence short-circuit impedance $\underline{Z}_{(1)}$ of a three-phase a.c. system: the impedance in the positive-phase-sequence system as viewed from the fault location.

Negative-sequence short-circuit impedance $\underline{Z}_{(2)}$ of a three-phase a.c. system: the impedance in the negative-phase-sequence system as viewed from the fault location.

Zero-sequence short-circuit impedance $\underline{Z}_{(0)}$ of a three-phase a.c. system: the impedance in the zero-phase-sequence system as viewed from the fault location. It includes the threefold value of the neutral-to-earth impedance.

Subtransient reactance X_d'' of a synchronous machine: the reactance effective at the instant of the short circuit. For calculating short-circuit currents, use the saturated value X_d''.

Minimum time delay t_{min} of a circuit-breaker: the shortest possible time from commencement of the short-circuit current until the first contacts separate in one pole of a switching device.

3.1.2 Symmetrical components of asymmetrical three-phase systems

In three-phase networks a distinction is made between the following kinds of fault:

a) three-phase fault (I_{k3}'')
b) phase-to-phase fault clear of ground (I_{k2}'')
c) two-phase-to-earth fault (I_{k2E}''; I_{kE2E}'')
d) phase-to-earth fault (I_{k1}'')
e) double earth fault (I_{kEE}'')

A 3-phase fault affects the three-phase network symmetrically. All three conductors are equally involved and carry the same rms short-circuit current. Calculation need therefore be for only one conductor.

All other short-circuit conditions, on the other hand, incur asymmetrical loadings. A suitable method for investigating such events is to split the asymmetrical system into its symmetrical components.

With a symmetrical voltage system the currents produced by an asymmetrical loading (I_1, I_2 and I_3) can be determined with the aid of the symmetrical components (positive-, negative- and zero-sequence system).

The symmetrical components can be found with the aid of complex calculation or by graphical means.

We have:

Current in pos.-sequence system $\underline{I}_m = \frac{1}{3}(\underline{I}_1 + \underline{a}\ I_2 + \underline{a}^2\underline{I}_3)$

Current in neg.-sequence system $\underline{I}_g = \frac{1}{3}(\underline{I}_1 + \underline{a}^2\underline{I}_2 + \underline{a}\ \underline{I}_3)$

Current in zero-sequence system $\underline{I}_o = \frac{1}{3}(\underline{I}_1 + \underline{I}_2 + \underline{I}_3)$

For the rotational operators of value 1:

$$\underline{a} = e^{j120^\circ};\ \underline{a}^2 = e^{j240^\circ};\ 1 + \underline{a} + \underline{a}^2 = 0$$

The above formulae for the symmetrical components also provide information for a graphical solution.

If the current vector leading the current in the reference conductor is rotated 120° *backwards,* and the lagging current vector 120 ° *forwards,* the resultant is equal to three times the vector $\underline{I}_m$ in the reference conductor. The negative-sequence components are apparent.

If one turns in the other direction, the positive-sequence system is evident and the resultant is three times the vector $\underline{I}_g$ in the reference conductor.

Geometrical addition of all three current vectors ($\underline{I}_1$, $\underline{I}_2$ and $\underline{I}_3$) yields three times the vector $\underline{I}_0$ in the reference conductor.

If the neutral conductor is unaffected, there is no zero-sequence system.

3.2 Fundamentals of calculation according to DIN VDE 0102 / IEC 909

In order to select and determine the characteristics of equipment for electrical networks it is necessary to know the magnitudes of the short-circuit currents and short-circuit powers which may occur.

The short-circuit current at first runs asymmetrically to the zero line, Fig. 3-1. It contains an alternating-current component and a direct-current component.

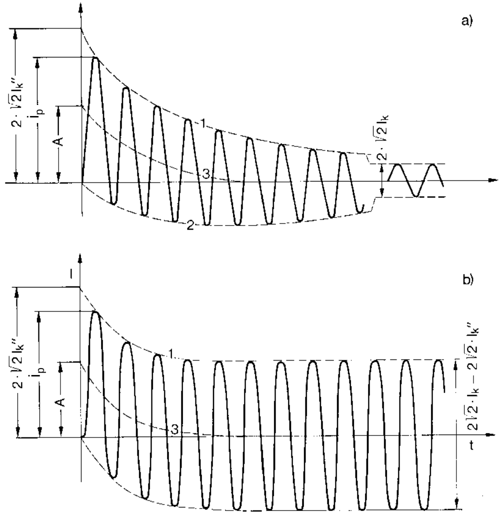


Fig. 3-1

Curve of short-circuit current: a) near-to-generator fault, b) far-from-generator fault
I_k'' *initial symmetrical short-circuit current,* i_p *peak short-circuit current,* I_k *steady state short-circuit current, A initial value of direct current, 1 upper envelope, 2 lower envelope, 3 decaying direct current.*

Calculatlon of initial symmetrical short-circuit current I_k''

The calculation of short-circuit currents is always based on the assumption of a dead short circuit. Other influences, especially arc resistances, contact resistances, conductor temperatures, inductances of current transformers and the like, can have the effect of lowering the short-circuit currents. Since they are not amenable to calculation, they are accounted for in Table 3-1 by the factor c.

Initial symmetrical short-circuit currents are calculated with the equations in Table 3-2.

Table 3-1

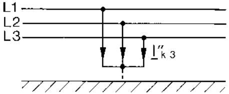
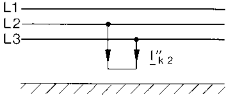
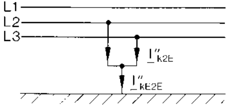
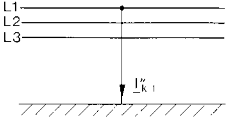
Voltage factor *c*

Nominal voltage	Voltage factor c for calculating	
	the greatest short-circuit current c_{max}	the smallest short-circuit current c_{min}
Low voltage		
100 V to 1000 V		
(see IEC 38, Table I)		
a) 230 V / 400 V	1.00	0.95
b) other voltages	1.05	1.00
Medium voltage		
>1 kV to 35 kV	1.10	1.00
(see IEC 38, Table III)		
High-voltage		
> 35 kV to 230 kV	1.10	1.00
(see IEC 38, Table IV)		
380 kV	1.10	1.00

Note: cU_n should not exceed the highest voltage U_m for power system equipment.

Table 3-2

Formulae for calculating initial short-circuit current and short-circuit powers

Kind of fault		Dimension equations (IEC 909)	Numerical equations of the % / MVA systems
Three-phase fault with or without earth fault		$I''_{k3} = \frac{1.1 \cdot U_n}{\sqrt{3}\,\lvert\underline{Z}_1\rvert}$ $S''_k = \sqrt{3}\,U_n\,I''_{k3}$	$I''_{k3} = \frac{1.1 \cdot 100\,\%}{\lvert\sqrt{3}\,\underline{Z}_1\rvert} \cdot \frac{1}{U_n}$ $S''_k = \frac{1.1 \cdot 100\,\%}{\underline{Z}_1}$
Phase-to-phase fault clear of ground		$I''_{k2} = \frac{1.1 \cdot U_n}{\lvert\underline{Z}_1 + \underline{Z}_2\rvert}$	$I''_{k2} = \frac{1.1 \cdot 100\,\%}{\lvert\underline{Z}_1 + \underline{Z}_2\rvert} \cdot \frac{1}{U_n}$
Two-phase-to-earth fault		$I''_{kE2E} = \frac{\sqrt{3} \cdot 1.1\,U_n}{\left\lvert\underline{Z}_1 + \underline{Z}_0 + \underline{Z}_0\frac{\underline{Z}_1}{\underline{Z}_2}\right\rvert}$	$I''_{kE2E} = \frac{\sqrt{3} \cdot 1.1 \cdot 100\,\%}{\left\lvert\underline{Z}_1 + \underline{Z}_0 + \underline{Z}_0\frac{\underline{Z}_1}{\underline{Z}_2}\right\rvert} \cdot \frac{1}{U_n}$
Phase-to-earth fault		$I''_{k1} = \frac{\sqrt{3} \cdot 1.1 \cdot U_n}{\lvert\underline{Z}_1 + \underline{Z}_2 + \underline{Z}_0\rvert}$	$I''_{k1} = \frac{\sqrt{3} \cdot 1.1 \cdot 100\,\%}{\lvert\underline{Z}_1 + \underline{Z}_2 + \underline{Z}_0\rvert} \cdot \frac{1}{U_n}$

In the right-hand column of the Table, I''_k is in kA, S''_k in MVA, U_n in kV and Z in % / MVA.
The directions of the arrows shown here are chosen arbitrarily.

Calculation of peak short-circuit current i_p

When calculating the peak short-circuit current i_p, sequential faults are disregarded. Three-phase short circuits are treated as though the short circuit occurs in all three conductors simultaneously. We have:

$$i_p = \kappa \cdot \sqrt{2} \cdot I''_k.$$

The factor κ takes into account the decay of the d. c. component. It can be calculated as

$\kappa = 1.02 + 0.98\ e^{-3\ R/X}$ or taken from Fig. 3-2.

Exact calculation of i_p with factor κ is possible only in networks with branches having the same ratios R/X. If a network includes parallel branches with widely different ratios R/X, the following methods of approximation can be applied:

a) Factor κ is determined uniformly for the smallest ratio R/X. One need only consider the branches which are contained in the faulted network and carry partial short-circuit currents.

b) The factor is found for the ratio R/X from the resulting system impedance $Z_k = R_k + jX_k$ at the fault location, using $1.15 \cdot \kappa_k$ for calculating i_p. In low-voltage networks the product $1.15 \cdot \kappa$ is limited to 1.8, and in high-voltage networks to 2.0.

c) Factor κ can also be calculated by the method of the equivalent frequency as in IEC 909 para. 9.1.3.2.

The maximum value of $\kappa = 2$ is attained only in the theoretical limiting case with an active resistance of $R = 0$ in the short-circuit path. Experience shows that with a short-circuit at the generator terminals a value of $\kappa = 1.8$ is not exceeded with machines < 100 MVA.

With a unit-connected generator and high-power transformer, however, a value of $\kappa = 1.9$ can be reached in unfavourable circumstances in the event of a short circuit near the transformer on its high-voltage side, owing to the transformer's very small ratio R/X. The same applies to networks with a high fault power if a short circuit occurs after a reactor.

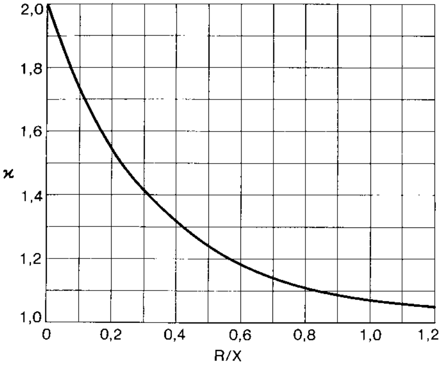


Fig. 3-2

Factor κ

Calculation of steady-state short-circuit current I_k

Three-phase fault with single supply

$I_k = I''_{kQ}$	network
$I_k = \lambda \cdot I_{rG}$	synchronous machine

Three-phase fault with single supply from more than one side

$I_k = I_{bkW} + I''_{kQ}$

I_{bkw}	symmetrical short-circuit breaking current of a power plant
I''_{kQ}	initial symmetrical short-circuit current of network

Three-phase fault in a meshed network

$I_k = I''_{koM}$

I''_{koM}	initial symmetrical short-circuit current without motors

I_k depends on the excitation of the generators, on saturation effects and on changes in switching conditions in the network during the short circuit. An adequate approximation for the upper and lower limit values can be obtained with the factors λ_{max} and λ_{min}, Fig. 3-3 and 3-4. I_{rG} is the rated current of the synchronous machine.

For X_{dsat} one uses the reciprocal of the no-load/short-circuit ratio I_{k0}/I_{rG}(VDE 0530 Part 1).

The 1st series of curves of λ_{max} applies when the maximum excitation voltage reaches 1.3 times the excitation voltage for rated load operation and rated power factor in the case of turbogenerators, or 1.6 times the excitation for rated load operation in the case of salient-pole machines.

The 2nd series of curves of λ_{max} applies when the maximum excitation voltage reaches 1.6 times the excitation for rated load operation in the case of turbogenerators, or 2.0 times the excitation for rated load operation in the case of salient-pole machines.

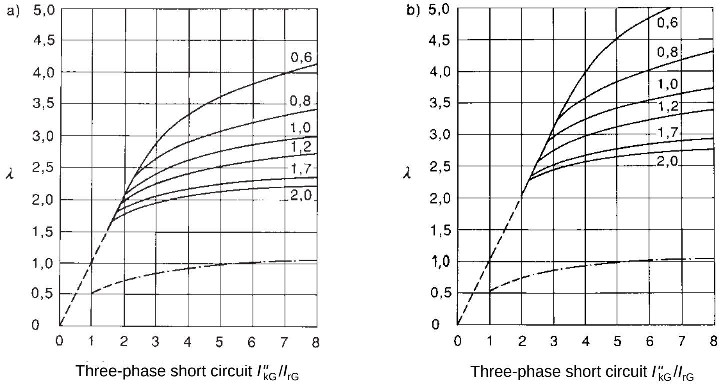


Fig. 3-3

Factors λ *for salient-pole machines in relation to ratio* I''_{kG}/I_{rG} *and saturated synchronous reactance* X_d *of 0.6 to 2.0, ——* $\lambda_{\max}$, *– · –* $\lambda_{\min}$;
a) Series 1 $U_{\text{fmax}} / U_{\text{fr}} = 1.6$; *b) Series 2* $U_{\text{fmax}} / U_{\text{fr}} = 2.0$.

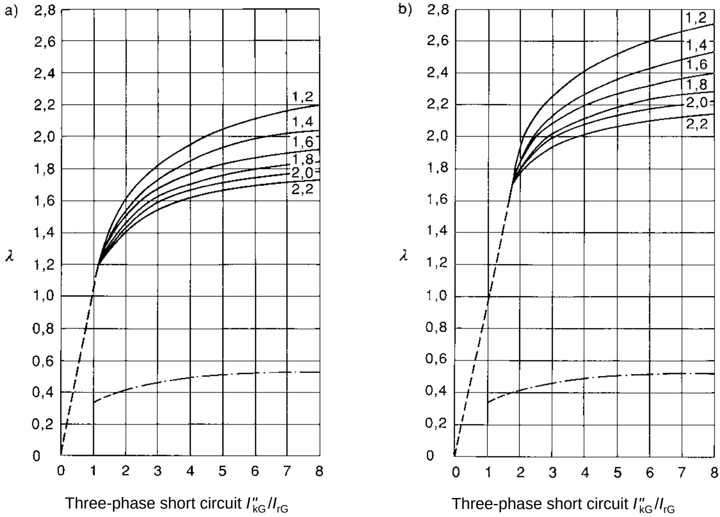


Fig. 3-4

Factors λ *for turbogenerators in relation to ratio* I''_{kG}/I_{rG} *and saturated synchronous reactance* X_d *of 1.2 to 2.2, ——* $\lambda_{\max}$, *– · –* $\lambda_{\min}$;
a) Series 1 $U_{\text{fmax}} / U_{\text{fr}} = 1.3$; *b) Series 2* $U_{\text{fmax}} / U_{\text{fr}} = 1.6$.

Calculation of symmetrical breaking current I_a

Three-phase fault with single supply

$I_a = \mu \cdot I''_{kG}$	synchronous machine
$I_a = \mu \cdot q \cdot I''_{kM}$	induction machine
$I_a = I''_{kQ}$	network

Three-phase fault with single supply from more than one side

$I_a = I_{aKW} + I''_{kQ} + I_{aM}$

I_{aKW}	symmetrical short-circuit breaking current of a power plant
I_{kQ}	initial symmetrical short-circuit current of a network
I_{aM}	symmetrical short-circuit breaking current of an induction machine

Three-phase fault in a meshed network

$I_a = I''_k$

A more exact result for the symmetrical short-circuit breaking current is obtained with IEC 909 section 12.2.4.3, equation (60).

The factor μ denotes the decay of the symmetrical short-circuit current during the switching delay time. It can be taken from Fig. 3-5 or the equations.

$\mu = 0.84 + 0.26\ e^{-0.26}\ I''_{kG}/\ I_{rG}$ for $t_{min} = 0.02$ s

$\mu = 0.71 + 0.51\ e^{-0.30}\ I''_{kG}/\ I_{rG}$ for $t_{min} = 0.05$ s

$\mu = 0.62 + 0.72\ e^{-0.32}\ I''_{kG}/\ I_{rG}$ for $t_{min} = 0.10$ s

$\mu = 0.56 + 0.94\ e^{-0.38}\ I''_{kG}/\ I_{rG}$ for $t_{min} = 0.25$ s

$\mu_{max} = 1$

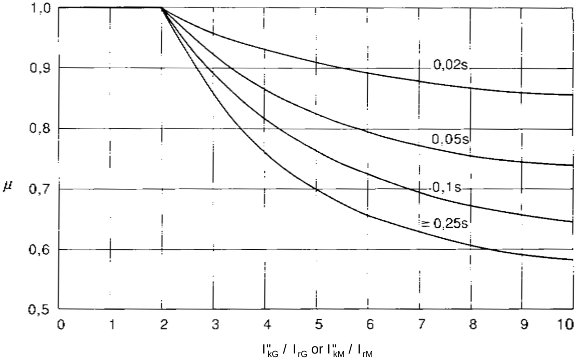


Fig. 3-5

Factor μ for calculating the symmetrical short-circuit breaking current I_a as a function of ratio I''_{kG}/I_{rG} or I''_{kM}/I_{rM}, and of switching delay time t_{min} of 0.02 to 0.25 s.

If the short circuit is fed by a number of independent voltage sources, the symmetrical breaking currents may be added.

With compound excitation or converter excitation one can put $\mu = 1$ if the exact value is not known. With converter excitation Fig. 3-5 applies only if $t_v \leq 0.25$ s and the maximum excitation voltage does not exceed 1.6 times the value at nominal excitation. In all other cases put $\mu = 1$.

The factor q applies to induction motors and takes account of the rapid decay of the motor's short-circuit current owing to the absence of an excitation field. It can be taken from Fig. 3-6 or the equations.

$q = 1.03 + 0.12 \ln m$ for $t_{\min} = 0.02$ s

$q = 0.79 + 0.12 \ln m$ for $t_{\min} = 0.05$ s

$q = 0.57 + 0.12 \ln m$ for $t_{\min} = 0.10$ s

$q = 0.26 + 0.12 \ln m$ for $t_{\min} = 0.25$ s

$q_{\max} = 1$

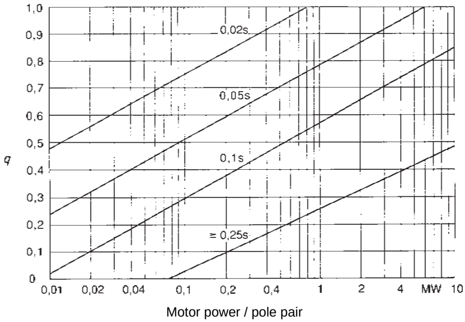


Fig. 3-6

Factor q for calculating the symmetrical short-circuit breaking current of induction motors as a function of the ratio motor power / pole pair and of switching delay time t_{min} *of 0.02 to 0.25 s.*

Taking account of transformers

The impedances of equipment in the higher- or lower-voltage networks have to be recalculated with the square of the rated transformer ratio $\ddot{u}_r$ (main tap).

The influence of motors

Synchronous motors and synchronous condensers are treated as synchronous generators.

Induction motors contribute values to I''_k, i_p and I_a and in the case of a two-phase short circuit, to I_k as well.

The heaviest short-circuit currents I''_k, i_p, I_a and I_k in the event of three-phase and two-phase short circuits are calculated as shown in Table 3-3.

For calculating the peak short-circuit current:
$\kappa_m = 1.65$ for HV motors, motor power per pole pair < 1MW
$\kappa_m = 1.75$ for HV motors, motor power per pole pair ≥ 1MW
$\kappa_m = 1.3$ for LV motors

Table 3-3

To calculate short-circuit currents of induction motors with terminal short circuit

	three-phase	two-phase
Initial symmetrical short-circuit current	$I''_{k3M} = \dfrac{c \cdot U_n}{\sqrt{3} \cdot Z_M}$	$I''_{k2M} = \dfrac{\sqrt{3}}{2} I''_{k3M}$
Peak short-circuit current	$I''_{p3M} = \kappa_m \sqrt{2} I''_{k3M}$	$I''_{p2M} = \dfrac{\sqrt{3}}{2} i_{p3M}$
Symmetrical short-circuit breaking current	$I_{a3M} = I''_{k3M}$	$I''_{a2M} \sim \dfrac{\sqrt{3}}{2} I''_{k3M}$
Steady-state short-circuit current	$I''_{k3M} = 0$	$I_{k2M} \sim \dfrac{1}{2} I''_{k3M}$

The influence of induction motors connected to the faulty network by way of transformers can be disregarded if

$$\frac{\Sigma P_{rM}}{\Sigma S_{rT}} \leqq \frac{0.8}{\dfrac{100 \, \Sigma S_{rT}}{S''_k} - 0.3}.$$

Here,

ΣP_{rM} is the sum of the ratings of all high-voltage and such low-voltage motors as need to be considered,

ΣS_{rT} is the sum of the ratings of all transformers feeding these motors and

S''_k is the initial fault power of the network (without the contribution represented by the motors).

To simplify calculation, the rated current I_{rM} of the low-voltage motor group can be taken as the transformer current on the low-voltage side.

%/MVA system

The %/MVA system is particularly useful for calculating short-circuit currents in high-voltage networks. The impedances of individual items of electrical equipment in %/MVA can be determined easily from the characteristics, see Table 3-4.

Table 3-4

Formulae for calculating impedances or reactances in %/MVA

Network component		Impedance z or reactance x	
Synchronous machine	$\frac{x''_d}{S_r}$	x''_d = Subtransient reactance S_r = Rated apparent power	in % in MVA
Transformer	$\frac{u_k}{S_r}$	u_k = Impedance voltage drop S_r = Rated apparent power	in % in MVA
Current-limiting reactor	$\frac{u_r}{S_D}$	u_r = Rated voltage drop S_D = Throughput capacity	in % in MVA
Induction motor	$\frac{I_r/I_{start}}{S_r} \cdot 100\,\%$	I_r = Rated current I_{start} = Starting current (with rated voltage and rotor short-circuited) S_r = Rated apparent power	 in MVA
Line	$\frac{Z' \cdot l \cdot 100\,\%}{U_n^2}$	Z' = Impedance per conductor U_n = Nominal system voltage l = Length of line	in Ω/km in kV in km
Series capacitor	$-\frac{X_c \cdot 100\,\%}{U_n^2}$	X_c = Reactance per phase U_n = Nominal system voltage	in Ω in kV
Shunt capacitor	$-\frac{100\,\%}{S_r}$	S_r = Rated apparent power	in MVA
Network	$\frac{1.1 \cdot 100\,\%}{S''_{kQ}}$	S''_{kQ} = Three-phase initial symmetrical short-circuit power at point of connection Q	in MVA

Table 3-5

Reference values for Z_2/Z_1 and Z_2/Z_0

		Z_2/Z_1	Z_2/Z_0
to calculate			
I''_k	near to generator	1	–
	far from generator	1	–
I_k	near to generator	0.05…0.25	–
	far from generator	0.25…1	–
Networks	with isolated neutral	–	0
	with earth compensation	–	0
	with neutral earthed via impedances	–	0…0.25
Networks with effectively earthed neutral		–	> 0.25

Calculating short-circuit currents by the %/MVA system generally yields sufficiently accurate results. This assumes that the ratios of the transformers are the same as the ratios of the rated system voltages, and also that the nominal voltage of the network components is equal to the nominal system voltage at their locations.

Short-circuit currents with asymmetrical faults

The equations for calculating initial short-circuit currents I''_k are given in Table 3-2.

The kind of fault which produces the highest short-circuit currents at the fault site can be determined with Fig. 3-7. The double earth fault is not included in Fig. 3-7; it results in smaller currents than a two-phase short-circuit. For the case of a two-phase-to-earth fault, the short-circuit current flowing via earth and earthed conductors I''_{kE2E} is not considered in Fig. 3-7.

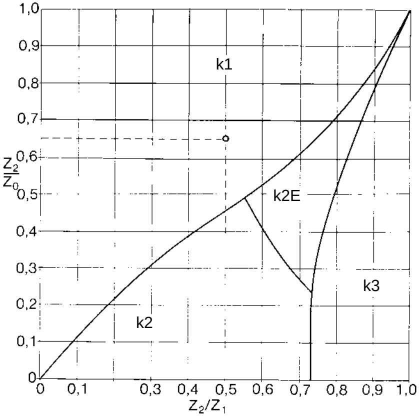


Fig. 3-7

Diagram for determining the fault with the highest short-circuit current

Example: $Z_2/Z_1 = 0.5$; $Z_2/Z_0 = 0.65$, the greatest short-circuit current occurs with a phase – to-earth fault.

The data in Fig. 3-7 are true provided that the impedance angles of $\underline{Z}_2/\underline{Z}_1$ and $\underline{Z}_0$ do not differ from each other by more than 15 °. Reference values for Z_2/Z_1 and Z_2/Z_0 are given in Table 3-5.

i_p and I_k are:

for phase-to-phase fault clear of ground: $i_{p2} = \kappa \cdot \sqrt{2} \cdot I''_{k2}$,
$I_{k2} = I_{a2} = I''_{k2}$;

for two-phase-to-earth fault: no calculation necessary;

for phase-to-earth fault: $i_{p1} = \kappa \cdot \sqrt{2} \cdot I''_{k1}$,
$I_{k1} = I_{a1} = I''_{k1}$.

Fig. 3-8 shows the size of the current with asymmetrical earth faults.

Minimum short-circuit currents

When calculating minimum short-circuit currents one has to make the following changes:

- Reduced voltage factor *c*
- The network’s topology must be chosen so as to yield the minimum short-circuit currents.

- Motors are to be disregarded
- The resistances R_L of the lines must be determined for the conductor temperature t_e at the end of the short circuit (R_{L20} conductor temperature at 20 °C).

  $R_L = [1 + 0.004\ (t_e - 20\ °C) / °C] \cdot R_{L20}$

  For lines in low-voltage networks it is sufficient to put $t_e = 80\,°C$.

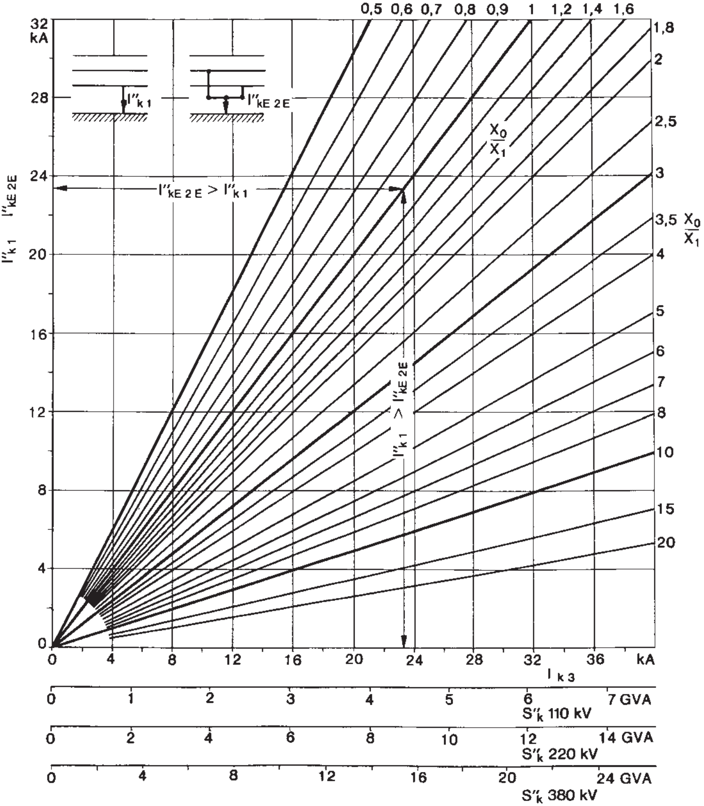


Fig. 3-8

Initial short-circuit current I''_k at the fault location with asymmetrical earth faults in networks with earthed neutral:

$S''_k = \sqrt{3} \cdot UI''_{k3}$ = *Initial symmetrical short-circuit power,*
I''_{kE2E} *Initial short-circuit current via earth for two-phase-to-earth fault,*
I''_{k1} *Initial short-circuit current with phase-to-earth fault,*
X_1, X_0 *Reactances of complete short-circuit path in positive- and zero-phase sequence system ($X_2 = X_1$)*

3.3 Impedances of electrical equipment

The impedances of electrical equipment are generally stated by the manufacturer. The values given here are for guidance only.

3.3.1 System infeed

The effective impedance of the system infeed, of which one knows only the initial symmetrical fault power S''_{kQ} or the initial symmetrical short-circuit current I''_{kQ} at junction point Q, is calculated as:

$$Z_Q = \frac{c \cdot U_{nQ}^2}{S''_{kQ}} = \frac{c \cdot U_{nQ}}{\sqrt{3} \cdot I''_{kQ}}$$

Here U_{nQ} Nominal system voltage

S''_{kQ} Initial symmetrical short-circuit power

I''_{kQ} Initial symmetrical short-circuit current

$\underline{Z}_Q$ $= R_Q + jX_Q$, effective impedance of system infeed for short-circuit current calculation

X_Q $= \sqrt{Z_Q^2 - R_Q^2}$.

If no precise value is known for the equivalent active resistance R_Q of the system infeed, one can put $R_Q = 0.1\, X_Q$ *with* $X_Q = 0.995\, Z_Q$. The effect of temperature can be disregarded.

If the impedance is referred to the low-voltage side of the transformer, we have

$$Z_Q = \frac{c \cdot U_{nQ}^2}{S''_{kQ}} \cdot \frac{1}{\ddot{u}_r^2} = \frac{c \cdot U_{nQ}}{\sqrt{3} \cdot I''_{kQ}} \cdot \frac{1}{\ddot{u}_r^2}.$$

3.3.2 Electrical machines

Synchronous generators with direct system connection

For calculating short-circuit currents the positive- and negative-sequence impedances of the generators are taken as

$$\underline{Z}_{GK} = K_G \cdot \underline{Z}_G = K_G\,(R_G + jX''_d)$$

with the correction factor

$$K_G = \frac{U_n}{U_{rg}} \cdot \frac{c_{max}}{1 + X''_d \cdot \sin \varphi_{rg}}$$

Here:

c_{max} Voltage factor

U_n Nominal system voltage

U_{rG} Rated voltage of generator

$\underline{Z}_{GK}$ Corrected impedance of generator

$\underline{Z}_{G}$ Impedance of generator ($\underline{Z}_G = R_G + jX''_d$)

X''_d Subtransient reactance of generator referred to impedance

$$x''_d = X''_d / Z_{rG} \qquad \underline{Z}_{rG} = U^2_{rG}/S_{rG}$$

It is sufficiently accurate to put:

$$\left.\begin{array}{l} R_G = 0.05 \cdot X''_d \text{ for rated powers} \geqq 100 \text{ MVA} \\ R_G = 0.07 \cdot X''_d \text{ for rated powers} < 100 \text{ MVA} \end{array}\right\} \text{with high-voltage generators}$$

$$R_G = 0.15 \cdot X''_d \text{ for low-voltage generators.}$$

The factors 0.05, 0.07 and 0.15 also take account of the decay of the symmetrical short-circuit current during the first half-cycle.

Guide values for reactances are shown in Table 3-6.

Table 3-6

Reactances of synchronous machines

Generator type	Turbogenerators	Salient-pole generators with damper winding[1]	without damper winding
Subtransient reactance (saturated) x''_d in %	9…22[2]	12…30[3]	20…40[3]
Transient reactance (saturated) x''_d in %	14…35[4]	20…45	20…40
Synchronous reactance (unsaturated) [5] x''_d in %	140…300	80…180	80…180
Negative-sequence reactance[6] x_2 in %	9…22	10…25	30…50
Zero-sequence reactance[7] x_0 in %	3…10	5…20	5…25

[1] Valid for laminated pole shoes and complete damper winding and also for solid pole shoes with strap connections.

[2] Values increase with machine rating. Low values for low-voltage generators.

[3] The higher values are for low-speed rotors ($n < 375 \text{ min}^{-1}$).

[4] For very large machines (above 1000 MVA) as much as 40 to 45 %.

[5] Saturated values are 5 to 20 % lower.

[6] In general $x_2 = 0.5\,(x''_d + x''_q)$. Also valid for transients.

[7] Depending on winding pitch.

Generators and unit-connected transformers of power plant units

For the impedance, use

$$\underline{Z}_{\mathrm{G,\,KW}} = K_{\mathrm{G,\,KW}}\,\underline{Z}_{\mathrm{G}}$$

with the correction factor

$$K_{\mathrm{G,\,KW}} = \frac{c_{\max}}{1 + X''_{\mathrm{d}} \cdot \sin \varphi_{\mathrm{rG}}}$$

$$\underline{Z}_{\mathrm{T,\,KW}} = K_{\mathrm{T,\,KW}}\,\underline{Z}_{\mathrm{TUS}}$$

with the correction factor

$$K_{\mathrm{T,\,KW}} = c_{\max}.$$

Here:

$\underline{Z}_{\mathrm{G,\,KW}}$ $\underline{Z}_{\mathrm{T,\,KW}}$	Corrected impedances of generators (G) and unit-connected transformers (T) of power plant units
$\underline{Z}_{\mathrm{G}}$	Impedance of generator
$\underline{Z}_{\mathrm{TUS}}$	Impedance of unit transformer, referred to low-voltage side

If necessary, the impedances are converted to the high-voltage side with the fictitious transformation ratio $ü_{\mathrm{f}} = U_{\mathrm{n}}/U_{\mathrm{rG}}$

Power plant units

For the impedances, use

$$\underline{Z}_{\mathrm{KW}} = K_{\mathrm{KW}}\,(ü^{2}_{\mathrm{r}}\,\underline{Z}_{\mathrm{G}} + \underline{Z}_{\mathrm{TOS}})$$

with the correction factor

$$K_{\mathrm{KW}} = \frac{U^{2}_{\mathrm{nQ}}}{U^{2}_{\mathrm{rG}}} \cdot \frac{U^{2}_{\mathrm{rTUS}}}{U^{2}_{\mathrm{rTOS}}} \cdot \frac{c_{\max}}{1 + (X''_{\mathrm{d}} - X''_{\mathrm{T}})\sin \varphi_{\mathrm{rG}}}$$

Here:

$\underline{Z}_{\mathrm{KW}}$	Corrected impedance of power plant unit, referred to high-voltage side
$\underline{Z}_{\mathrm{G}}$	Impedance of generator
$\underline{Z}_{\mathrm{TOS}}$	Impedance of unit transformer, referred to high-voltage side
U_{nQ}	Nominal system voltage
U_{rG}	Rated voltage of generator
X_{T}	Referred reactance of unit transformer
U_{rT}	Rated voltage of transformer

Synchronous motors

The values for synchronous generators are also valid for synchronous motors and synchronous condensers.

Induction motors

The short-circuit reactance Z_M of induction motors is calculated from the ratio I_{an}/I_{rM}:

$$Z_M = \frac{1}{I_{start}/I_{rM}} \cdot \frac{U_{rM}}{\sqrt{3} \cdot I_{rM}} = \frac{U^2_{rM}}{I_{start}/I_{rM} \cdot S_{rM}}$$

where	I_{start}	Motor starting current, the rms value of the highest current the motor draws with the rotor locked at rated voltage and rated frequency after transients have decayed,
	U_{rM}	Rated voltage of motor
	I_{rM}	Rated current of motor
	S_{rM}	Apparent power of motor ($\sqrt{3} \cdot U_{rM} \cdot I_{rM}$).

3.3.3 Transformers and reactors

Transformers

Table 3-7

Typical values of impedance voltage drop u_k of three-phase transformers

Rated primary voltage in kV	5…20	30	60	110	220	400
u_k in %	3.5…8	6…9	7…10	9…12	10…14	10…16

Table 3-8

Typical values for ohmic voltage drop u_R of three-phase transformers

Power rating in MVA	0.25	0.63	2.5	6.3	12.5	31.5
u_R in %	1.4…1.7	1.2…1.5	0.9…1.1	0.7… 0.85	0.6…0.7	0.5…0.6

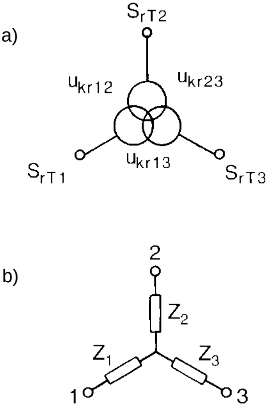
For transformers with ratings over 31.5 MVA, $u_R < 0\ 5$ %.

The positive- and negative-sequence transformer impedances are equal. The zero-sequence impedance may differ from this.

The positive-sequence impedances of the transformers $\underline{Z}_1 = \underline{Z}_T = R_T + jX_T$ are calculated as follows:

$$Z_T = \frac{U_{kr}}{100\ \%} \quad \frac{U^2_{rT}}{S_{rT}} \qquad R_T = \frac{u_{Rr}}{100\ \%} \quad \frac{U^2_{rT}}{S_{rT}} \qquad X_T = \sqrt{Z^2_T - R^2_T}$$

With three-winding transformers, the positive-sequence impedances for the corresponding rated throughput capacities referred to voltage U_{rT} are:



$$|\underline{Z}_{12}| = |\underline{Z}_1| + |\underline{Z}_2| = u_{kr12} \frac{U_{rT}^2}{S_{rT12}}$$

$$|\underline{Z}_{13}| = |\underline{Z}_1| + |\underline{Z}_2| = u_{kr13} \frac{U_{rT}^2}{S_{rT13}}$$

$$|\underline{Z}_{23}| = |\underline{Z}_2| + |\underline{Z}_3| = u_{kr23} \frac{U_{rT}^2}{S_{rT23}}$$

and the impedances of each winding are

$$\underline{Z}_1 = \frac{1}{2}(\underline{Z}_{12} + \underline{Z}_{13} - \underline{Z}_{23})$$

$$\underline{Z}_2 = \frac{1}{2}(\underline{Z}_{12} + \underline{Z}_{23} - \underline{Z}_{13})$$

$$\underline{Z}_3 = \frac{1}{2}(\underline{Z}_{13} + \underline{Z}_{23} - \underline{Z}_{12})$$

Fig. 3-9

Equivalent diagram a) and winding impedance b) of a three-winding transformer
u_{kr12} *short-circuit voltage referred to* S_{rT12}
u_{kr13} *short-circuit voltage referred to* S_{rT13}
$u_{kr2}3$ *short-circuit voltage referred to* S_{rT23}
S_{rT12}, S_{rT13}, S_{rT23} *rated throughput capacities of transformer*

Three-winding transformers are mostly high-power transformers in which the reactances are much greater than the ohmic resistances. As an approximation, therefore, the impedances can be put equal to the reactances.

The zero-sequence impedance varies according to the construction of the core, the kind of connection and the other windings.

Fig. 3-10 shows examples for measuring the zero-sequence impedances of transformers.

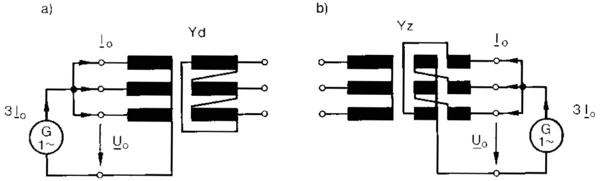
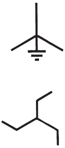
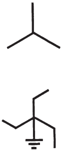


Fig. 3-10

Measurement of the zero-sequence impedances of transformers for purposes of short-circuit current calculation: a) connection Yd, b) connection Yz

Table 3-9

Reference values of X_0/X_1 for three-phase transformers

Connection					
Three-limb core	0.7…1 ∞	3…10 ∞	3…10 ∞	∞ 0.1…0.15	1…2.4 ∞
Five-limb core	1 ∞	10…100 ∞	10…100 ∞	∞ 0,1…0.15	1…2.4 ∞
3 single-phase transformers	1 ∞	10…100 ∞	10…100 ∞	∞ 0,1…0.15	1…2.4 ∞

Values in the upper line when zero voltage applied to upper winding, values in lower line when zero voltage applied to lower winding (see Fig. 3-10).

For low-voltage transformers one can use:

Connection Dy $R_{0T} \approx R_T \quad X_{0T} \approx 0.95\, X_T$

Connection Dz, Yz $R_{0T} \approx 0.4\, R_T \quad X_{0T} \approx 0.1\, X_T$

Connection Yy[1] $R_{0T} \approx R_T \quad X_{0T} \approx 7…100$[2] X_T

[1] Transformers in Yy are not suitable for multiple-earthing protection.
[2] HV star point not earthed.

Current-limiting reactors

The reactor reactance X_D is

$$X_D = \frac{\Delta u_r \cdot U_n}{100\,\% \cdot \sqrt{3} \cdot I_r} = \frac{\Delta u_r \cdot U_n^2}{100\,\% \cdot S_D}$$

where Δu_r Rated percent voltage drop of reactor

U_n Network voltage

I_r Current rating of reactor

S_D Throughput capacity of reactor.

Standard values for the rated voltage drop

Δu_r in %: 3, 5, 6, 8, 10.

Further aids to calculation are given in Sections 12.1 and 12.2. The effective resistance is negligibly small. The reactances are of equal value in the positive-, negative- and zero-sequence systems.

3.3.4 Three-phase overhead lines

The usual equivalent circuit of an overhead line for network calculation purposes is the Π circuit, which generally includes resistance, inductance and capacitance, Fig. 3-11.

In the positive phase-sequence system, the effective resistance R_L of high-voltage overhead lines is usually negligible compared with the inductive reactance. Only at the low- and medium-voltage level are the two roughly of the same order.

When calculating short-circuit currents, the positive-sequence capacitance is disregarded. In the zero-sequence system, account normally has to be taken of the conductor-earth capacitance. The leakage resistance R_a need not be considered.

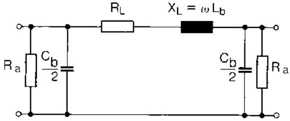


Fig. 3-11

Equivalent circuit of an overhead line

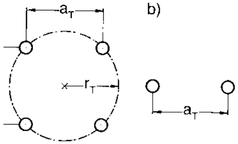


Fig. 3-12

Conductor configurations
a) 4-wire bundle
b) 2-wire bundle

Calculation of positive- and negative-sequence impedance

Symbols used:

a_T	Conductor strand spacing,
r	Conductor radius,
r_e	Equivalent radius for bundle conductors (for single strand $r_e = r$),
n	Number of strands in bundle conductor,
r_T	Radius of circle passing through midpoints of strands of a bundle (Fig. 3-12),
d	Mean geometric distance between the three wires of a three-phase system,
d_{12}, d_{23}, d_{31},	see Fig. 3-13,
r_S	Radius of earth wire,
μ_0	Space permeability $4\pi \cdot 10^{-4} \frac{\text{H}}{\text{km}}$,
μ_S	Relative permeability of earth wire,
μ_L	Relative permeability of conductor (in general $\mu_L = 1$),
ω	Angular frequency in s^{-1},
δ	Earth current penetration in m,
ρ	Specific earth resistance,
R_L	Resistance of conductor,
R_S	Earth wire resistance (dependent on current for steel wires and wires containing steel),
L_b	Inductance per conductor in H/km; $L_b = L_{1.}$

Calculation

The inductive reactance (X_L) for symmetrically twisted single-circuit and double-circuit lines are:

Single-circuit line: $X_L = \omega \cdot L_b = \omega \cdot \frac{\mu_0}{2\pi}\left(\ln \frac{d}{r_e} + \frac{1}{4n}\right)$ in Ω/km per conductor,

Double-circuit line: $X_L = \omega \cdot L_b = \omega \cdot \frac{\mu_0}{2\pi}\left(\ln \frac{d\,d'}{r_e d''} + \frac{1}{4n}\right)$ in Ω/km per conductor;

Mean geometric distances between conductors (see Fig. 3-13):

$$d = \sqrt[3]{d_{12} \cdot d_{23} \cdot d_{31}},$$
$$d' = \sqrt[3]{d'_{12} \cdot d'_{23} \cdot d'_{31}},$$
$$d'' = \sqrt[3]{d''_{11} \cdot d''_{22} \cdot d''_{33}}.$$

The equivalent radius r_e is

$$r_e = \sqrt[n]{n \cdot r \cdot r_T^{n-1}}.$$

In general, if the strands are arranged at a uniform angle *n:*

$$r_e = \frac{a_T}{2 \cdot \sin \frac{\pi}{n}},$$

e. g. for a 4-wire bundle $r_e = \frac{a_T}{2 \cdot \sin \frac{\pi}{4}} = \frac{a_T}{\sqrt{2}}$

The positive- and negative-sequence impedance is calculated as

$$\underline{Z}_1 = \underline{Z}_2 = \frac{R_1}{n} + X_L.$$

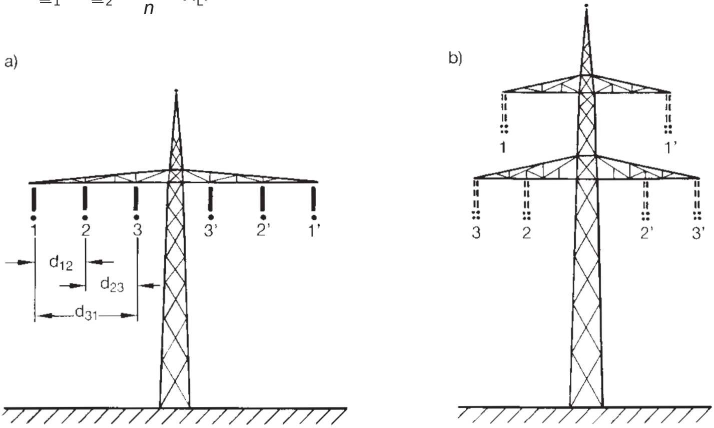


Fig. 3-13

Tower configurations: double-circuit line with one earth wire; a) flat, b) "Donau'"

Fig. 3-14 and 3-15 show the positive-sequence (and also negative-sequence) reactances of three-phase overhead lines.

Calculation of zero-sequence impedance

The following formulae apply:

Single-circuit line without earth wire $\underline{Z}_0^{\mathrm{I}} = R_0 + \mathrm{j}X_0,$

Single-circuit line with earth wire $\underline{Z}_0^{\mathrm{Is}} = \underline{Z}_0^{\mathrm{I}} - 3\,\dfrac{\underline{Z}_{\mathrm{as}}^2}{\underline{Z}_{\mathrm{s}}},$

Double-circuit line without earth wire $\underline{Z}_0^{\mathrm{II}} = \underline{Z}_0^{\mathrm{I}} + 3\,\underline{Z}_{\mathrm{ab}},$

Double-circuit line with earth wire $\underline{Z}_0^{\mathrm{IIs}} = \underline{Z}_0^{\mathrm{II}} - \ 6\,\dfrac{\underline{Z}_{\mathrm{as}}^2}{\underline{Z}_{\mathrm{s}}},$

For the zero-sequence resistance and zero-sequence reactance included in the formulae, we have:

Zero-sequence resistance

$$R_0 = R_{\mathrm{L}} + 3\,\frac{\mu_0}{8}\,\omega, \qquad d = \sqrt[3]{d_{12}\,d_{23}\,d_{31}};$$

Zero-sequence reactance

$$X_0 = \omega\,\frac{\mu_0}{2\,\pi}\left(3\,\ln\frac{\delta}{\sqrt[3]{rd^2}} + \frac{\mu_{\mathrm{L}}}{4\,n}\right) \qquad \delta = \frac{1.85}{\sqrt{\mu_0\,\dfrac{1}{\rho}\,\omega}}\,.$$

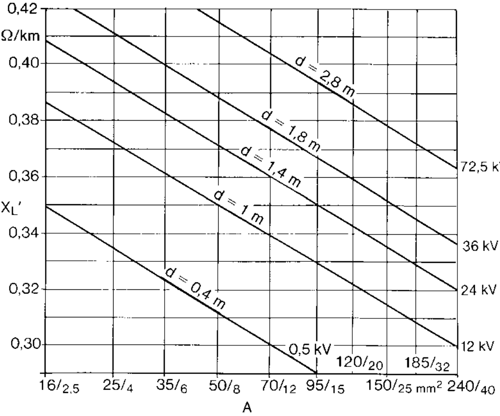


Fig. 3-14

Reactance X_{L}' (positive phase sequence) of three-phase transmission lines up to 72.5 kV, f = 50 Hz, as a function of conductor cross section A, single-circuit lines with aluminium / steel wires, d = mean geometric distance between the 3 wires.

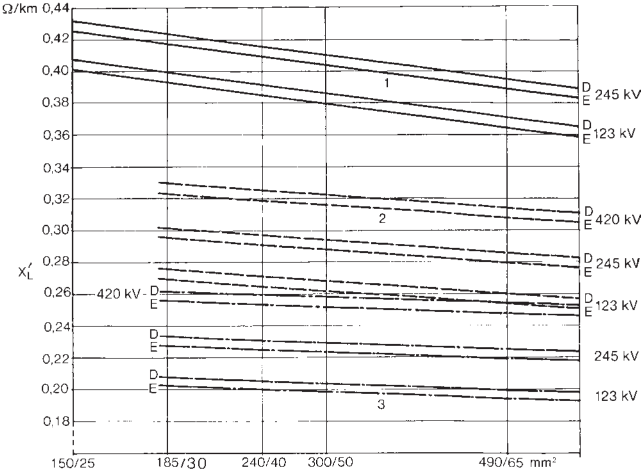


Fig. 3-15

Reactance X_L' (positive-sequence) of three-phase transmission lines with alumimium/ steel wires ("Donau" configuration), f = 50 Hz. Calculated for a mean geometric distance between the three conductors of one system, at 123 kV: d = 4 m, at 245 kV: d = 6 m, at 420 kV: d = 9.4 m;
E denotes operation with one system; D denotes operation with two systems; 1 single wire, 2 two-wire bundle, a = 0.4 m, 3 four-wire bundle, a = 0.4 m.

Table 3-10

Earth current penetration δ in relation to specific resistance ρ at f = 50 Hz

Nature of soil as per:	DIN VDE 0228 and CCITT	Alluvial Marl	land Clay	Porous Sandstone, clay schist	Quartz, impervious Limestone	Limestone	Granite, gneiss Clayey slate	
	DIN VDE 0141	Moor-land	—	Loam, clay and soil arable land	Wet sand	Wet gravel	Dry sand or gravel	Stony ground
ρ	Ωm	30	50	100	200	500	1 000	3 000
$\sigma = \frac{1}{\rho}$	μS/cm	333	200	100	50	20	10	3.33
δ	m	510	660	930	1 320	2 080	2 940	5 100

The earth current penetration δ denotes the depth at which the return current diminishes such that its effect is the same as that of the return current distributed over the earth cross section.

Compared with the single-circuit line without earth wire, the double-circuit line without earth wire also includes the additive term $3 \cdot \underline{Z}_{\mathrm{a\,b}}$, where $\underline{Z}_{\mathrm{a\,b}}$ is the alternating impedance of the loops system a/earth and system b/earth:

$$\underline{Z}_{\mathrm{a\,b}} = \frac{\mu_0}{8}\omega + \mathrm{j}\,\omega\frac{\mu_0}{2\pi}\ln\frac{\delta}{d_{\mathrm{a\,b}}},$$

$$d_{\mathrm{a\,b}} = \sqrt{d' d''}$$

$$d' = \sqrt[3]{d'_{12} \cdot d'_{23} \cdot d'_{31}},$$

$$d'' = \sqrt[3]{d''_{11} \cdot d''_{22} \cdot d''_{33}}.$$

For a double-circuit line with earth wires (Fig. 3-16) account must also be taken of:

1. Alternating impedance of the loops conductor/earth and earth wire/earth:

$$\underline{Z}_{\mathrm{as}} = \frac{\mu_0}{8}\omega + \mathrm{j}\,\omega\frac{\mu_0}{2\pi}\ln\frac{\delta}{d_{\mathrm{as}}}, \qquad d_{\mathrm{as}} = \sqrt[3]{d_{1\mathrm{s}}\, d_{2\mathrm{s}}\, d_{3\mathrm{s}}};$$

for two earth wires:

$$d_{\mathrm{as}} = \sqrt[6]{d_{1\mathrm{s}1}\, d_{2\mathrm{s}1}\, d_{3\mathrm{s}1}\, d_{1\mathrm{s}2}\, d_{2\mathrm{s}2}\, d_{3\mathrm{s}2}}$$

2. Impedance of the loop earth wire/earth:

$$\underline{Z}_{\mathrm{s}} = R + \frac{\mu_0}{8}\omega + \mathrm{j}\,\omega\frac{\mu_0}{2\pi}\left(\ln\frac{\delta}{r} + \frac{\mu_{\mathrm{s}}}{4\,n}\right).$$

The values used are for one earth wire $n = 1$; $r = r_{\mathrm{s}}$; $R = R_{\mathrm{s}}$;

for two earth wires $n = 2$; $r = \sqrt{r_{\mathrm{s}}\, d_{\mathrm{s1s2}}}$; $R = \frac{R_{\mathrm{s}}}{2}$

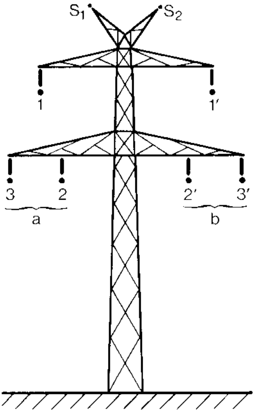


Fig: 3-16

Tower configuration: Double-circuit line with two earth wires, system a and b

Values of the ratio R_s/R_- (effective resistance / d. c. resistance) are roughly between 1.4 and 1.6 for steel earth wires, but from 1.05 to 1.0 for well-conducting earth wires of Al / St, Bz or Cu.

For steel earth wires, one can take an average of $\mu_s \approx 25$, while values of about $\mu_s = 5$ to 10 should be used for Al / St wires with one layer of aluminium. For Al / St earth wires with a cross-section ratio of 6:1 or higher and two layers of aluminium, and also for earth wires or ground connections of Bz or Cu, $\mu_s \approx 1$.

The operating capacitances C_b of high-voltage lines of 110 kV to 380 kV lie within a range of $9 \cdot 10^{-9}$ to $14 \cdot 10^{-9}$ F/km. The values are higher for higher voltages.

The earth wires must be taken into account when calculating the conductor / earth capacitance. The following values are for guidance only:

Flat tower: $C_E = (0.6 \ldots 0.7) \cdot C_b$.

“Donau” tower: $C_E = (0.5 \ldots 0.55) \cdot C_b$

The higher values of C_E are for lines with earth wire, the lower values for those without earth wire.

The value of C_E for double-circuit lines is lower than for single-circuit lines.

The relationship between conductor / conductor capacitance C_g, conductor / earth capacitance C_E and operating capacitance C_b is

$$C_b = C_E + 3 \cdot C_g.$$

Technical values for transmission wires are given in Section 13.1.4.

Table 3-11

Reference values for the impedances of three-phase overhead lines: “Donau” tower, one earth wire, conductor Al/St 240/40, specific earth resistance $\rho = 100\ \Omega \cdot \mathrm{m}$, $f = 50$ Hz

Voltage	d	d_{ab}	d_{as}	Earth wire	Impedance	Operation with one system zero-sequence impedance		Operation with two systems zero-sequence impedance	
					$\underline{Z}_1 = R_1 + \mathrm{j}\,X_1$	$\underline{Z}_0^{1}$	$\frac{X_0'}{X_1}$	$\underline{Z}_0^{11}$	$\frac{X_0''}{X_1}$
	m	m	m		Ω/km per cond.	Ω/km per conductor		Ω/km per cond. and system	
123 kV	4	10	11	St 50	0.12 + j 0.39	0.31 + j 1.38	3.5	0.50 + j 2.20	5.6
				Al/St 44/32		0.32 + j 1.26	3.2	0.52 + j 1.86	4.8
				Al/St 240/40		0.22 + j 1.10	2.8	0.33 + j 1.64	4.2
245 kV	6	15.6	16.5	Al/St 44/32	0.12 + j 0.42	0.30 + j 1.19	2.8	0.49 + j 1.78	4.2
				Al/St 240/40		0.22 + j 1.10	2.6	0.32 + j 1.61	3.8
245 kV 2-wire bundle	6	15.6	16.5	Al/St 240/40	0.06 + j 0.30	0.16 + j 0.98	3.3	0.26 + j 1.49	5.0
420 kV 4-wire bundle	9.4	23	24	Al/St 240/40	0.03 + j 0.26	0.13 + j 0.91	3.5	0.24 + j 1.39	5.3

3.3.5 Three-phase cables

The equivalent diagram of cables can also be represented by Π elements, in the same way as overhead lines (Fig. 3-11). Owing to the smaller spacings, the inductances are smaller, but the capacitances are between one and two orders greater than with overhead lines.

When calculating short-circuit currents the positive-sequence operating capacitance is disregarded. The conductor/earth capacitance is used in the zero phase-sequence system.

Calculation of positive and negative phase-sequence impedance

The a.c. resistance of cables is composed of the d.c. resistance (R_{-}) and the components due to skin effect and proximity effect. The resistance of metal-clad cables (cable sheath, armour) is further increased by the sheath and armour losses.

The d.c. resistance (R_{-}) at 20 °C and A = conductor cross section in mm^2 is

for copper: $R'_{-} = \frac{18.5}{A}$ in $\frac{\Omega}{\text{km}}$,

for aluminium: $R'_{-} = \frac{29.4}{A}$ in $\frac{\Omega}{\text{km}}$,

for aluminium alloy: $R'_{-} = \frac{32.3}{A}$ in $\frac{\Omega}{\text{km}}$.

The supplementary resistance of cables with conductor cross-sections of less than 50 mm^2 can be disregarded (see Section 2, Table 2-8).

The inductance L and inductive reactance X_L at 50 Hz for different types of cable and different voltages are given in Tables 3-13 to 3-17.

For low-voltage cables, the values for positive- and negative-sequence impedances are given in DIN VDE 0102, Part 2/11.75.

Table 3-12

Reference value for supplementary resistance of different kinds of cable in Ω/km, f = 50 Hz

Type of cable	cross-section mm^2	50	70	95	120	150	185	240	300	400
Plastic-insulated cable										
NYCY[1] 0.6/1 kV		—	0.003	0.0045	0.0055	0.007	0.0085	0.0115	0.0135	0.018
NYFGbY[2]	3.5/6 kV to 5.8/10 kV	—	0.008	0.008	0.0085	0.0085	0.009	0.009	0.009	0.009
NYCY[2]		—	—-	0.0015	0.002	0.0025	0.003	0.004	0.005	0.0065
Armoured lead-covered cable up to 36 kV		0.010	0.011	0.011	0.012	0.012	0.013	0.013	0.014	0.015
Non-armoured aluminium-covered cable up to 12 kV		0.0035	0.0045	0.0055	0.006	0.008	0.010	0.012	0.014	0.018
Non-armoured single-core cable (laid on one plane, 7 cm apart) up to 36 kV										
with lead sheath		0.012	0.012	0.012	0.012	0.012	0.012	0.012	0.012	0.012
with aluminium sheath		0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005
Non-armoured single-core oil-filled cable with lead sheath (bundled) 123 kV		—	—	0.009	0.009	0.009	0.0095	0.0095	0.010	0.0105
(laid on one plane, 18 cm apart) 245 kV		—	—	—	—	0.0345	0.035	0.035	0.035	0.035
Three-core oil-filled cable,										
armoured with lead sheath,	36 to 123 kV	0.010	0.011	0.011	0.012	0.012	0.013	0.013	0.014	0.015
non-armoured with	36 kV	—	0.004	0.006	0.007	0.009	0.0105	0.013	0.015	0.018
aluminium sheath,	123 kV	—	—	0.0145	0.0155	0.0165	0.018	0.0205	0.023	0.027

[1] With NYCY 0.6/1 kV effective cross section of C equal to half outer conductor.

[2] With NYFGbY for 7.2/12 kV, at least 6 mm^2 copper.

Table 3-13

Armoured three-core belted cables[1], inductive reactance X'_L (positive phase sequence) per conductor at $f = 50$ HZ

Number of cores and conductor cross-section mm²	$U = 3.6$ kV X'_L Ω/km	$U = 7.2$ kV X'_L Ω/km	$U = 12$ kV X'_L Ω/km	$U = 17.5$ kV X'_L Ω/km	$U = 24$ kV X'_L Ω/km
3 × 6	0.120	0.144	—	—	—
3 × 10	0.112	0.133	0.142	—	—
3 × 16	0.105	0.123	0.132	0.152	—
3 × 25	0.096	0.111	0.122	0.141	0.151
3 × 35	0.092	0.106	0.112	0.135	0.142
3 × 50	0.089	0.10	0.106	0.122	0.129
3 × 70	0.085	0.096	0.101	0.115	0.122
3 × 95	0.084	0.093	0.098	0.110	0.117
3 × 120	0.082	0.091	0.095	0.107	0.112
3 × 150	0.081	0.088	0.092	0.104	0.109
3 × 185	0.080	0.087	0.09	0.10	0.105
3 × 240	0.079	0.085	0.089	0.097	0.102
3 × 300	0.077	0.083	0.086	—	—
3 × 400	0.076	0.082	—	—	—

1) Non-armoured three-core cables: –15 % of values stated.
Armoured four-core cables: + 10 % of values stated.

Table 3-14

Hochstädter cable (H cable) with metallized paper protection layer, inductive reactance X'_L (positive phase sequence) per conductor at $f = 50$ Hz

Number of cores and conductor cross-section mm²	$U = 7.2$ kV X'_L Ω/km	$U = 12$ kV X'_L Ω/km	$U = 17.5$ kV X'_L Ω/km	$U = 24$ kV X'_L Ω/km	$U = 36$ kV X'_L Ω/km
3 × 10 re	0.134	0.143	—	—	—
3 × 16 re or se	0.124	0.132	0.148	—	—
3 × 25 re or se	0.116	0.123	0.138	0.148	—
3 × 35 re or se	0.110	0.118	0.13	0.14	0.154
3 × 25 rm or sm	0.111	0.118	—	—	—
3 × 35 rm or sm	0.106	0.113	—	—	—
3 × 50 rm or sm	0.10	0.107	0.118	0.126	0.138
3 × 70 rm or sm	0.096	0.102	0.111	0.119	0.13
3 × 95 rm or sm	0.093	0.098	0.107	0.113	0.126
3 × 120 rm or sm	0.090	0.094	0.104	0.11	0.121
3 × 150 rm or sm	0.088	0.093	0.10	0.107	0.116
3 × 185 rm or sm	0.086	0.090	0.097	0.104	0.113
3 × 240 rm or sm	0.085	0.088	0.094	0.10	0.108
3 × 300 rm or sm	0.083	0.086	0.093	0.097	0.105

Table 3-15

Armoured SL-type cables1), inductive reactance X'_L (positive phase sequence) per conductor at f = 50 HZ

Number of cores and conductor cross-section mm^2	U = 7.2 kV X'_L Ω / km	U = 12 kV X'_L Ω / km	U = 17.5 kV X'_L Ω / km	U = 24 kV X'_L Ω / km	U = 36 kV X'_L Ω / km
3 x 6 re	0.171	—	—	—	—
3 x 10 re	0.157	0.165	—	—	—
3 x 16 re	0.146	0.152	0.165	—	—
3 x 25 re	0.136	0.142	0.152	0.16	—
3 x 35 re	0.129	0.134	0.144	0.152	0.165
3 x 35 rm	0.123	0.129	—	—	—
3 x 50 rm	0.116	0.121	0.132	0.138	0.149
3 x 70 rm	0.11	0.115	0.124	0.13	0.141
3 x 95 rm	0.107	0.111	0.119	0.126	0.135
3 x 120 rm	0.103	0.107	0.115	0.121	0.13
3 x 150 rm	0.10	0.104	0.111	0.116	0.126
3 x 185 rm	0.098	0.101	0.108	0.113	0.122
3 x 240 rm	0.096	0.099	0.104	0.108	0.118
3 x 300 rm	0.093	0.096	0.102	0.105	0.113

1) These values also apply to SL-type cables with H-foil over the insulation and for conductors with a high space factor (rm / v and r se / 3 f). Non-armoured SL-type cables: –15 % of values stated.

Table 3-16

Cables with XLPE insulation, inductive reactance X'_L (positive phase sequence) per conductor at f = 50 Hz, triangular arrangement

Number of cores and conductor cross-section mm^2	U = 12 kV X'_L Ω / km	U = 24 kV X'_L Ω / km	U = 36 kV X'_L Ω / km	U = 72.5 kV X'_L Ω / km	U = 123 kV X'_L Ω / km
3 x 1 x 35 rm	0.135	—	—	—	—
3 x 1 x 50 rm	0.129	0.138	0.148	—	—
3 x 1 x 70 rm	0.123	0.129	0.138	—	—
3 x 1 x 95 rm	0.116	0.123	0.132	—	—
3 x 1 x 120 rm	0.110	0.119	0.126	0.151	0.163
3 x 1 x 150 rm	0.107	0.116	0.123	0.148	0.160
3 x 1 x 185 rm	0.104	0.110	0.119	0.141	0.154
3 x 1 x 240 rm	0.101	0.107	0.113	0.138	0.148
3 x 1 x 300 rm	0.098	0.104	0.110	0.132	0.145
3 x 1 x 400 rm	0.094	0.101	0.107	0.129	0.138
3 x 1 x 500 rm	0.091	0.097	0.104	0.126	0.132
3 x 1 x 630 rm	—	—	—	0.119	0.129

Table 3-17

Cables with XLPE insulation, inductive reactance X'_L (positive phase sequence) per conductor at $f = 50$ Hz

Number of cores and conductor cross-section mm²	$U = 12$ kV X'_L Ω / km
3 x 50 se	0.104
3 x 70 se	0.101
3 x 95 se	0.094
3 x 120 se	0.091
3 x 150 se	0.088
3 x 185 se	0.085
3 x 240 se	0.082

Zero-sequence impedance

It is not possible to give a single formula for calculating the zero-sequence impedance of cables. Sheaths, armour, the soil, pipes and metal structures absorb the neutral currents. The construction of the cable and the nature of the outer sheath and of the armour are important. The influence of these on the zero-sequence impedance is best established by asking the cable manufacturer. Dependable values of the zero-sequence impedance can be obtained only by measurement on cables already installed.

The influence of the return line for the neutral currents on the zero-sequence impedance is particularly strong with small cable cross-sections (less than 70 mm²). If the neutral currents return *exclusively* by way of the neutral (4th) conductor, then

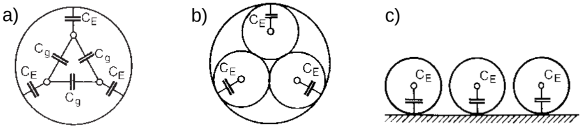
$$R_{0L} = R_L + 3 \cdot R_{\text{neutral}}, \qquad X_{0L} \approx (3{,}5\ldots4.0)x_L$$

The zero-sequence impedances of low-voltage cables are given in DIN VDE 0102, Part 2 / 11.75.

Capacitances

The capacitances in cables depend on the type of construction (Fig. 3-17).

With belted cables, the operating capacitance C_b is $C_b = C_E + 3\ C_g$, as for overhead transmission lines. In SL and Hochstädter cables, and with all single-core cables, there is no capacitive coupling between the three conductors; the operating capacitance C_b is thus equal to the conductor/earth capacitance C_E. Fig. 3-18 shows the conductor/earth capacitance C_E of belted three-core cables for service voltages of 1 to 20 kV, as a function of conductor cross-section A. Values of C_E for single-core, SL and H cables are given in Fig. 3-19 for service voltages from 12 to 72.5 kV.



$C_b = C_E = 3\ C_g$ $\quad C_g = 0 \longrightarrow C_b = C_E \quad C_g = 0 \longrightarrow C_b = C_E$

Fig. 3-17 $\quad C_E \approx 0{,}6\ C_b$

Partial capacitances for different types of cable:
a) Belted cable, b) SL and H type cables, c) Single-core cable

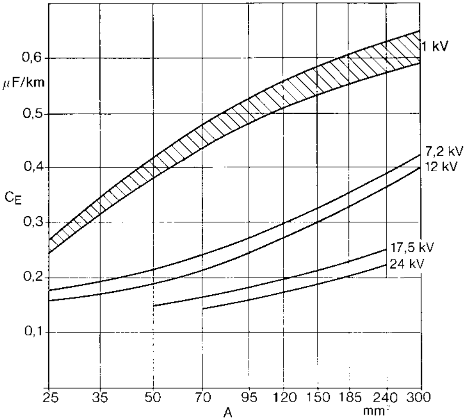


Fig. 3-18

Conductor/earth capacitance C_E of *belted three-core cables as a function of conductor cross-section A. The capacitances of 1 kV cables must be expected to differ considerably.*

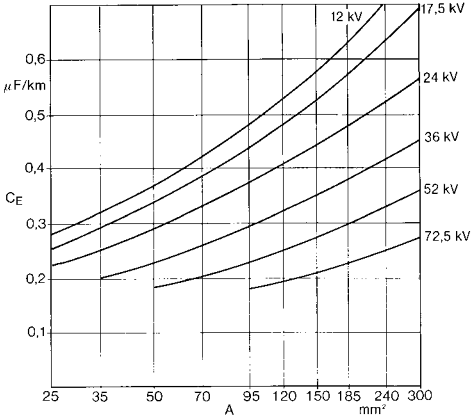


Fig. 3-19

Conductor/earth capacitance C_E of *single-core, SL- and H-type cables as a function of conductor cross-section A.*

The conductor/earth capacitances of XLPE-insulated cables are shown in Tables 3-18 and 3-19.

Table 3-18

Cables with XLPE insulation, conductor / earth capacitance C'_E per conductor

Number of cores and conductor cross-section mm²	U = 12 kV C'_E µF/km	U = 24 kV C'_E µF/km	U = 36 kV C'_E µF/km	U = 72.5 kV C'_E µF/km	U = 123 kV C'_E µF/km
3 x 1 x 35 rm	0.239	—	—	—	—
3 x 1 x 50 rm	0.257	0.184	0.141	—	—
3 x 1 x 70 rm	0.294	0.202	0.159	—	—
3 x 1 x 95 rm	0.331	0.221	0.172	—	—
3 x 1 x 120 rm	0.349	0.239	0.184	0.138	0.110
3 x 1 x 150 rm	0.386	0.257	0.196	0.147	0.115
3 x 1 x 185 rm	0.423	0.285	0.208	0.156	0.125
3 x 1 x 240 rm	0.459	0.312	0.233	0.165	0.135
3 x 1 x 300 rm	0.515	0.340	0.251	0.175	0.145
3 x 1 x 400 rm	0.570	0.377	0.276	0.193	0.155
3 x 1 x 500 rm	0.625	0.413	0.300	0.211	0.165
3 x 1 x 630 rm	—	—	—	0.230	0.185

Table 3-19

Cables with XLPE insulation, conductor / earth capacitance C'_E per conductor

Number of cores and conductor cross-section mm²	U = 12 kV C'_E µF/km
3 x 50 se	0.276
3 x 70 se	0.312
3 x 95 se	0.349
3 x 120 se	0.368
3 x 150 se	0.404
3 x 185 se	0.441
3 x 240 se	0.496

3.3.6 Busbars in switchgear installations

In the case of large cross-sections the resistance can be disregarded.

Average values for the inductance per metre of bus of rectangular section and arranged as shown in Fig. 3-20 can be calculated from

$$L' = 2 \cdot \left[\ln \left(2 \frac{\pi \cdot D + b}{\pi \cdot B + 2\, b} \right) + 0.33 \right] \cdot 10^{-7} \text{ in H/m.}$$

Here:

D Distance between centres of outer main conductor,

b Height of conductor,

B Width of bars of one phase,

L' Inductance of one conductor in H/m.

To simplify calculation, the value for L' for common busbar cross sections and conductor spacings has been calculated per 1 metre of line length and is shown by the curves of Fig. 3-20. Thus,

$$X = 2\,\pi \cdot f \cdot L' \cdot l$$

Example:

Three-phase busbars 40 m long, each conductor comprising three copper bars 80 mm × 10 mm ($A = 2400\ \text{mm}^2$), distance $D = 30$ cm, $f = 50$ Hz. According to the curve, $L' = 3.7 \cdot 10^{-7}$ H/m; and so

$$X = 3.7 \cdot 10^{-7}\ \text{H/m} \cdot 314\ \text{s}^{-1} \cdot 40\ \text{m} = 4.65\ \text{m}\,\Omega.$$

The busbar arrangement has a considerable influence on the inductive resistance.

The inductance per unit length of a three-phase line with its conductors mounted on edge and grouped in phases (Fig. 3-20 and Fig. 13-2a) is relatively high and can be usefully included in calculating the short-circuit current.

Small inductances can be achieved by connecting two or more three-phase systems in parallel. But also conductors in a split phase arrangement (as in Fig. 13-2b) yield very small inductances per unit length of less than 20 % of the values obtained with the method described. With the conductors laid flat side by side (as in the MNS system) the inductances per unit length are about 50 % of the values according to the method of calculation described.

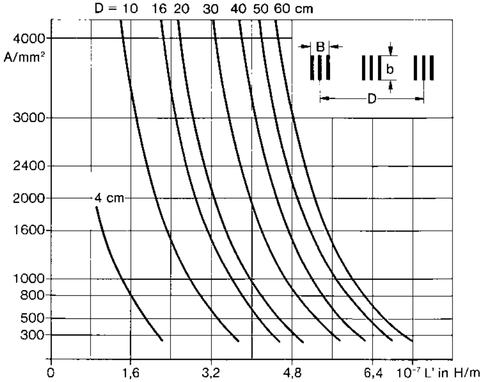


Fig. 3-20

Inductance L´ of busbars of rectangular cross section

3.4 Examples of calculation

More complex phase fault calculations are made with computer programs (Calpos®). See Section 6.1.5 for examples.

When calculating short-circuit currents in high-voltage installations, it is often sufficient to work with reactances because the reactances are generally much greater in magnitude than the effective resistances. Also, if one works only with reactances in the following examples, the calculation is on the safe side. Corrections to the reactances are disregarded.

The ratios of the nominal system voltages are taken as the transformer ratios. Instead of the operating voltages of the faulty network one works with the nominal system

Example:

Three-phase busbars 40 m long, each conductor comprising three copper bars 80 mm × 10 mm ($A = 2400\ \text{mm}^2$), distance $D = 30$ cm, $f = 50$ Hz. According to the curve, $L' = 3.7 \cdot 10^{-7}$ H/m; and so

$$X = 3.7 \cdot 10^{-7}\ \text{H/m} \cdot 314\ \text{s}^{-1} \cdot 40\ \text{m} = 4.65\ \text{m}\,\Omega.$$

The busbar arrangement has a considerable influence on the inductive resistance.

The inductance per unit length of a three-phase line with its conductors mounted on edge and grouped in phases (Fig. 3-20 and Fig. 13-2a) is relatively high and can be usefully included in calculating the short-circuit current.

Small inductances can be achieved by connecting two or more three-phase systems in parallel. But also conductors in a split phase arrangement (as in Fig. 13-2b) yield very small inductances per unit length of less than 20 % of the values obtained with the method described. With the conductors laid flat side by side (as in the MNS system) the inductances per unit length are about 50 % of the values according to the method of calculation described.

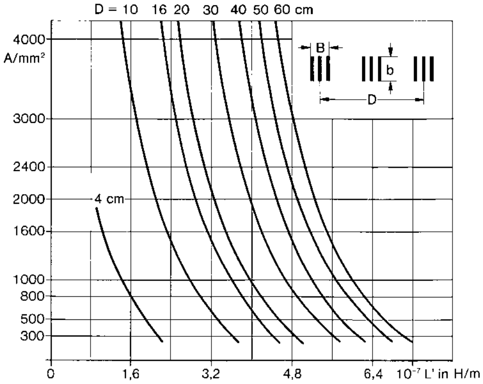


Fig. 3-20

Inductance L´ of busbars of rectangular cross section

3.4 Examples of calculation

More complex phase fault calculations are made with computer programs (Calpos®). See Section 6.1.5 for examples.

When calculating short-circuit currents in high-voltage installations, it is often sufficient to work with reactances because the reactances are generally much greater in magnitude than the effective resistances. Also, if one works only with reactances in the following examples, the calculation is on the safe side. Corrections to the reactances are disregarded.

The ratios of the nominal system voltages are taken as the transformer ratios. Instead of the operating voltages of the faulty network one works with the nominal system voltage. It is assumed that the nominal voltages of the various network components are the same as the nominal system voltage at their respective locations. Calculation is done with the aid of the %/MVA system.

Example 1

To calculate the short-circuit power S''_k, the peak short-circuit current i_p and the symmetrical short-circuit breaking current I_a in a branch of a power plant station service busbar. This example concerns a fault with more than one infeed and partly common current paths. Fig. 3-21 shows the equivalent circuit diagram.

For the reactances of the equivalent circuit the formulae of Table 3-4 give:

Network reactance $$x_Q = \frac{1.1 \cdot 100}{S''_{kQ}} = \frac{110}{8000} = 0.0138\ \%/\mathrm{MVA},$$

Transformer *1* $$x_{T1} = \frac{u_K}{S_{rT1}} = \frac{13}{100} = 0.1300\ \%/\mathrm{MVA},$$

Generator $$x_G = \frac{x''_d}{S_{rG}} = \frac{11.5}{93.7} = 0.1227\ \%/\mathrm{MVA},$$

Transformer *2* $$x_{T2} = \frac{u_K}{S_{rT2}} = \frac{7}{8} = 0.8750\ \%/\mathrm{MVA},$$

Induction motor $$x_{M1} = \frac{I_{rM}/I_{start}}{S_{rM}} \cdot 100 = \frac{1}{5 \cdot 2.69} \cdot 100 = 7.4349\ \%/\mathrm{MVA},$$

Induction-
motor group $$x_{M2} = \frac{I_{rM}/I_{start}}{S_{rM}} \cdot 100 = \frac{1}{5 \cdot 8 \cdot 0.46} \cdot 100 = 5.4348\ \%/\mathrm{MVA}.$$

For the location of the fault, one must determine the total reactance of the network. This is done by step-by-step system transformation until there is only one reactance at the terminals of the equivalent voltage source: this is then the short-circuit reactance.

Calculation can be made easier by using Table 3-20, which is particularly suitable for calculating short circuits in unmeshed networks. The Table has 9 columns, the first of which shows the numbers of the lines. The second column is for identifying the parts and components of the network. Columns 3 and 4 are for entering the calculated values.

The reactances entered in column 3 are added in the case of series circuits, while the susceptances in column 4 are added for parallel configurations.

Columns 6 to 9 are for calculating the maximum short-circuit current and the symmetrical breaking current.

To determine the total reactance of the network at the fault location, one first adds the reactances of the 220 kV network and of transformer *1*. The sum 0.1438 %/MVA is in column 3, line 3.

The reactance of the generator is then connected in parallel to this total. This is done by forming the susceptance relating to each reactance and adding the susceptances (column 4, lines 3 and 4).

The sum of the susceptances 15.1041 %/MVA is in column 4, line 5. Taking the reciprocal gives the corresponding reactance 0.0662 %/MVA, entered in column 3, line 5. To this is added the reactance of transformer 2. The sum of 0.9412 %/MVA is in column 3, line 7.

The reactances of the induction motor and of the induction motor group must then be connected in parallel to this total reactance. Again this is done by finding the susceptances and adding them together.

The resultant reactance of the whole network at the site of the fault, 0.7225%/MVA, is shown in column 3, line 10. This value gives

$$S''_k = \frac{1.1 \cdot 100\ \%}{x_k} \qquad \frac{1.1 \cdot 100\ \%}{0.7225\ \%/\mathrm{MVA}} = 152\ \mathrm{MVA},\ \text{(column 5, line 10)}.$$

To calculate the *breaking capacity* one must determine the contributions of the individual infeeds to the short-circuit power S''_k.

The proportions of the short-circuit power supplied via transformer *2* and by the motor group and the single motor are related to the total short-circuit power in the same way as the susceptances of these branches are related to their total susceptance.

Contributions of individual infeeds to the short-circuit power:

Contribution of single motor $$S''_{kM1} = \frac{0.1345}{1.381} \cdot 152 = 14.8\ \mathrm{MVA},$$

Contribution of motor group $$S''_{kM2} = \frac{0.184}{1.381} \cdot 152 = 20.3\ \mathrm{MVA},$$

Contribution via transformer *2* $$S''_{kT2} = \frac{1.0625}{1.381} \cdot 152 = 116.9\ \mathrm{MVA}.$$

The proportions contributed by the 220 kV network and the generator are found accordingly.

Contribution of generator $$S''_{kG} = \frac{8.150}{15.104} \cdot 116.9 = 63.1\ \mathrm{MVA},$$

Contribution of 220 kV network $$S''_{kQ} = \frac{6.954}{15.104} \cdot 116.9 = 53.8\ \mathrm{MVA}.$$

The calculated values are entered in column 5. They are also shown in Fig. 3-21b.

To find the factors μ and q

When the contributions made to the short-circuit power S''_k by the 220 kV network, the generator and the motors are known, the ratios of S''_k/S_r are found (column 6). The corresponding values of μ for $t_v = 0.1$ s (column 7) are taken from Fig. 3-5.

Values of q (column 8) are obtained from the ratio motor rating / number of pole pairs (Fig. 3-6), again for $t_v = 0.1$ s.

Single motor

$$\frac{S''_{kM1}}{S_{rM1}} = \frac{14.8}{2.69} = 5.50 \rightarrow \mu = 0.74 \qquad \frac{\text{motor rating}}{\text{no. pole pairs}} = \frac{2.3}{2} = 1.15 \rightarrow q = 0.59$$

Motor group

$$\frac{S''_{kM2}}{S_{rM2}} = \frac{20.3}{8 \cdot 0.46} = 5.52 \rightarrow \mu = 0.74 \qquad \frac{\text{motor rating}}{\text{no. pole pairs}} = \frac{0.36}{3} = 1.12 \rightarrow q = 0.32$$

Generator $$\frac{S''_{kG}}{S_{rG}} = \frac{63.1}{93.7} = 0.67 \rightarrow \mu = 1$$

For the contribution to the short-circuit power provided by the 220 kV network, $\mu = 1$, see Fig. 3-5, since in relation to generator G 3 it is a far-from-generator fault.

Contributions of individual infeeds to the “breaking capacity”

The proportions of the short-circuit power represented by the 220 kV network, the generator and the motors, when multiplied by their respective factors μ and q, yield the contribution of each to the breaking capacity, column 9 of Table 3-20.

Single motor $S_{\mathrm{aM1}} = \mu\, q\, S''_{\mathrm{kM1}} = 0.74 \cdot 0.59 \cdot 14.8\ \mathrm{MVA} = 6.5\ \mathrm{MVA}$

Motor group $S_{\mathrm{aM2}} = \mu\, q\, S''_{\mathrm{kM2}} = 0.74 \cdot 0.32 \cdot 20.3\ \mathrm{MVA} = 4.8\ \mathrm{MVA}$

Generator $S_{\mathrm{aG}} = \mu\ \ S''_{\mathrm{kG}} = 1 \cdot 63.1\ \mathrm{MVA} = 63.1\ \mathrm{MVA}$

220 kV network $S_{\mathrm{aQ}} = \mu\ \ S''_{\mathrm{kQ}} = 1 \cdot 53.8\ \mathrm{MVA} = 53.8\ \mathrm{MVA}$

The total breaking capacity is obtained as an approximation by adding the individual breaking capacities. The result $S_{\mathrm{a}} = 128.2$ MVA is shown in column 9, line 10.

Table 3-20

Example 1, calculation of short-circuit current

1	2 Component	3 x %/MVA	4 $\frac{1}{x}$ MVA/%	5 S''_{k} MVA	6 $S''_{\mathrm{k}}/S_{\mathrm{r}}$	7 μ (0.1 s)	8 q (0.1 s)	9 S_{a} MVA
1	220 kV network	0.0138	—	53.8	—	1	—	53.8
2	transformer *1*	0.1300	—	—	—	—	—	—
3	1 and 2 in series	0.1438 →	6.9541	—	—	—	—	—
4	93.7 MVA generator	0.1227 →	8.1500	63.1	0.67	1	—	63.1
5	3 and 4 in parallel	0.0662 ←	15.1041	—	—	—	—	—
6	transformer *2*	0.8750	—	—	—	—	—	—
7	5 and 6 in series	0.9412 →	1.0625	116.9	—	—	—	—
8	induction motor 2.3 MW/2.69 MVA	7.4349 →	0.1345	14.8	5.50	0.74	0.59	6.5
9	motor group $\Sigma = 3.68$ MVA	5.4348 →	0.1840	20.3	5.52	0.74	0.32	4.8
10	fault location 7, 8 and 9 in parallel	0.7225 ←	1.3810	152.0	—	—	—	128.2

At the fault location:

$$I''_{\mathrm{k}} = \frac{S''_{\mathrm{k}}}{\sqrt{3} \cdot U_{\mathrm{n}}} = \frac{152.0\ \mathrm{MVA}}{\sqrt{3} \cdot 6.0\ \mathrm{kV}} = 14.63\ \mathrm{kA},$$

$$I_{\mathrm{p}} = \kappa \cdot \sqrt{2} \cdot I''_{\mathrm{k}} = 2.0 \cdot \sqrt{2} \cdot 14.63\ \mathrm{kA} = 41.4\ \mathrm{kA}\ (\text{for } \kappa = 2.0),$$

$$I_{\mathrm{a}} = \frac{S_{\mathrm{a}}}{\sqrt{3} \cdot U_{\mathrm{n}}} = \frac{128.2\ \mathrm{MVA}}{\sqrt{3} \cdot 6.0\ \mathrm{kV}} = 12.3\ \mathrm{kA}.$$

Example 2

Calculation of the phase-to-earth fault current I''_{k1}.

Find I''_{k1} at the 220 kV busbar of the power station represented by Fig. 3-22.

Calculation is made using the method of symmetrical components. First find the positive-, negative- and zero-sequence reactances X_1, X_2 and X_0 from the network data given in the figure.

Positive-sequence reactances (index 1)

Overhead line $X_{1L} = 50 \cdot 0.32\,\Omega \cdot \frac{1}{2} = 8\,\Omega$

220 kV network $X = 0.995 \cdot \frac{1.1 \cdot (220\text{ kV})^2}{8000\text{ MVA}} = 6.622\,\Omega$

Power plant unit $X_G = 0.14 \cdot \frac{(21\text{ kV})^2}{125\text{ MVA}} = 0.494\,\Omega$

$$X_T = 0.13 \cdot \frac{(220\text{ kV})^2}{130\text{ MVA}} = 48.4\,\Omega$$

$$X_{KW} = \mathrm{K}_{KW}\,(\ddot{u}_r^2 \cdot X_G + X_T)$$

$$K_{KW} = \frac{1.1}{1 + (0.14 - 0.13) \cdot 0.6}$$

$$X_{KW} = 1.093 \left[\left(\frac{220}{21}\right)^2 \cdot 0.494 + 48.4\right] \Omega = 112.151\,\Omega$$

At the first instant of the short circuit, $x_1 = x_2$. The negative-sequence reactances are thus the same as the positive-sequence values. For the generator voltage: $U_{rG} = 21$ kV with sin $\varphi_{rG} = 0.6$, the rated voltages of the transformers are the same as the system nominal voltages.

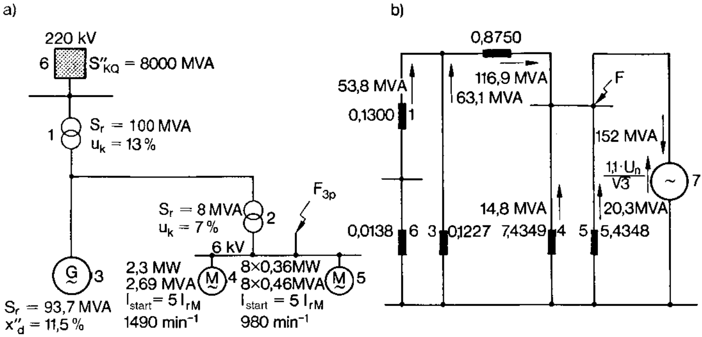


Fig. 3-21

a) Circuit diagram, b) Equivalent circuit diagram in positive phase sequence with equivalent voltage source at fault location, reactances in %/MVA: 1 transformer 1, 2 transformer 2, 3 generator, 4 motor, 5 motor group, 6 220 kV network, 7 equivalent voltage at the point of fault.

Zero-sequence reactances (index 0)

A zero-sequence system exists only between earthed points of the network and the fault location. Generators G1 and G 2 and also transformer T1 do not therefore contribute to the reactances of the zero-sequence system.

Overhead line
2 circuits in parallel $\quad X_{0L} = 3.5 \cdot X_{1L} = 28\ \Omega$

220 kV network $\quad X_{0Q} = 2.5 \cdot X_{1Q} = 16.555\ \Omega$

Transformer T 2 $\quad X_{0T_2} = 0.8 \cdot X_{1T} \cdot 1.093 = 42.321\ \Omega$

With the reactances obtained in this way, we can draw the single-phase equivalent diagram to calculate I''_{k1} (Fig. 3-22b).

Since the total positive-sequence reactance at the first instant of the short circuit is the same as the negative-sequence value, it is sufficient to find the total positive and zero sequence reactance.

Calculation of positive-sequence reactance:

$$\frac{1}{x_1} = \frac{1}{56.076\ \Omega} + \frac{1}{14.622\ \Omega} \rightarrow x_1 = 11.598\ \Omega$$

Calculation of zero-sequence reactance:

$$\frac{1}{x_0} = \frac{1}{42.321\ \Omega} + \frac{1}{44.556\ \Omega} \rightarrow x_0 = 21.705\ \Omega$$

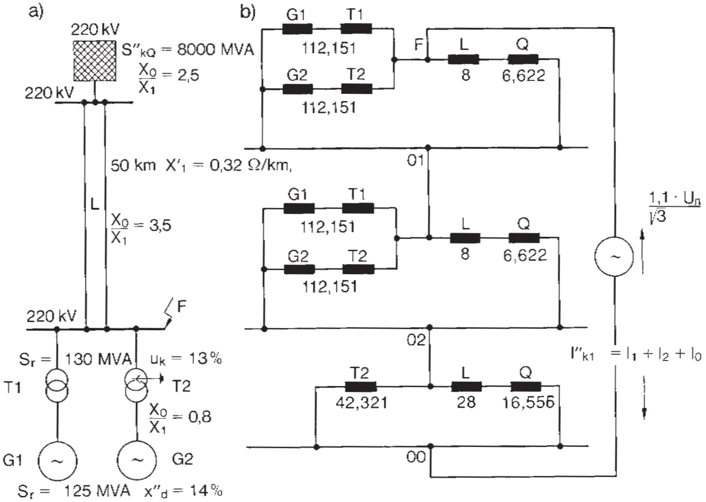


Fig. 3-22

a) Circuit diagram, b) Equivalent circuit diagram in positive phase sequence, negative phase sequence and zero phase sequence with connections and equivalent voltage source at fault location F for I''_{k1}.

With the total positive-, negative- and zero-sequence reactances, we have

$$I''_{k1} = \frac{1.1 \cdot \sqrt{3} \cdot U_n}{x_1 + x_2 + x_0} = \frac{1.1 \cdot \sqrt{3} \cdot 220}{44.901} = 9.34\ \text{kA}.$$

The contributions to I''_{k1} represented by the 220 kV network (Q) or power station (KW) are obtained on the basis of the relationship

$$\underline{I}''_{\mathrm{k1}} = \underline{I}_1 + \underline{I}_2 + \underline{I}_0 = 3 \cdot \underline{I}_1 \text{ with } \underline{I}_0 = \underline{I}_1 = \underline{I}_2 = 3.11 \text{ kA}$$

to right and left of the fault location from the equations:

$$\underline{I}''_{\mathrm{k1Q}} = \underline{I}_{1\mathrm{Q}} + \underline{I}_{2\mathrm{Q}} + \underline{I}_{0\mathrm{Q}}, \text{ and } \underline{I}''_{\mathrm{k1KW}} = \underline{I}_{1\mathrm{KW}} + \underline{I}_{2\mathrm{KW}} + \underline{I}_{0\mathrm{KW}}.$$

The partial component currents are obtained from the ratios of the respective impedances.

$$I_{1\mathrm{Q}} = I''_{2\mathrm{Q}} = 3.11 \text{ kA} \cdot \frac{56.08}{70.70} = 2.47 \text{ kA}$$

$$I_{0\mathrm{Q}} = 3.11 \text{ kA} \cdot \frac{42.32}{86.88} = 1.51 \text{ kA}$$

$$I_{1\mathrm{KW}} = 0.64 \text{ kA}$$

$$I_{0\mathrm{KW}} = 1.60 \text{ kA}$$

$$\underline{I}''_{\mathrm{k1Q}} = (2.47 + 2.47 + 1.51) \text{ kA} = 6.45 \text{ kA}$$

$$\underline{I}''_{\mathrm{k1KW}} = (0.641 + 0.64 + 1.60) \text{ kA} = 2.88 \text{ kA}$$

Example 3

The short-circuit currents are calculated with the aid of Table 3-2.

20 kV network: $x_{1\mathrm{Q}} = 0.995 \dfrac{1.1 \cdot (0.4)^2}{250} = 0.0007\ \Omega$

$r_{1\mathrm{Q}} \approx 0.1\, x_{1\mathrm{Q}} = 0.00007\ \Omega$

Transformer: $x_{1\mathrm{T}} = 0.058 \dfrac{(0.4)^2}{0.63} = 0.0147\ \Omega$

$r_{1\mathrm{T}} = 0.015 \dfrac{(0.4)^2}{0.63} = 0.0038\ \Omega$

$x_{0\mathrm{T}} = 0.95 \cdot x_{1\mathrm{T}} = 0.014\ \Omega$

$r_{0\mathrm{T}} \approx r_{1\mathrm{T}} = 0.0038\ \Omega$

Cable: $x_{1\mathrm{L}} = 0.08 \cdot 0.074 = 0.0059\ \Omega$

$r_{1\mathrm{L}20} = 0.08 \cdot 0.271 = 0.0217\ \Omega$

$r_{1\mathrm{L}80} = 1.24 \cdot r_{1\mathrm{L}20} = 0.0269\ \Omega$

$x_{0\mathrm{L}} \approx 7.36 \cdot x_{1\mathrm{L}} = 0.0434\ \Omega$

$r_{0\mathrm{L}20} \approx 3.97 \cdot r_{1\mathrm{L}20} = 0.0861\ \Omega$

$r_{0\mathrm{L}80} = 1.24 \cdot r_{0\mathrm{L}20} = 0.1068\ \Omega$

Maximum and minimum short-circuit currents at fault location F 1

a. Maximum short-circuit currents

$$\underline{Z}_1 = \underline{Z}_2 = (0.0039 + \mathrm{j}\, 0.0154)\ \Omega; \quad \underline{Z}_0 = (0.0038 + \mathrm{j}\, 0.0140)\ \Omega$$

$$I''_{\mathrm{k3}} = \frac{1.0 \cdot 0.4}{\sqrt{3} \cdot 0.0159} \text{ kA} = 14.5 \text{ kA}$$

$$I''_{\mathrm{k2}} = \frac{\sqrt{3}}{2} I''_{\mathrm{k3}} = 12.6 \text{ kA}$$

$$I''_{\mathrm{k1}} = \frac{\sqrt{3} \cdot 1.0 \cdot 0.4}{0.0463} \text{ kA} = 15.0 \text{ kA.}$$

b. Minimum short-circuit currents

The miminum short-circuit currents are calculated with c = 0.95.

Maximum and minimum short-circuit currents at fault location F 2

a. Maximum short-circuit currents

$$\underline{Z}_1 = \underline{Z}_2 = (0.0265 + \mathrm{j}\,0.0213)\ \Omega; \quad \underline{Z}_0 = (0.0899 + \mathrm{j}\,0.0574)\ \Omega$$

$$I''_{\mathrm{k3}} = \frac{1.0 \cdot 0.4}{\sqrt{3} \cdot 0.0333}\ \mathrm{kA} = 6.9\ \mathrm{kA}$$

$$I''_{\mathrm{k2}} = \frac{\sqrt{3}}{2} I''_{\mathrm{k3}} = 6.0\ \mathrm{kA}$$

$$I''_{\mathrm{k1}} = \frac{\sqrt{3} \cdot 1.0 \cdot 0.4}{0.1729}\ \mathrm{kA} = 4.0\ \mathrm{kA}.$$

b. Minimum short-circuit currents

The minimum short-circuit currents are calculated with c = 0.95 and a temperature of 80 °C.

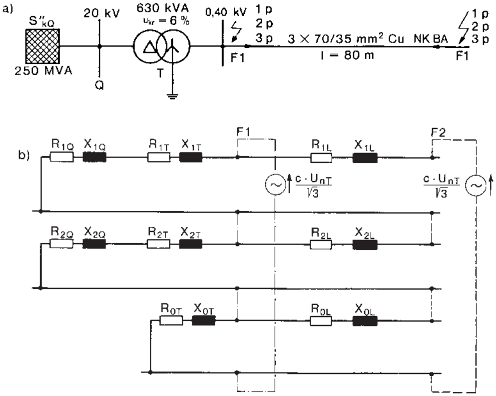


Fig. 3-23

a) Circuit diagram of low-voltage network,
b) Equivalent diagram in component systems and connection for single-phase fault

Table 3-21

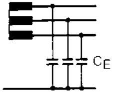
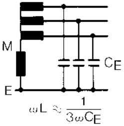
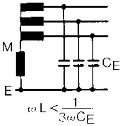
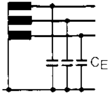
Summary of results

Fault location	Max. short-circuit currents			Min. short-circuit currents		
	3p kA	2p kA	1p kA	3p kA	2p kA	1p kA
Fault location F 1	14.5	12.6	15.0	13.8	12.0	14.3
Fault location F 2	6.9	6.0	4.0	6.4	5.5	3.4

The breaking capacity of the circuit-breakers must be at least 15.0 kA or 6.9 kA. Protective devices must be sure to respond at 12 kA or 3.4 kA. These figures relate to fault location F1 or F2.

3.5 Effect of neutral point arrangement on fault behaviour in three-phase high-voltage networks above 1 kV

Table 3-22

Arrangement of neutral point	isolated	with arc suppression coil	current-limiting *R* or *X*	low-resistance earth
				
Examples of use	Networks of limited extent, power plant auxiliaries	Overhead-line networks 10…123 kV	Cable networks 10…230 kV system e. g. in towns	High-voltage networks (123 kV) to 400 kV (protective multiple earthing in l. v. network)
Between system and earth are:	Capacitances, (inst. transformer inductances)	Capacitances, Suppression coils	Capacitances, Neutral reactor	(Capacitances), Earth conductor
$\lvert \underline{Z}_0 / \underline{Z}_1 \rvert$	$\left\lvert \frac{1/\mathrm{j}\omega C_E}{\underline{Z}_1} \right\rvert$	very high resistance	inductive: 4 to 60 resistive: 30 to 60	2 to 4
Current at fault site with single-phase fault Calculation (approximate) $E_1 = \frac{c \cdot U_n}{\sqrt{3}} = E''$	Ground-fault current $\underline{I}_E$ (capacitive) $\underline{I}_E \approx \mathrm{j}\, 3\, \omega C_E \cdot E_1$	Residual ground-fault current $\underline{I}_R$ $\underline{I}_R \approx 3\, \omega C_E (\delta + \mathrm{j}\nu)\, E_1$ δ = loss angle ν = interference	Ground-fault current $\underline{I}_{k1}$ $\underline{I}''_{k1} = \underline{I}_R \approx \frac{3\, E_1}{\mathrm{j}\,(X_1 + X_2 + X_0)}$ $\frac{\underline{I}''_{k1}}{\underline{I}''_{k3}} = \frac{3\, X_1}{2\, X_1 + X_0} = \frac{3}{2 + X_0 / X_1}$	

(continued)

Table 3-22 (continued)

Arrangement of neutral point	isolated	with arc suppression coil	current-limiting *R* or *X*	low-resistance earth
I''_{k2} / I''_{k3}	I_{CE} / I''_{k3}	I_{R} / I''_{k3}	*inductive*: 0.05 to 0.5 *resistive*: 0.1 to 0.05	0.5 to 0.75
U_{LEmax} / U_n	≈ 1	1 to (1.1)	inductive: 0.8 to 0.95 resistive: 0.1 to 0.05	0.75 to $\leqq$ 0.80
U_{0max} / U_n	≈ 0.6	0.6 to 0.66	inductive: 0.42 to 0.56 resistive: 0.58 to 0.60	0.3 to 0.42
Voltage rise in whole network	yes	yes	no	no
Duration of fault	10 to 60 min Possible short-time earthing with subsequent selective disconnection by neutral current (< 1 s)	10 to 60 min	< 1 s	< 1 s
Ground-fault arc	Self-quenching up to several A	Self-quenching	Partly self-quenching usually sustained	Sustained
Detection	Location by disconnection, ground-fault wiping-contact relay, wattmeter relay. (With short-time earthing: disconnection by neutral current)		Selective disconnection by neutral current (or short-circuit protection)	Short-circuit protection
Risk of double earth fault	yes	yes	slight	no
Means of earthing DIN VDE 0141	Earth electrode voltage $U_E \leq$ 125 V Touch voltage $\leqq$ 65 V		Earth electrode voltage U_E > 125 V permissible Touch voltages $\leqq$ 65V	
Measures against interference with communication circuits DIN VDE 0228	Generally not necessary needed only with railway block lines	Not necessary	Overhead lines: possibly required if approaching over a considerable distance Cables: generally not necessary	

4 Dimensioning switchgear installations

4.1 Insulation rating

Rating the dielectric withstand of equipment is based on the expected dielectric stresses. This is a combination of the stress caused by the power-frequency continuous voltage and the stress caused by the mostly short-term overvoltages. The insulation coordination for power-frequency continuous voltages ≤ 1 kv is based on DIN VDE 0110 and DIN VDE 0109 (currently still in draft form). In the case of voltages > 1 kV the specifications in DIN EN 60071-1 (VDE 0111 Part l) and the application guide in DIN EN 60071-2 (VDE 0111 Part 2) apply.

The *insulation coordination* is defined in DIN EN 60071-1 (VDE 0111 Part l) as the selection of the dielectric withstand required for equipment that is to be used at a specific site in a network. This process requires knowledge of the operational conditions in the network and the planned overvoltage protection devices, and the probability of an insulation fault on equipment which can be accepted under economic and operational aspects.

The *“dielectric withstand”* can be defined here by a rated insulation level or by a standard insulation level. A rated insulation level is considered any combination of standard withstand voltages, a standard insulation level is considered a rated insulation level whose standard withstand voltages in combination with the associated highest voltage for equipment U_m are recommended in selection tables (Tables 4-1 and 4-2). These combinations are based on operational experience with networks that meet the IEC standard. However, they are not associated with specific operational conditions.

When discussing insulation, a distinction is made between external and internal insulation. *External insulation* consists of clearances in air and the dielectrically stressed surfaces of solid insulation. It is exposed to atmospheric and other effects such as pollution, moisture, animals etc. It can be either protected (indoor) or unprotected (outdoor). The *internal insulation* can be solid, fluid or gaseous insulation material. It is protected against atmospheric and other external effects.

There is also a distinction between *self-restoring and non-self-restoring insulation,* but only with reference to the response of the insulation under dielectric tests. Insulation is considered self-restoring if its insulation properties are restored after a breakdown during the test.

The power frequency voltages and the overvoltages acting on an insulation or an overvoltage protection device can be classified by causes and processes into the following categories:

- power frequency continuous voltages resulting from normal system operation
- temporary overvoltages (power frequency) resulting from earth faults, switching operations (e.g. load shedding, resonances, ferroresonance or similar)
- slow-front overvoltages resulting from switching operations or direct lightning strikes at great distance, with rise times between 20 µs and 5000 µs and times to half-value up to 20 ms

- fast-front overvoltages resulting from switching operations or lightning strikes with rise times between 0.1 µs and 20 µs and times to half-value up to 300 µs
- very fast-front overvoltages resulting from faults or switching operations in gas-insulated switchgear with rise times below 0.1 µs and superimposed oscillations in the frequency range of 30 kHz to 100 MHz with a total duration of 3 ms
- combined overvoltages, primarily between conductors and at open breaker gaps.

It is assumed that within one of these categories the different voltage characteristics can have the same dielectric effects on the insulation or can be converted to a specified characteristic. The following standardized voltage shapes are defined as representative voltage characteristics for the above categories – except for the very fast-front overvoltages:

- standard short-duration power-frequency voltage with a frequency between 48 Hz and 62 Hz and a duration of 60 s
- standard switching impulse voltage; a voltage pulse with a rise time of 250 µs and a time to half-value of 2500 µs
- standard lightning impulse voltage; a voltage pulse with a rise time of 1.2 µs and a time to half-value of 50 µs
- combined standard switching impulse voltage; two simultaneous voltage impulses of opposite polarity

Insulation coordination procedure

The procedure in accordance with DIN EN 60071-1 (VDE 0111 Part l) in its current form requires basic knowledge of the physical processes, the operating conditions and the dielectric response of the equipment with its application. Fig. 4-1 shows the predicted process sequence as a flow chart.

The starting point of the coordination procedure is the system analysis, which should determine what voltage stresses can be expected under operational conditions, possibly with the aid of switching tests in the system. This should also include overvoltage protection devices. The investigations for all ranges of service voltages must include the stress on the conductor-earth insulation, the stress between the conductors and the longitudinal stress on the switching apparatus. The overvoltages must be assessed by peak value, curve and rate of occurrence and classified under the corresponding (curve) categories. The results of the system analysis will include peak values and rate of occurrence of voltage stress in the following categories: short-duration power-frequency voltage, switching impulse voltage, lightning impulse voltage etc. They are shown in the flow chart (Fig. 4-1) as U_{rp}, *representative voltages and overvoltages*.

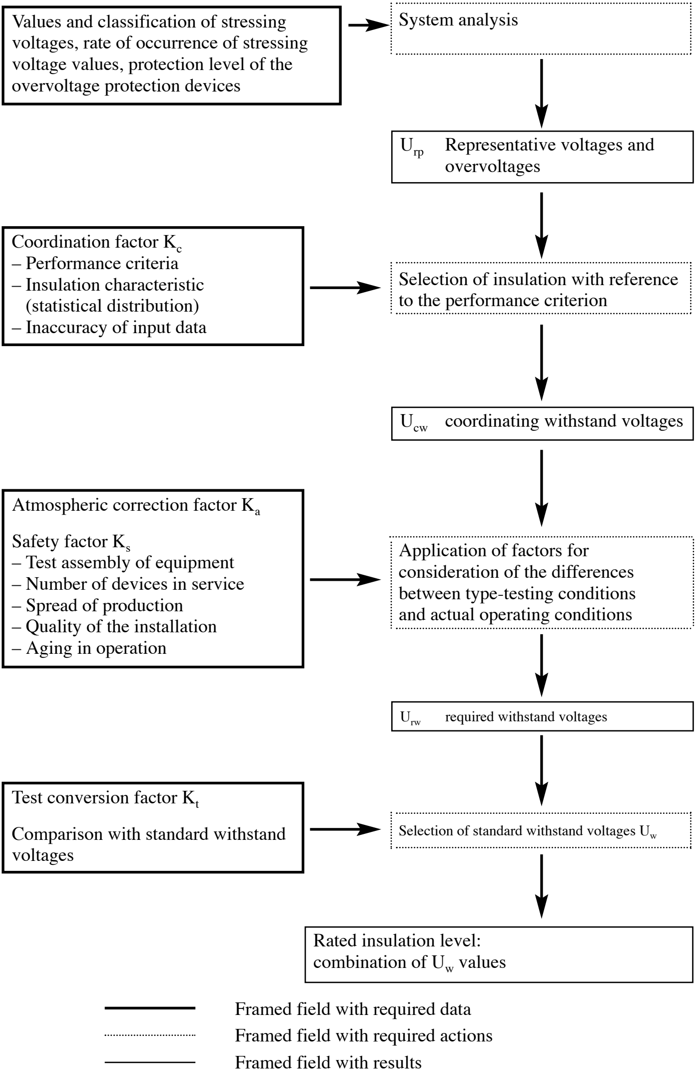


Fig. 4-1

Flow chart for determining the rated insulation level or the standard insulation level

The *performance criterion* is of fundamental importance for the next step. This is given in the form of a permissible fault rate, how often a device at that specific point on the system may be subject to insulation faults caused by the representative voltages and overvoltages (U_{rp}). The next step is to determine the lowest values of the withstand voltages, the equipment must satisfy to meet the Performance criterion. They are referred to as *coordinating withstand voltages* (U_{cw}). The difference between the value of a representative overvoltage and that of the associated coordinating withstand voltage is characterized by the coordination factor K_c, which must be multiplied by the representative overvoltage to derive the coordinating withstand voltage.

To determine the coordination factor K_c with transient overvoltages, a deterministic procedure, a statistical procedure or a combination of the two may be selected. Input quantities are the probability function of the overvoltages (U_{rp}), as the result of the system analysis on one hand and on the other hand, the disruptive discharge probability distribution of the insulation in question. The coordination factor should also include an allowance for any inaccuracies in the input quantities.

The deterministic procedure is used in cases where, for example, with an internal insulation only a conventional withstand voltage ($P_w = 100\%$) can be assumed and this is also protected by a surge arrester. The deterministic layout is also used in the case of overvoltage protection of equipment linked to overhead lines, when the difference between an existing statistical withstand-voltage characteristic ($P_w = 90\%$) and the assumed conventional withstand voltage of the same insulation configuration is taken into consideration by the coordination factor K_c. The deterministic procedure does not leave a defined fault rate for the equipment during operation.

In the statistical procedure, the overvoltage and disruptive discharge probability are available as statistical data and can be combined simultaneously, e.g. with the Monte Carlo method. This calculation must be done for the different kinds of insulation concerned and for different system configurations to determine the total non-availability of a device or an installation.

An insulation can therefore only be economically optimized by statistical design when the downtime expenses are defined for specific fault types. Therefore, the more complex statistical procedure can only be applied in very specific cases, such as the design of switchgear installations for the maximum transmission voltages.

The next step leads from the coordinating withstand voltages (U_{cw}) to the *required withstand voltages* (U_{rw}). Two correction factors are used here. The atmospheric correction factor K_a primarily corrects for the air pressure at the set-up area of the equipment with external insulation, i.e. primarily the altitude. Ambient temperature and humidity have the tendency of acting against each other in their influence on the withstand voltage. The atmospheric conditions generally do not influence the internal insulation.

The atmospheric correction factor is calculated as follows:

$$K_a = e^{m \frac{H}{8150}}$$

H: altitude in metres

m: an exponent that for clean insulators is different from 1 only with switching impulses and that depending on the voltage and geometry of the insulation is to be taken as a guidance value from characteristics (cf. DIN EN 60071-2, Fig. 9!). In the case of contaminated insulators, m is in the range between 0.5 and 0.8 for the power-frequency withstand voltage test.

The safety factor K_s considers the number of all other influences that could result in a difference between the equipment in operation and the test object in the type test.

These are:

- aging caused by thermal, dielectric, chemical and mechanical stresses,
- spread caused by manufacturing conditions,
- spread caused by installation, such as changes in the connection technology, parallel loading or numerous devices in operation in comparison to type-testing one single specimen only, etc.

Recommended safety factors are:

- for internal insulation: $K_s = 1.15$,
- for external insulation: $K_s = 1.05$.

If the safety factor of 1.15 applicable for internal insulation is also used for external insulation, the atmospheric correction is also covered to an operational altitude of 1000 m.

The required withstand voltages (U_{rw}) determined to this point are the minimum withstand voltages that must be verified for a device by type tests to ensure that the failure rate predicted in the performance criterion is not exceeded at the operational site in the system. The required withstand voltages can basically be discarded for each of the (curve) categories described above.

The selection tables (Tables 4-1 and 4-2) show standard withstand voltages for the testing of equipment. They show standard voltages for the voltage range I (≤ 245 kV) for testing with short-time power-frequency withstand voltage and with lightning impulse withstand voltage. Voltage range II (> 245 kV) lists standard voltages for testing with lightning impulse withstand voltage and switching impulse withstand voltage.

If the system analysis shows required withstand voltages (U_{rw}) in categories for which the selection tables do not have standard values, conversion to one of the categories listed there is recommended by using corresponding *test conversion factors*. Test conversion factors are listed for the two voltage ranges for internal and external insulation in DIN EN 60071-2 in Tables 2 and 3.

Table 4-1

Standardized insulation levels in voltage range I (1 kV < U_m ≤ 245 kV) as per DIN EN 60071-1 (VDE 0111 Part 1)

Highest voltage for equipment U_m kV rms value	Standard short-time power-frequency withstand voltage kV rms value	Standard lightning impulse withstand voltage kV peak value
3.6	10	20 40
7.2	20	40 60
12	28	60 75 95
17.5	38	75 95
24	50	95 125 145
36	70	145 170
52	95	250
72.5	140	325
123	(185) 230	450 550
145	(185) 230 275	(450) 550 650
170	(230) 275 325	(550) 650 750
245	(275) (325) 360 395 460	(650) (750) 850 950 1050

Note: if the values in parentheses are not sufficient to verify that the required conductor-conductor withstand voltages are met, additional withstand voltage tests will be required.

Table 4-2

Standardized insulation levels in range II: U_m > 245 kV
as per DIN EN 60071-1 (VDE 0111 Part 1)

Highest voltage for equipment U_m kV rms value	Standard switching-impulse withstand voltage			Standard lightning impulse withstand voltage kV peak value
	Longitudinal insulation (note 1) kV peak value	Conductor-earth kV peak value	Ratio conductor-conductor to conductor-earth peak value	
300	750	750	1.50	850 950
	750	850	1.50	950 1 050
362	850	850	1.50	950 1 050
	850	950	1.50	1 050 1 175
420	850	850	1.60	1 050 1 175
	950	950	1.50	1 175 1 300
	950	1 050	1.50	1 300 1 425
525	950	950	1.70	1 175 1 300
	950	1 050	1.60	1 300 1 425
	950	1 175	1.50	1 425 1 550
765	1 175	1 300	1.70	1 675 1 800
	1 175	1 425	1.70	1 800 1 950
	1 175	1 550	1.60	1 950 2 100

Note 1: value of the impulse voltage in combined test.

Note 2: the introduction of U_m = 550 kV (instead of 525 kV), 800 kV (instead of 765 kV), 1200 kV and another value between 765 kV and 1200 kV and the associated standard withstand voltages is being considered.

A standardized insulation level from Tables 4-1 and 4-2 must be selected to ensure that in all test voltage categories the values of the required withstand voltages (U_{rw}) are reached or exceeded.

At least two combinations of rated voltage values are assigned to almost every value for the maximum equipment voltage U_m. The result of the procedure for the insulation coordination determines whether the higher or lower values are required, or whether the insulation level of another equipment voltage is to be used.

Note:

The space available here only allows the basics of the (new) procedure for insulation coordination to be considered, but not with all the details. Proper application of the procedure is not trivial; it requires complete familiarity with the material.

This will result in continuing use of the previous procedure in general practice. An exact test will only be economically justifiable with specific projects.

4.2 Dimensioning of power installations for mechanical and thermal short-circuit strength

(as per DIN EN 60865-1 (November 1994), classification VDE 0103, see also IEC 60865-1 (1993-09))1)

Symbols used

A	cross section of conductor, with bundle conductors (composite main conductors): total cross- section
a, l or l_s	distances in Fig. 4-2
a_m, a_s	effective main conductor and sub-conductor spacing (Fig. 4-3 and Table 4-3)
a_{12}, $a_{13} \ldots a_{1n}$	geometrical distances between the sub-conductors
k_{12}, $k_{13} \ldots k_{1n}$	correction factors (Fig. 4-3)
E	Young's modulus
f	operating frequency of the current circuit
f_c	relevant characteristic frequency of a main conductor
F_m or F_s	electrodynamic force between the main or sub-conductors
I_{th}	thermally equivalent short-time current (rms value)
I''_k	initial symmetrical short-circuit current (rms value)
I''_{k2}	initial symmetrical short-circuit current with phase-to-phase short circuit (rms value)
i_p, i_{p2}, i_{p3}	peak short-circuit current or cut-off current of current limiting switchgear or fuses (peak value) with symmetrical short circuit (i_{p2}, i_{p3}: with phase-to-phase or three-phase short circuit)

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1) see KURWIN calculation program in Table 6-2

A standardized insulation level from Tables 4-1 and 4-2 must be selected to ensure that in all test voltage categories the values of the required withstand voltages (U_{rw}) are reached or exceeded.

At least two combinations of rated voltage values are assigned to almost every value for the maximum equipment voltage U_m. The result of the procedure for the insulation coordination determines whether the higher or lower values are required, or whether the insulation level of another equipment voltage is to be used.

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(as per DIN EN 60865-1 (November 1994), classification VDE 0103, see also IEC 60865-1 (1993-09))[1]

Symbols used

A	cross section of conductor, with bundle conductors (composite main conductors): total cross- section
a, l or l_s	distances in Fig. 4-2
a_m, a_s	effective main conductor and sub-conductor spacing (Fig. 4-3 and Table 4-3)
a_{12}, $a_{13} \dots a_{1n}$	geometrical distances between the sub-conductors
k_{12}, $k_{13} \dots k_{1n}$	correction factors (Fig. 4-3)
E	Young’s modulus
f	operating frequency of the current circuit
f_c	relevant characteristic frequency of a main conductor
F_m or F_s	electrodynamic force between the main or sub-conductors
I_{th}	thermally equivalent short-time current (rms value)
I''_k	initial symmetrical short-circuit current (rms value)
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[1] see KURWIN calculation program in Table 6-2

J	axial planar moment of inertia (Table 1-22)
m	factor for thermal effect of the d.c. component (Fig. 4-15)
m'	mass per unit length (kg / m) of a conductor without ice, with bundle conductors: total mass per unit length
n	factor for the thermal effect of the a.c. component (Fig. 4-15)
R_{p02}, R'_{p02}	minimum and maximum stress of the yield point (Table 13-1)
S_{thr}	rated short-time current density (rms value) for 1 s
T_{k}	short-circuit duration
T_{k1}	short-circuit duration with auto-reclosing: duration of the 1st current flow
t	number of sub-conductors
V_{r} orV_{σ}	factors for conductor stress
V_{F}	ratio of dynamic force to static force on the support
V_{r}	factor for unsuccessful three-phase auto-reclosure in three-phase systems
Z or Z_{s}	moment of resistance of main or sub-conductor during bending (Table 1-22, shown there with W), also called section modulus as used in DIN EN 60865-1 and in KURWIN
α	factor for force on support (Table 4-4), dependent on the type of busbar and its clamping condition
β	factor for main conductor stress (Table 4-4), dependent on the type of busbar and its clamping condition
γ	factor for determining the relevant characteristic frequency of a conductor (Table 4-4)
κ	factor for calculating the peak short-circuit current i_{p} as in Fig. 3-1
μ_0	magnetic field constant ($4\pi \cdot 10^{-7}$ H/m)
σ	conductor bending stress

4.2.1 Dimensioning of bar conductors for mechanical short-circuit strength

Parallel conductors whose length l is high in comparison to their distance *a* from one another are subjected to forces evenly distributed along the length of the conductor when current flows. In the event of a short circuit, these forces are particularly high and stress the conductors by bending and the means of fixing by cantilever, pressure or tensile force. This is why busbars must not be designed for the load current only but also to resist the maximum occurring short-circuit current. The load on the busbars and supports to be expected in the event of a short circuit must therefore be calculated. The mechanical short-circuit strength of power installations can also be determined by testing.

The following information is not only applicable to busbars but also to tubular conductors, or very generally to rigid conductors. It is also applicable to two- and three-phase short circuits in a.c. and three-phase systems.

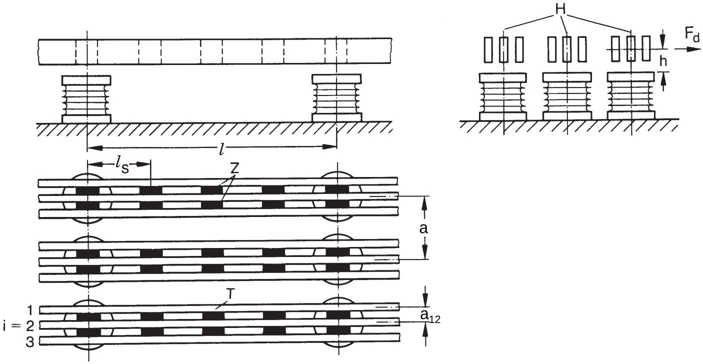


Fig. 4-2

Busbar configuration with three main conductors H with three sub-conductors T each, with spacers Z: a main conductor centre-line spacing, a_{1i} *geometrical sub-conductor centre-line spacing clearance (e.g. between the 1st and 2nd sub-conductor* a_{12}*),* F_d *support load, h distance between point of application of force and the upper edge of the support,* l *support distance,* l_s *maximum distance of a spacer from the support or the adjacent spacer.*

IEC 61660-2 applies to calculations in d.c. systems.

When calculating F with three-phase short-circuits for i_p the value $0.93 \cdot i_{p3}$ can be used. The factor 0.93 considers the greatest possible load that can be experienced by the middle conductor of a single-plane configuration in three-phase systems.

The electrodynamic force between the main conductors through which the same current flows is

$$F_m = \frac{\mu_0}{2\pi} \cdot i_p^2 \cdot \frac{l}{a}$$

or as a numerical equation

$$F_m = 0.2 \cdot i_{p2}^2 \cdot \frac{l}{a} \text{ or } F_m = 0.173 \cdot i_{p3}^2 \cdot \frac{l}{a}.$$

If the main conductor consists of t single conductors, the electrodynamic force F_s between the sub-conductors is

$$F_s = \frac{\mu_0}{2\pi} \cdot \left(\frac{i_p}{t}\right)^2 \cdot \frac{l_s}{a_s}$$

or as a numerical equation

$$F_s = 0.2 \cdot \left(\frac{i_p}{t}\right)^2 \cdot \frac{l_s}{a_s}$$

Numerical equations with i_p in kA, F_m in N and l in the same unit as a.

Effective conductor spacing

As previously mentioned, these equations are strictly speaking only for filament-shaped conductors or in the first approximation for conductors of any cross section, so long as their distance from one another is significantly greater than the greatest conductor dimension. If this condition is not met, e.g. with busbar packets comprising rectangular bar conducters, the individual bars must be divided into current filaments and the forces between them calculated. In this case, the actual effective main conductor spacing $a_m = a / k_{1s}$ must be used as the main conductor spacing.

Here, k_{1s} must be taken from Fig. 4-3 where $a_{1s} = a$ and d the total width of the busbar packet in the direction of the short-circuit force. b – as shown in Fig. 4-3 – is the height of the busbars perpendicular to the direction of the short-circuit force.

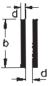
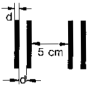
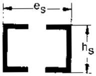
The actual effective sub-conductor clearance is

$$\frac{1}{a_s} = \frac{k_{12}}{a_{12}} + \frac{k_{13}}{a_{13}} + \ldots + \frac{k_{1n}}{a_{1n}}$$

For the most frequently used conductor cross sections, a_s is listed in Table 4-3.

Table 4-3

Effective sub-conductor spacing a_s for rectangular cross sections of bars and U-sections (all quantities in cm) as per DIN EN 60865-1 (VDE 0103)

Configuration of bars	Bar thickness *d* cm	Bar width *b*							
		4 cm	5 cm	6 cm	8 cm	10 cm	12 cm	16 cm	20 cm
	0.5	2.0	2.4	2.7	3.3	4.0	—	—	—
	1	2.8	3.1	3.4	4.1	4.7	5.4	6.7	8.0
	0.5	—	1.3	1.5	1.8	2.2	—	—	—
	1	1.7	1.9	2.0	2.3	2.7	3.0	3.7	4.3
	1	1.4	1.5	1.6	1.8	2.0	2.2	2.6	3.1
	0.5	—	1.4	1.5	1.8	2.0	—	—	—
	1	1.74	1.8	2.0	2.2	2.5	2.7	3.2	—
		U 60	U 80	U100	U120	U140	U160	U180	U 200
	h_s =	6	8	10	12	14	16	18	20
	e_s =	8.5	10	10	12	14	16	18	20
	a_s =	7.9	9.4	10	12	14	16	18	20

Stresses on conductors and forces on supports

The bending stress σ of a busbar must not exceed a specified limit in the event of a short circuit to avoid excessive stress on the material. In specifying this limit a sustained bending of the busbar of up to 1 % of the support length has been assumed, because a deformation of this magnitude is virtually undetectable with the naked eye.

The stress on rigid conductors (busbars) and the forces on the supports are influenced by the oscillation response of the conductors. This in return is dependent on the clamping conditions and the permissible plastic deformation or the natural frequency of the conductor. First the upper limit values of the stress are given with consideration to the plastic deformation, while the following section shows the stresses arising from consideration of the oscillation response.

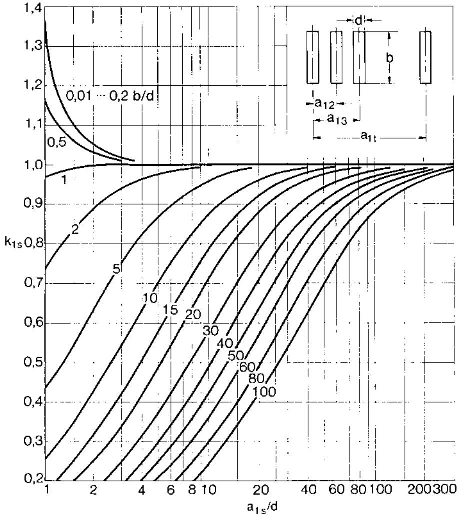


Fig. 4-3

Correction factor k_{1s} for effective main conductor and sub-conductor spacing where s = 2…t

Main conductor stress: $\sigma_m = V_\sigma \cdot V_r \cdot \beta \cdot \frac{F_m \cdot l}{8 \cdot Z}$

Sub-conductor stress: $\sigma_s = V_{\sigma s} \cdot V_r \cdot \frac{F_s \cdot l_s}{16 \cdot Z_s}$

When considering the plastic deformation

$V_\sigma \cdot V_r = V_{\sigma s} \cdot V_r = 1$ in two-phase a.c. systems

$V_\sigma \cdot V_r = V_{\sigma s} \cdot V_r = 1$ in three-phase systems without three-phase auto-reclosure

$V_\sigma \cdot V_r = V_{\sigma s} \cdot V_r = 1.8$ in three-phase systems with three-phase auto-reclosure

The resulting conductor stress is a combination of the main and sub-conductor stress:

$\sigma_{tot} = \sigma_m + \sigma_s$

The force F_d on each support:

$F_d = V_F \cdot V_r \cdot \alpha \cdot F_m$

with

$V_F \cdot V_r = 1$ for $\sigma_{tot} \geq 0.8 \cdot R'_{p0.2}$

$V_F \cdot V_r = \frac{0.8 \cdot R'_{p0.2}}{\sigma_{tot}}$ for $\sigma_{tot} < 0.8 \cdot R'_{p0.2}$

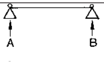
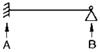
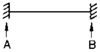
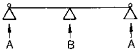
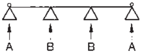
However, in two-phase a.c. systems $V_F \cdot V_r$ does not require a value greater than 2 and in three-phase systems no greater than 2.7.

If it is unclear whether a busbar can be considered supported or fixed at any specific support point, the least suitable case must be taken for rating the busbar and the support.

If the condition $\sigma_{tot} \geq 0.8 \cdot R'_{p0.2}$ is met, the busbar cannot transfer any forces greater than the static forces to the supports, because it will be previously deformed ($V_F \cdot V_r = 1$). However, if σ_{tot} is well below $0.8 \cdot R'_{p0.2}$, it is recommended that conductor and support loads be determined as follows taking into consideration the relevant characteristic frequency of the conductor.

Table 4-4

Factors α, β and γ as per DIN EN 60865-1 (VDE 0103)

Type of busbar and its clamping condition			Force on support Factor α	Main conductor stress Factor β	Relevant charcteristic frequency Factor γ
Single-span beam	both sides supported		*A*: 0.5 *B*: 0,5	1.0	1.57
	fixed, supported		*A*: 0.625 *B*: 0.375	0.73	2.45
	both sides fixed		*A*: 0.5 *B*: 0.5	0.50	3.56
Continuous beam with multiple supprts and *N* equal or approximately equal support distances	$N = 2$		*A*: 0.375 *B*: 1.25	0.73	2.45
	$N \geqq 3$		*A*: 0.4 *B*: 1.1	0.73	3.56

Note to Table 4-4

Continuous beams with multiple supports are continuous bars or tubular conductors that have one or more supports along their length. They are secured against horizontal displacement at one of the supports. The length to be used in the calculation l is the distance between the supports, i.e. the length of the spans, not the length of the continuous beam.

The factors α and β apply for equal support distances. Support distances are still considered equal when the smallest support distance is at least 0.2 times the value of the largest. In this case, end supports are not subject to a higher force than the inner supports. Use the largest support distance for l in the formula.

Stresses on conductors and forces on supports with respect to conductor oscillation

If the characteristic frequency f_c of a conductor is taken into account, lower values for stresses on conductors and forces on supports may be derived than if the characteristic frequency is not considered. If higher values are found here, they are not relevant.

The characteristic frequency of a conductor is

$$f_c = \frac{\gamma}{l^2} \sqrt{\frac{E \cdot J}{m'}}$$

For determining the characteristic frequency of a main conductor, the factor γ is used depending on the clamping conditions in Table 4-4. If the main conductor consists of several sub-conductors, *J* and *m'* refer to the main conductor. The data of a sub-conductor should be used for *J* and *m'* if there are no stiffening elements along the length of the support distance. In the event that stiffening elements are present, see DIN EN 60865-1 and IEC 60865-1 for additional information. The installation position of the bar conductor with reference to the direction of the short-circuit force must be considered for the axial planar moment of inertia. $\gamma = 3.56$ and l for the distance between two stiffening elements must be used for calculating the sub-conductor stresses.

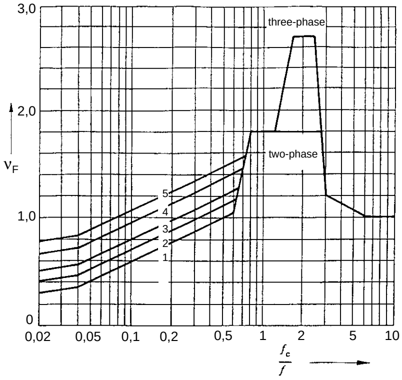


Fig. 4-4
Factor V_F to determine the forces on supports

1: $\kappa \geq 1.60$
2: $\kappa = 1.40$
3: $\kappa = 1.25$
4: $\kappa = 1.10$
5: $\kappa = 1.00$

κ *values for Fig. 4-4 and 4-5*

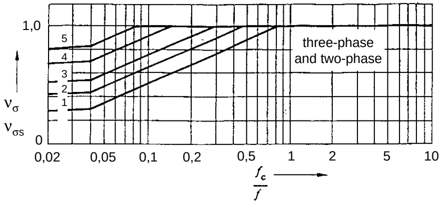


Fig. 4-5

Factors V_σ and $V_{\sigma s}$ to determine the conductor stresses

When the characteristic frequencies are considered, the values for V_σ, $V_{\sigma s}$, V_F and V_r to calculate the main conductor and sub-conductor stresses and the forces on supports using the formulae given above may be taken from Fig. 4-4, 4-5 and 4-6 (as per DIN EN 60865-1 (VDE 0103)). At short-circuit durations T_k or T_{k1} of 0.1 s or less the actual stresses and forces may be considerably less than the calculated values with $f_c \leq f$.

With elastic supports the actual value of f_c is less than the calculated value. This needs to be taken into account for $f_c > 2.4\,f$.

Information on digitizing these curves is given in DIN EN 60865-1 and in IEC 60865-1.

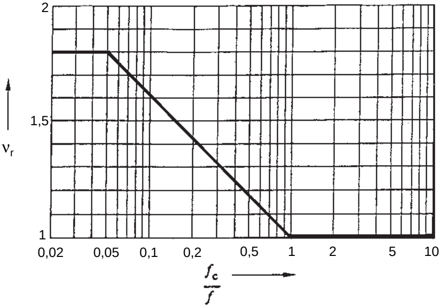


Fig. 4-6

Factor V_r, to be used with three-phase auto-reclosing in three-phase systems; in all other cases $V_r = 1$.

Maximum permissible stresses

Conductors are considered short-circuit proof when

$$\sigma_{tot} \leq q \cdot R_{p0.2} \quad \text{and}$$

$$\sigma_s \leq R_{p0.2}$$

The plasticity factor q for rectangular busbars is 1.5, for U and I busbars 1.19 or 1.83. Here $q = 1.19$ applies with U busbars with bending around the axis of symmetry of the U, otherwise 1.83. With I busbars $q = 1.83$ applies for bending around the vertical axis of the I, otherwise 1.19. For tubular conductors (with D = external diameter and s = wall thickness) calculate as follows

$$q = 1.7 \cdot \frac{1 - (1 - 2\frac{s}{D})^3}{1 - (1 - 2\frac{s}{D})^4}.$$

The force F_d on the supports must not exceed the minimum breaking force guaranteed by the manufacturer F_r (DIN 48113, DIN EN 60168 – VDE 0674 Part 1) of the insulators. The comparison value for the devices is the rated mechanical terminal load for static + dynamic load. Because this value is not defined in the device standards, it must be obtained from the manufacturer of the devices.

In the case of post insulators that are stressed by cantilever force the distance h of the point of application of force (Fig. 4-2) must be considered.

$F_{red} = k_{red} \cdot F_r$ = reduced rated full load of support.

The reduction factor k_{red} for the approved cantilever force is calculated with the bending moment at the foot of the insulator.

Moments of resistance of composite main conductors

If a stress as in Fig. 4-7a is applied, the main conductor moment of resistance is the sum of the sub-conductor moments of resistance. The same applies for a stress applied as in Fig. 4-7b when there is no or only one stiffening element per span. **Note:** The moment of resistance is also called section modulus, as used in DIN EN 60865-1 and in the calculation program KURWIN.

If there are two or more stiffeners, the calculation can be made with higher values for the main conductor moment of resistance. In the case of busbar packets with two or three sub-conductors with a rectangular cross section of 60 %, with more sub-conductors with a rectangular cross section of 50 % and with two or more sub-conductors with a U-shaped cross section of 50 % of the moment of resistance based on the axis 0-0 (ideal) can be used.

If four rectangular sub-conductors are connected in pairs by two or more stiffening elements but there are no stiffening elements between the pairs with the 5 cm spacing, 14 % of the ideal values given in Table 4-5, i.e. $Z_y = 1.73\ b\ d^2$, may be used. The stiffening elements must be installed so that the sub-conductors are prevented from being displaced in a longitudinal direction. The plasticity factor q is exactly as large as that for non-combined main conductors.

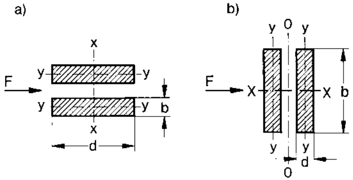
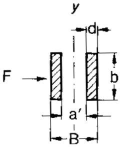


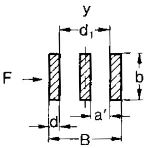
Fig. 4-7

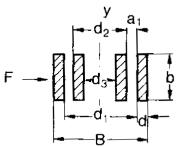
Direction of force and bending axes with conductor packets

Table 4-5

Formulae for calculating the ideal moments of inertia and resistance of composite main conductors with two or more stiffening elements (100 % values).







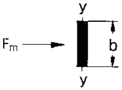
$$J_y = \frac{b}{12}(B^3 - a'^3) \qquad J_y = \frac{b}{12}(B^3 - d_1^3 + d^3) \qquad J_y = \frac{b}{12}(B^3 - d_1^3 + d_2^3 - d_3^3)$$

$$Z_y = \frac{b}{6\,B}(B^3 - a'^3) \qquad Z_y = \frac{b}{6\,B}(B^3 - d_1^3 + d^3) \qquad Z_y = \frac{b}{6\,B}(B^3 - d_1^3 + d_2^3 - d_3^3)$$

Cross section mm	J_y cm^4	Z_y cm^3	J_y cm^4	Z_y cm^3	J_y cm^4	Z_y cm^3
Calculated values for J_y in cm^4 and Z_y in cm^3, if $a' = d$ and $d_3 = 5$ cm						
50/5	1.355	1.80	5.15	4.125	—	—
50/10	10.830	7.20	41.25	16.5	341.65	62.10
60/5	1.626	2.16	6.18	4.95	—	—
60/10	12.996	8.64	49.50	19.8	409.98	74.52
80/5	2.168	2.88	8.24	6.60	—	—
80/10	17.328	11.52	66.00	26.4	546.64	99.36
100/5	2.71	3.6	10.3	8.25	—	—
100/10	21.66	14.4	82.5	33	683.3	124.2
120/10	26	17.28	99.00	39.6	819.96	149.04

Table 4-6

Moments of inertia and resistance for flat bars

Configuration	flat ▬ ▬ ▬		upright ❙ ❙ ❙	
Busbar dimensions				
mm	Z_x cm^3	J_x cm^4	Z_y cm^3	J_y cm^4
12 × 2	0.048	0.0288	0.008	0.0008
15 × 2	0.075	0.0562	0.010	0.001
15 × 3	0.112	0.084	0.022	0.003
20 × 2	0.133	0.133	0.0133	0.00133
20 × 3	0.200	0.200	0.030	0.0045
20 × 5	0.333	0.333	0.083	0.0208
25 × 3	0.312	0.390	0.037	0.005
25 × 5	0.521	0.651	0.104	0.026
30 × 3	0.450	0.675	0.045	0.007
30 × 5	0.750	1.125	0.125	0.031
40 × 3	0.800	1.600	0.060	0.009
40 × 5	1.333	2.666	0.166	0.042
40 × 10	2.666	5.333	0.666	0.333
50 × 5	2.080	5.200	0.208	0.052
50 × 10	4.160	10.400	0.833	0.416
60 × 5	3.000	9.000	0.250	0.063
60 × 10	6.000	18.000	1.000	0.500
80 × 5	5.333	21.330	0.333	0.0833
80 × 10	10.660	42.600	1.333	0.666
100 × 5	8.333	41.660	0.4166	0.104
100 × 10	16.660	83.300	1.666	0.833
120 × 10	24.000	144.000	2.000	1.000
160 × 10	42.600	341.300	2.666	1.333
200 × 10	66.600	666.000	3.333	1.660

Calculation example

Busbar configuration as shown in Fig. 4-2 with three main conductors of three sub-conductors each with rectangular cross section 80 mm × 10 mm of 3.2 m length from

E – Al Mg Si 0.5 F 17.

$R_{p0.2}$ = 12 000 N/cm^2 (Table 13-1)

$R'_{p0.2}$ = 18 000 N/cm^2 (Table 13-1)

Stiffeners for each main conductor consist of the tee-off bars and one extra stiffening element in each of the conductors (phases) L1 and L3.

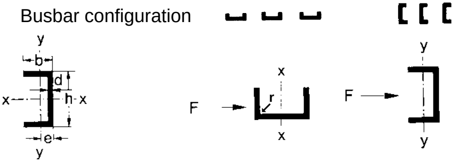
l_s = 40 cm
l = 80 cm
a = 12 cm
a_m = 12.4 cm with k_{1s} = 0.97 as shown in Fig. 4-3 where a_{1s} = a, d = 5 cm, b = 8 cm
a_s = 2.3 cm (Table 4-3)
Z_s = 1.333 cm³ (Table 4-6)
Z_y = 26.4 cm³ (Table 4-5)
$Z = 0.6 \cdot Z_y = 0.6 \cdot 26.4\ \text{cm}^3 = 15.84\ \text{cm}^3$
$v_\sigma \cdot v_r = v_{\sigma s} \cdot v_r = 1$
α = 1.1 (Table 4-4 for continuous beam with N ≧ 3, end bay supports α = 0.4)
β = 0.73 (Table 4-4)

Table 4-7

Moments of inertia and resistance for U busbars

Busbar configuration

U section



Size mm	h mm	b mm	d mm	r mm	e mm	W_x cm³	J_x cm⁴	W_y cm³	J_y cm⁴
50	50	25	4	2	7.71	5.24	13.1	1.20	2.07
60	60	30	4	2	8.96	7.83	23.5	1.76	3.71
70	70	32.5	5	2	9.65	12.4	43.4	2.57	5.87
80	80	37.5	6	2	11.26	19.38	77.5	4.08	10.70
100	100	37.5	8	2	10.96	33.4	167	5.38	14.29
120	120	45	10	3	13.29	59.3	356	9.63	30.53
140	140	52.5	11	3	15.27	90.3	632	14.54	54.15
160	160	60	12	3	17.25	130	1042	20.87	89.22
180	180	67.5	13	3	19.23	180	1622	28.77	138.90
200	200	75	14	3	21.21	241	2414	38.43	206.72

The prospective peak short-circuit current without auto-reclosing is i_{p3} = 90 kA.

$$F_m = 0.173 \cdot i_{p3}^2 \cdot \frac{l}{a_m} = 0.173 \cdot 90^2 \cdot \frac{80}{12.4} = 9041\ \text{N}$$

$$\sigma_m = V_\sigma \cdot V_r \cdot \beta \cdot \frac{F_m \cdot l}{8 \cdot Z} = 1.0 \cdot 0.73 \ \frac{9041\ \text{N} \cdot 80\ \text{cm}}{8 \cdot 15.84\ \text{cm}^3} = 4167\ \text{N/cm}^2$$

$$F_s = 0.2 \left(\frac{i_{p3}}{t}\right)^2 \cdot \frac{l_s}{a_s} = 0.2 \left(\frac{90}{3}\right)^2 \cdot \frac{40}{2.3} = 3130\ \text{N}$$

$$\sigma_s = V_{\sigma s} \cdot V_r \cdot \frac{F_s \cdot l_s}{16 \cdot Z_s} = 1.0 \cdot \frac{3130\ \text{N} \cdot 40\ \text{cm}}{16 \cdot 1.333\ \text{cm}^3} = 5870\ \text{N/cm}^2$$

$$\sigma_{\text{tot}} = \sigma_{\text{m}} + \sigma_{\text{s}} = 4\,167 \text{ N/cm}^2 + 5\,870 \text{ N/cm}^2 = 10\,037 \text{ N/cm}^2$$

$$\sigma_{\text{tot}} = 10\,037 \text{ N/cm}^2 < 0.8 \cdot R'_{\text{p0.2}}$$

$$V_{\text{F}} \cdot V_{\text{r}} = \frac{0.8 \cdot R'_{\text{p0.2}}}{\sigma_{\text{tot}}} = \frac{0.8 \cdot 18\,000}{10\,037} = 1.44$$

$$F_{\text{d}} = V_{\text{F}} \cdot V_{\text{r}} \cdot \alpha \cdot F_{\text{m}} = 1.44 \cdot 1.1 \cdot 9\,041 = 14\,321 \text{ N}$$

Conductor stresses

$$\sigma_{\text{tot}} = 10\,037 \text{ N/cm}^2 < 1.5 \cdot R_{\text{p0,2}} = 18000 \text{ N/cm}^2$$

$$\sigma_{\text{s}} = 5\,870 \text{ N/cm}^2 < R_{\text{p0,2}} = 12\,000 \text{ N/cm}^2$$

The busbars can be manufactured in accordance with the planned design.

Force on support

If the height of the point of application of force in Fig. 4-2 h $\leq$ 50 mm, a post insulator of form C as in Table 13-34 at a rated force F = 16 000 N may be used. If the point of application of the force F is higher than shown in the table, the forces must be converted to take the maximum bending moment at the foot of the insulator into account.

Assessment with respect to the conductor oscillations

Main conductor:
γ = 3.56 (Table 4-4)
l = 80 cm
E = 70 000 N/mm^2 (Table 13-1)
J = $b\,d^3/12$ = 0.67 cm^4 (for single conductors, Table 1-22)
m' = 2.16 kg/m (per sub-conductor, cf. Table 13-7)
f_c = 82.4 Hz (where 1 N = 1 kg m/s^2), valid without stiffening elements
f_c = 144 Hz with stiffening elements (see DIN EN 60865-1)
V_r = 1 (as in Fig. 4-6 where f = 50 Hz and f_c/f = 2.88)
V_σ = 1, V_F = 1.5 (as in Fig. 4-4 and 4-5)
(Regarding the elasticity of the supports, smaller values for f_c must be used, i.e. for V_F with values up to 2.7.)

Sub-conductors:
γ = 3.56, l = 40 cm, f_{cs} = 330 Hz, V_r = 1, $V_{\sigma s}$ = 1

In this case the short, rigid busbars, taking conductor vibrations into account, do not yield smaller values for products $V_\sigma V_r$, $V_{\sigma s} V_r$, $V_F V_r$, i.e. lower stresses than when the plastic deformation is taken into account. This makes the above results determining.

Table 4-8

Permissible short-circuit conductor temperatures and rated short-time current densities for plastic-insulated cables

Insulation material	Nominal voltage U_0/U kV	Conductor temperature at beginning of the short circuit	Permissible end temperature	Conductor material	Rated short-time current density (1 s) A /mm²
PVC	0.6/1…6/10	70 °C	160 °C[1]	Cu	115
				Al	76
			140 °C[2]	Cu	103
				Al	68
XLPE	all ranges LV and HV	90 °C	250 °C[3]	Cu	143
				Al	94

[1] for cross sections ≤ 300 mm²
[2] for cross sections > 300 mm²
[3] not permitted for soldered connections

For extremely short break times with short circuits (T_k < 15 ms), current limiting comes into play and the thermal short-circuit current capability of carriers can only be assessed by comparison of the Joule integrals $\int i^2\, d\, t = f\,(\hat{I}''_k)$. The cut-off power of the overcurrent protection device must be less than the still permissible heat energy of the conductor.

Permissible Joule integrals for plastic-insulated conducters:

A = 1.5	2.5	4	10	25	50	mm²
$\int i^2\, d\, t$ = $2.9 \cdot 10^4$	$7.8 \cdot 10^4$	$2.2 \cdot 10^5$	$1.3 \cdot 10^6$	$7.6 \cdot 10^6$	$3.3 \cdot 10^7$	A^2s

Current limiting overcurrent protection devices such as fuses or current limiting breakers are particularly advantageous for short-circuit protection of carriers. Their cut-off power in the event of a short circuit is small. As a result the Joule heat impulse $\int i^2\, d\, t$ increases with increasing prospective short-circuit current I''_k with the zero-current interrupter many times faster than with the current limiter.

4.3 Dimensioning of wire and tubular conductors for static loads and electrical surface-field strength

4.3.1 Calculation of the sag of wire conductors in outdoor installations

Busbars and tee-offs must be rated for normal service current and for short circuit in accordance with DIN EN 60865-1, see Sec. 4.2.

Al/St wire conductors are primarily used for the tensioned busbars, for connecting equipment and tee-off conductors Al wire conductors with a similar cross section are used.

For wire data, see Sections 13.1.4, Tables 13-22 to 13-33.

Wire conductor sag is determined by the dead-end strings, the weight of the wire, the anticipated ice load, the supplementary load of tee-offs or fixed contacts for single-column disconnectors, by the wire-pulling force, by built-in springs or the spring stiffness of the supports and the cable temperature.

The wire conductor sag is calculated on the basis of the greatest sag occurring in the installation at a conductor temperature of + 80 °C, with very short span lengths possibly also at

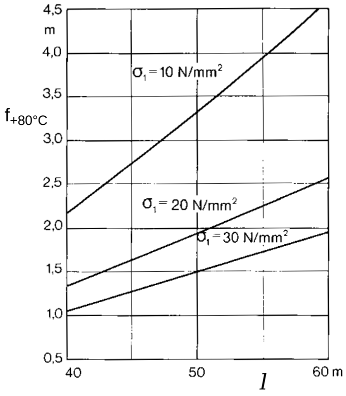


Fig. 4-17

Sag f for two-conductor bundles Al/St 240/40 mm^2, with 123-kV double endstrings, for spans of l = 40…60 m at conductor temperature +80°C. The following are included: two dead-end strings each 2.0 m in length, weight 80 kg (with 900 N ice load) and a tee-off of 10 kg in weight every 10 m. (Parameters of the family of curves: initial wire tension σ_1 at – 5 °C and normal ice load), f sag in m, l span length in m.

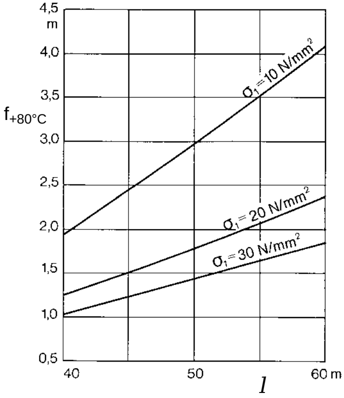


Fig. 4-18

Sag f for two-conductor bundles Al/St 300/50 mm^2, with 123-kV double endstrings, for spans of l = 40…60 m at conductor temperature +80°C. The following are included: two dead-end strings, each 2.0 m in length, weight 80 kg (with 900 N ice load) and a tee-off of 10 kg in weight every 10 m. (Parameters of the family of curves: initial wire tension σ_1 at – 5 °C and normal ice load), f sag in m, l span length in m.

As per DIN VDE 0210 the following applies:

- A distinction between the conductor with normal and increased supplementary load must be made. The ice load is designated with supplementary load. The normal supplementary load is assumed to be (5 + 0.1 d) N per 1 m of conductor or sub-conductor length. Here, d is the conductor diameter in mm[1]. The increased supplementary load is agreed depending on local conditions.
- For insulators, the normal supplementary load of 50 N per 1 m insulator string must be taken into account.

Typical values for a rough determination of the sags of tensioned busbars, tensioned and suspended wire links and lightning protection wires are given in Fig. 4-17 to 4-25.

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[1] The normal supplementary load for conductors of 20 to 40 mm diameter corresponds to a layer of ice of 10 to 8 mm with a specific gravity of ice of 765 kg/m^3.
In contrast, from January 2000 as per DIN VDE 0101 (HD 637 S1), ice thicknesses of 1, 10 or 20 mm with a specific gravity of ice of 900 kg/m^3 will be assumed.

Sag of the tensioned busbars with loads, dead-end strings and tee-offs at every 10 m (width of bay) with a weight of 10 kg each

The sags and tensions of the busbar wires are influenced by their dead-end strings and tee-offs (point loads).

The busbar sags in a 123-kV outdoor installation with a bay width of 10.0 m can be roughly determined using the diagrams in Figs. 4-17 to 4-20. These give the most common types of wire conductors like two-conductor bundle 240/40 mm^2, two-conductor bundle 300/50 mm^2, single-conductor wire 380/50 mm^2 and single-conductor wire 435/55 mm^2, for spans of 40…60 m and initial wire tensions σ_1 = 10.0…30.0 N/mm^2 with ice load as per DIN VDE 0210, values for the sags occuring at + 80 °C conductor temperature. This ice load is (5 + 0.1 d) N/m with wire diameter d in mm.

At 245- and 420-kV outdoor installations in diagonal arrangement with single-column disconnectors the busbars take the weight of the disconnector fixed contacts instead of the tee-off wires. To limit the temperature-dependent change in sag, spring elements are frequently included in the span to maintain the suspended contacts within the reach of the disconnector scissors.

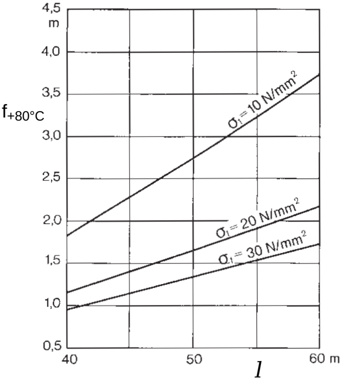

Fig. 4-19

Sag f for single-conductor wires Al/St 380/50 mm^2, with 123-kV double-end strings, for spans of l = 40…60 m at conductor temperature + 80°C. The following are included: two dead-end strings, each 2.0 m in length, weight 80 kg (with 900 N ice load) and a tee-off every 10 m of 10 kg in weight. (Parameters of the family of curves initial wire tension σ_1 at – 5 °C and normal ice load), f sag in m, l span length in m.

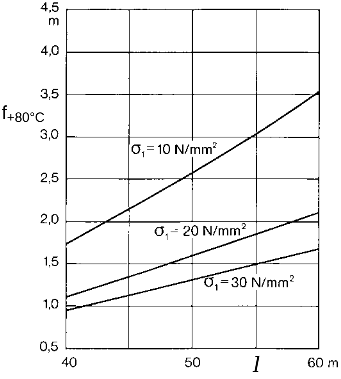

Fig. 4-20

Sag f for single-conductor wires Al/St 435/55 mm^2, with 123-kV double-end strings, for spans of l = 40…60 m at conductor temperature + 80°C. The following are included: two dead-end strings, each 2.0 m in length, weight 80 kg (with 900 N ice load) and a tee-off every 10 m of 10 kg in weight. (Parameters of the family of curves initial wire tension σ_1 at – 5 °C and normal ice load), f sag in m, l span length in m.

Sag of the spanned wire conductors

In many outdoor installations spanned wire conductors with dead-end strings are required. They generally only have a wire tee-off at the ends of the stays (near the string insulators).

The sag can be calculated as follows when σ_x is known:

$$f_x = \frac{g_n}{2 \cdot \sigma_x \cdot A} \left[m' \cdot (0.25\, l^2 - l_k^2) + m_k \cdot l_k\right]$$

f_x sag m, σ_x horizontal component of the cable tension N/mm², m' mass per unit length of wire kg/m, with ice load if applicable, m_K weight of insulator string in kg, A conductor cross section in mm², l span including insulator strings in m, l_k length of the insulator string in m, g_n gravity constant. The sags of some wire conductor spanned with double-end strings in 123 and 245-kV switchgear installations can be taken from the curves in Fig. 4-21 as a function of the span.

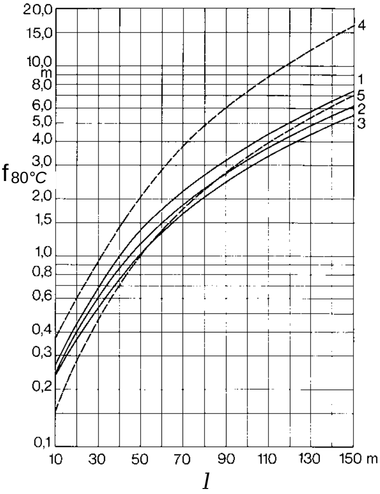

Fig. 4-21

Sag $f_{80\,°C}$ for spanned wire connections for spans up to 150 m with conductor temperature + 80 °C:

1 two-conductor bundle Al/St 560/50 mm², 245-kV-double-end strings, σ_1 20,0 N/mm² at – 5 °C and normal ice load

2 two-conductor bundles Al/St 380/50 mm², 245-kV-double-end strings, σ_1 30.0 N/mm² at – 5 °C and normal ice load

3 two-conductor bundles Al/St 240/40 mm², 245-kV-double-end strings, σ_1 40.0 N/mm² at – 5 °C and normal ice load

4 two-conductor bundles Al/St 240/40 mm², 123-kV-double-end strings, σ_1 10.0 N/mm² at – 5 °C and normal ice load

5 two-conductor bundles Al/St 435/50 mm², 123-kV-double-end strings, σ_1 20.0 N/mm² at – 5 °C and normal ice load

(sag in logarithmic scale)

Fracture of an insulator of a double dead-end string

For safety reasons the wire connections in switchgear installations have double dead-end strings. The fracture of an insulator results in an increase in the sag in the middle of the span.

The greatest sag f_k is roughly calculated as follows

$$f_k = \sqrt{f_\vartheta^2 + \frac{3}{8} \cdot 0{,}5\, y \cdot l}$$

f_ϑ = sag at ϑ °C
l = span length
y = length of yoke of double-end string

The curves in Fig. 4-22 can be used to make an approximate determination for y = 0.4 m of the greatest occurring sags.

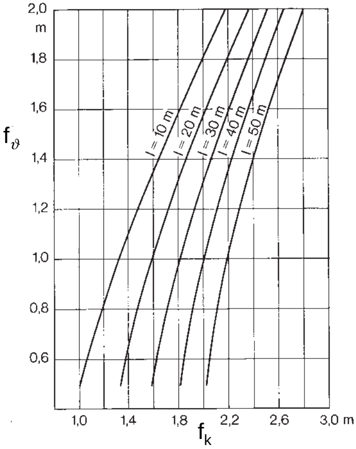

Fig. 4-22

General determination of changes in sag in the event of a fracture of an insulator of the double-end spring. Length of yoke between two insulators y = 0.4 m, f_k maximum sag in m, f_ϑ sag at ϑ °C in m, parameter l length of span.

Sag of the earth wire

Outdoor installations are protected against lightning strikes by earth wires. Al/St wires are generally used. Section 5.4 shows the configuration and the protection range of the earth wires in detail. They are placed along the busbar and at right-angles to the overhead line and transformer feeder bays.

The ice load on the wires must also be considered here. For Al/St 44/32 and Al/St 50/30 earth wires in Fig. 4-25, the sags can be determined at conductor temperature + 40 °C (because there is no current heat loss) and for span lengths to 60 m at cable tensions σ_1 = 10.0 to 30.0 N/mm^2. In practice, the earth wires are generally spanned so their sag is identical to that of the busbars.

Wire connections of equipment

In outdoor installations the high-voltage equipment is generally connected with wire condcutors. The applicable wire pull depends on the approved pull (static + dynamic) of the apparatus terminals. The minimum clearances and conductor heights over walkways in switchgear installations are specified in Section 4.6. These are minimum dimensions. For rating for mechanical short-circuit current capability, see Section 4.2.

The sags and conductor tensions can be calculated with standard formulae used in designing overhead lines. The sag in midspan is calculated with the parabolic equation:

$$f_x = \frac{(m' g_n + F_z)\, l^2}{8 \cdot \sigma_x \cdot A}$$

f_x	sag in m	σ_x	horizontal component of the cond. tension N/mm^2
A	cond. cross section mm^2	m'	conductor weight per unit length in kg/m
l	span in m	F_z	normal ice load in N/m (in DIN VDE 0210 designated as supplementary load). $F_z = (5 + 0.1\ d)$ N/m.

Values for DIN wire conductors, see Section 13.1.4, Tables 13.22 to 13.29.

Tensions in wire connections

For the conductor sag of 0.5 m accepted in practice at + 80 °C conductor temperature, the required tensions depending on the span for the Al wire conductor cross sections 240, 300, 400, 500, 625 and 800 mm^2 can be taken from the curves in Figs. 4-23 and 4-24. The permissible mechanical terminal load of the installed devices and apparatus must be observed.

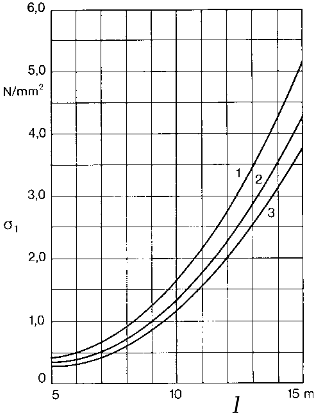

Fig. 4-23

Tensions σ_1 for suspended wire connections at –5 °C and normal ice load: 1 cable Al 240 mm^2; 2 cable Al 400 mm^2, 3 cable Al 625 mm^2

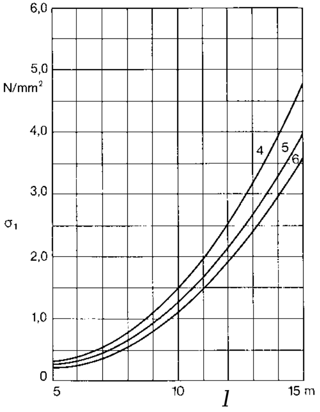

Fig. 4-24

Tensions σ_1 for suspended wire connections at –5 °C and normal ice load: 4 cable Al 300 mm^2; 5 cable Al 500 mm^2, 6 cable Al 800 mm^2

Sag in proximity to terminal points

When connecting the rotary disconnector, ensure that the cable sag does not affect the functioning of the disconnector arm. As shown in Fig. 4-26, the sag determines the minimum height of the conductor at the distance *c* from the terminal point *A*. The sag at distance *c* is calculated as follows:

$$f_c = \frac{4 \cdot f_{max} \cdot c \cdot (l - c)}{l^2}$$

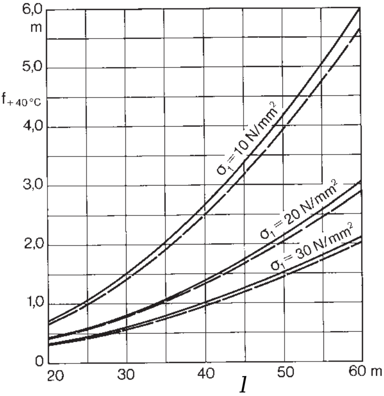

Fig. 4-25

Sag f for earth wire Al/St 44/32 mm² ——— and Al/St 50/30 mm² — — — for spans of 20 to 60 m at conductor temperature + 40 °C (no Joule heat). (Parameters of the family of curves: initial tension σ_1 at –5 °C and normal ice load), f sag in m, l span length in m.

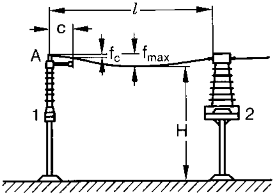

Fig. 4-26

Sag of a connection of equipment at distance c from terminal point A.
1 rotary disconnector, 2 current transformer, A terminal point, l length of device connection, f_{max} sag in midspan, f_c sag at distance c, H height above ground (see Fig. 4-37).

4.3.2 Calculation of deflection and stress of tubular busbars

In general, the deflection *f* and the stress σ of a tube is the result of its own weight

$$f = \frac{1}{i} \cdot \frac{Q \cdot l^3}{E \cdot J} \text{ and } \sigma = \frac{k \cdot Q \cdot l}{W}$$

Where:

$Q = m' \cdot g_n \cdot l$	load by weight of the tube between the support points
l	span (between the support points)
E	module of elasticity (for copper = 11 · 10^6, for Al = 6.5…7.0 · 10^6, for steel = 21 · 10^6, for E-AlMgSi 0.5 F 22 = 7 · 10^6 N/cm²; see Table 13-1)

J	moment of inertia (for tube $J = 0.049\,[D^4 - d^4]$) as in Table 1-22
W	moment of resistance for bending (for tube $W = 0.098\,[D^4 - d^4]/D$) as in Table 1-22
m'	weight of tube per unit of length (without supplementary load) in kg/m (see Tables 13-5, 13-9 and 13-10)
g_n	gravity constant 9.81 m/s^2
i, k	factors (see Table 4-9)

Table 4-9

Factors for calculating the deflection of tubular busbars

Type of support	i	k
Tube supported at both ends	*77*	*0.125*
Tube one end fixed, one freely supported	*185*	*0.125*
Tube fixed at both ends	*384*	*0.0834*
Tube on three support points	*185*	*0.125*
Tube on four support points	*145*	*0.1*
Tube on more than four support points	*130*	*0.11*

As per DIN VDE 0101, an ice load equivalent to a layer of ice of 1.5 cm with a specific gravity of 7 kN/m^3 must be taken into account (see footnote 1) on page 151). When doing the calculation with ice, the load Q (due to the weight of the tube) must be increased by adding the ice load.

A permissible value for the compliance is only available as a typical value for optical reasons. For the compliance under own weight, this is l /150 or D and for the compliance under own weight and ice l / 80.

Permissible value for the stress under own weight plus ice is $R_{p0.2}$ / 1.7 with $R_{p0.2}$ as in Table 13-1. Permissible value with simultaneous wind load is $R_{p0.2}$ / 1.5.

Example:

Given an aluminium tube E-AlMgSi 0.5 F 22 as in Table 13-10, with external diameter 80 mm, wall thickness 5 mm, span 8 m, supported at both ends. Then

$$Q = m' \cdot g_n \cdot l = 3.18\ \frac{\text{kg}}{\text{m}} \cdot 9.81\ \frac{\text{m}}{s^2} \cdot 8\ \text{m} = 250\ \text{N}$$

$$J = 0.049\ (8^4 - 7^4)\ \text{cm}^4 = 83\ \text{cm}^4$$

$$W = 0.098\ \frac{(8^4 - 7^4)}{8}\ \text{cm}^3 = 20.8\ \text{cm}^3$$

The deflection is:

$$f = \frac{1}{77} \cdot \frac{250\ \text{N} \cdot 8^3 \cdot 10^6\ \text{cm}^3}{7 \cdot 10^6\ (\text{N/cm}^2) \cdot 83\ \text{cm}^4} = 2{,}9\ \text{cm}$$

The stress is:

$$\sigma = \frac{0.125 \cdot 250\ \text{N} \cdot 800\ \text{cm}}{20.8\ \text{cm}^3} = 12\ \frac{\text{N}}{\text{mm}^2}$$

Deflection and stress are acceptable.

4.3.3 Calculation of electrical surface field strength

The corona effect on the conductor surface of overhead lines is a partial electrical discharge in the air when the electrical field strength exceeds a critical value on the conductor surface.

There is no specification for the permissible surface field strength for outdoor installations. In general for overhead lines, the value is 16…19 kV/cm, in individual cases up to 21 kV/cm is approved. These values should also be retained with switchgear installations. The surface field strength *E* can be calculated with the following formula:

$$E = \frac{U}{\sqrt{3}} \cdot \frac{\beta}{r_L \cdot \ln\left(\frac{a}{r_e} \cdot \frac{2 \cdot h}{\sqrt{4\,h^2 + a^2}}\right)}$$

where $$\beta = \frac{1 + (n - 1)\;r_L / r_T}{n}$$

$$r_e = \sqrt[n]{n \cdot r_L \cdot r_T^{\,n-1}}$$

$$r_T = \frac{a_T}{2 \cdot \sin(\pi / n)}$$

The following apply in the equations:

E	electrical surface field strength
U	nominal voltage
β	multiple conductor factor (for tube = 1)
r_L	conductor radius
r_T	radius of the bundle
r_e	equivalent radius of bundle conductor
a_T	centre-to-centre distance of sub-conductors
a	centre-to-centre distance of main conductors
h	conductor height above ground
n	number of sub-conductors per bundle

Example:

Lower busbars in a 420-kV outdoor installation with Al/St 4 × 560/50 mm^2, as in Fig. 3-17a, Section 3.4.4, at a medium height of 9.5 m above ground: U = 380 kV, r_L = 1.61 cm, a_T = 10 cm, a = 500 cm, h = 950 cm, n = 4. With these figures, the above equations yield:

$$r_T = \frac{10\text{ cm}}{2 \cdot \sin\frac{\pi}{4}} = 7.07\text{ cm}$$

$$r_e = \sqrt[4]{4 \cdot 1.61 \cdot 7.07^3} = 6.91\text{ cm}$$

$$\beta = \frac{1 + (4 - 1)\;\frac{1.61}{7.07}}{4} = 0.42$$

$$E = \frac{380\text{ kV}}{\sqrt{3}} \cdot \frac{0{,}42}{1.61\text{ cm}\,\ln\left(\frac{500}{6.91} \cdot \frac{2 \cdot 950}{\sqrt{4 \cdot 950^2 + 500^2}}\right)} = 13.5\,\frac{\text{kV}}{\text{cm}}$$

The calculated value is within the permissible limits. This configuration can be designed with these figures.

4.4 Dimensioning for continuous current rating

4.4.1 Temperature rise in enclosed switch boards

Electrical equipment in switchboards gives off loss heat to the ambient air. To ensure fault-free function of this equipment, the specified limit temperatures must be retained inside the switchboard.

The following applies according to the relevant IEC or VDE specifications

– with open installations as ambient temperature the temperature of the ambient room air (room temperature ϑ).

– in closed installations as ambient temperature the temperature inside the enclosure (inside air temperature ϑ_i).

– as temperature rise the difference between inside air temperature (ϑ_i) and room air temperature (ϑ).

The most significant heat sources inside the enclosure are the conducting paths in the main circuit. This includes the circuit-breakers and fuses, including their connections and terminals and all the auxiliary equipment in the switchboard.

Inductive heat sources such as eddy currents in steel parts only result in local temperature rises. Their contribution is generally negligible for currents < 2500 A.

The power dissipation for the electrical equipment can be found in the relevant data sheets.

In fully enclosed switchboards (protection classes above IP 50) the heat is dissipated to the outside air primarily by radiation and external convection. Thermal conduction is negligibly small.

Experiments have shown that in the inside temperature is distributed depending on the height of the panel and on the equipment configuration. The density variations of the heated air raises the temperature in the upper section of the enclosure.

The temperature distribution can be optimized when the electrical equipment with the greatest power dissipation is positioned in the lower part of the panel, so the entire enclosure is involved in heat dissipation as far as possible.

When installed on a wall, the panel should have 8…10 cm clearance from the wall. This allows the rear wall of the panel to be involved effectively in dissipating heat.

The average air temperature inside the enclosure, neglecting the heat radiation, can be calculated as follows:

$$\Delta \vartheta = \frac{P_{\mathrm{V\,eff}}}{\alpha \cdot A_{\mathrm{M}}}$$

$\Delta \vartheta$	Temperature increase of air inside enclosure
$P_{\mathrm{V\,eff}}$	power dissipation with consideration of load factor as per DIN EN 60439-1 (VDE 0660 Part 500) Tab. 1
A_{M}	heat-dissipating surface of enclosure

α Heat transfer coefficient:

6 W/($m^2 \cdot K$)	if sources of heat flow are primarily in the lower half of the panel,
4.5 W/($m^2 \cdot K$)	where sources of heat flow are equally distributed throughout the height of the panel,
3 W/($m^2 \cdot K$)	if sources of heat flow are primarily in the upper half of the panel.

If there are air vents in the enclosure, such as with IP 30, heat dissipation is primarily by convection.

The heat transfer from the air in the interior of the enclosure to the ambient air is much better in this case than with fully enclosed designs. It is influenced by the following:

- the size of the panel,
- the ratio of air outlet and inlet vents to the entire heat-dissipating surface,
- the position of air inlets and outlets,
- the distribution of heat sources inside the panel and
- the temperature difference.

The internal air temperature will be in the range of 0.5 to 0.7 times of that calculated in the above equation.

If switchgear assemblies develop higher heat loss or if they have a non-linear flow model, they must be equipped with internal fans to force the heat generated out to the surrounding space. An external room ventilation system will then be required to extract the heat from the switchgear room.

VDE specifies + 40 °C as the upper limit for the room temperature and – 5 °C for the lower limit.

The electrical equipment cannot be applied universally above this range without additional measures. Excessive ambient temperatures at the devices affects functioning or load capacity. The continuous current cannot always be fully used, because a room temperature of + 40 °C does not leave sufficient reserve for the overtemperature inside the enclosure.

The assessment must be based on the assumption that the overtemperatures set in VDE 0660 Part 500 Tab. 3 should not be exceeded and that the equipment will operate properly.

Example:

Panel in protection class IP 54, fitted with 12 inserts. Every insert has fuses, air-break contactors and thermal overcurrent relays for motor control units. Heat flow sources are evenly distributed throughout the height of the panel.

power dissipation P_v = 45 W per insert.
load factor a = 0.6 (as per VDE 0660 Part 500 Tab. 1)
heat-dissipating enclosure surface $A_M = 4\ m^2$.

With the stated component density, a check is required to ensure that the electrical equipment is subject to a maximum operating temperature of 55 °C. Room temperature $\vartheta = 35$ °C.

Effective power dissipation $P_{V\,eff} = a^2 \cdot P_V = 0.6^2 \cdot 12 \cdot 45\ W = 194.4\ W$.

$$\Delta\,\vartheta = \frac{P_{V\,eff}}{\alpha \cdot A_M} = \frac{194.4\ W \cdot m^2\ K}{4.5\ W \cdot 4\ m^2} = 10.8\ K$$

$$\vartheta_i = \vartheta + \Delta\,\vartheta = 35 + 10{,}8 = 45.8\ °C.$$

For additional details on determining and assessing the temperature rise in switchboards, see DIN EN 60439-1 (VDE 0660 Part 500) Section 8.2.1 and Section 7.3 of this publication.

4.4.2 Ventilation of switchgear and transformer rooms

Design criteria for room ventilation

The air in the room must meet various requirements. The most important is not to exceed the permissible maximum temperature. Limit values for humidity and air quality, e.g. dust content, may also be set.

Switchboards and gas-insulated switchgear have a short-term maximum temperature of 40 °C and a maximum value of 35°C for the 24h average. The installation requirements of the manufacturers must be observed for auxiliary transformers, power transformers and secondary installations.

The spatial options for ventilation must also be considered. Ventilation cross sections may be restricted by auxiliary compartments and buildings. If necessary, the loss heat can be vented through a chimney. If HVAC (air-conditioning) installations and air ducts are installed, the required space and the configuration must be included at an early stage of planning.

Ultimately, economic aspects such as procurement and operating expenses must be taken into account as well as the reliability (emergency power supply and redundancy) of the ventilation.

At outside air temperatures of up to 30 °C, natural ventilation is generally sufficient. At higher temperatures there is danger that the permissible temperature for the equipment may be exceeded.

Figs. 4-27 and 4-28 show frequently used examples of room ventilation.

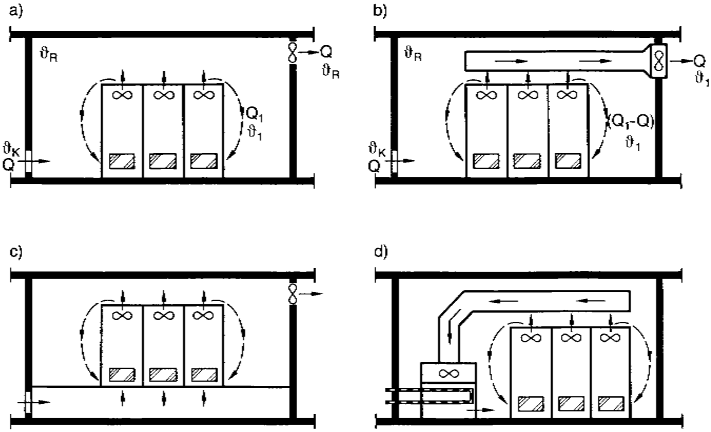

Fig. 4-27

Compartment ventilation: a) Simple compartment ventilation, b) compartment ventilation with exhaust hood above the switchboard, c) ventilation with false floor, d) ventilation with recirculating cooling system

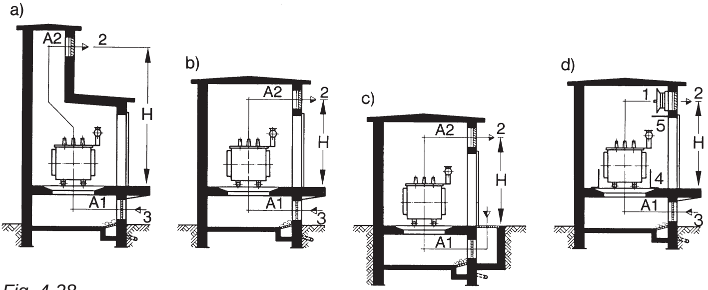

Fig. 4-28

Cross section through transformer cells:

a) incoming air is channelled over ground, exhaust air is extracted through a chimney. b) as in a), but without chimney. c) incoming air is channelled below ground, exhaust air is removed through an opening in the wall of the transformer compartment. d) transformer compartment with fan. A_1 = incoming air cross section, A_2 = exhaust air cross section, H = "chimney" height, 1 = fan, 2 = exhaust air slats, 3 = inlet air grating or slats, 4 = skirting, 5 = ceiling.

The ventilation efficiency is influenced by the configuration and size of the incoming air and exhaust air vents, the rise height of the air (centre of incoming air opening to centre of exhaust air opening), the resistance in the path of the air and the temperature difference between incoming air and outgoing air. The incoming air vent and the exhaust air vent should be positioned diagonally opposite to each other to prevent ventilation short circuits.

If the calculated ventilation cross section or the chimney opening cannot be dimensioned to ensure sufficient air exchange, a fan will have to be installed. It must be designed for the required quantity of air and the pressure head.

If the permissible room temperature is only slightly above or even below the maximum outside temperature, refrigeration equipment or air-conditioning is used to control the temperature.

In ventilated and air-conditioned compartments occupied by personnel for extended periods the quality regulations for room air specified by DIN 1946 must be observed.

The resistance of the air path is generally:

$$R = R_1 + m^2 R_2.$$

Here: R_1 resistance and acceleration figures in the incoming air duct, R_2 resistance and acceleration figures in the exhaust air duct, m ratio of the cross section A_1 of the incoming air duct to the cross section A_2 of the exhaust air duct. Fig. 4-28 shows common configurations.

The total resistance consists of the components together. The following values for the individual resistance and acceleration figures can be used for an initial approximation:

acceleration	1	slow change of direction	0…0.6
right-angle bend	1.5	wire screen	0.5…1
rounded bend	1	slats	2.5…3.5
a bend of 135 °	0.6	cross section widening	0.25…0.9 1)

1) The smaller value applies for a ratio of fresh air cross section to compartment cross section of 1:2, the greater value for 1:10.

Calculation of the quantity of cooling air:

$$\dot{V}_0 = \frac{Q_L}{c_{pL} \cdot \Delta\vartheta}; \qquad \Delta\vartheta = T_2 - T_1$$

With temperature and height correction[1] the following applies for the incoming air flow:

$$\dot{V}_1 = \dot{V}_0 \cdot \frac{T_1}{T_0} \cdot e^{-\frac{g \cdot H}{R_L \cdot T_0}}$$

V_0 = standard air volume flow at sea level, p_0 = 1013 mbar, T_0 = 273 K = 0 °C,
T_1 = cooling air temperature (in K),
T_2 = exhaust air temperature (in K),
g = gravitational acceleration, $g = 9.81 \frac{m}{s^2}$,
H_0 = height above sea level,
R_L = gas constant of the air, $R_L = 0.287 \frac{kJ}{kg \cdot K}$,
c_{pL} = specific heat capacity of the air, $c_{pL} = 1.298 \frac{kJ}{m^3 \cdot K}$,
Q_L = total quantity of heat exhausted by ventilation: $Q_L = P_V + \Sigma Q$,
P_V = device power loss,
ΣQ = heat exchange with the environment.

---

[1] May be neglected at up to medium installation height and in moderate climates

At high power dissipation and high temperatures, solar radiation and thermal conduction through the walls can be neglected. Then $Q_L = P_V$.

Example:

At given incoming air and exhaust air temperature, the power dissipation P_V should be exhausted by natural ventilation. The volume of air required should be calculated:

T_2 = 40 °C = 313 K, T_1 = 30°C = 303 K, P_V = 30 kW = 30 kJ/s, height above sea level = 500 m

$$\dot{V}_1 = \frac{P_V}{c_{pL}\,(T_2 - T_1)} \cdot \frac{T_1}{T_0} \cdot e^{-\frac{g \cdot H}{R_L \cdot T_0}} = 2{,}4\,\frac{m^3}{s} = 8640\,\frac{m^3}{h}$$

If the warm air is exhausted directly over the heat source, this will increase the effective temperature difference $\Delta\vartheta$ to the difference between the temperature of the outside air and the equipment exhaust air temperature. This will allow the required volume of cooling air to be reduced.

Calculation of the resistances in the air duct and the ventilation cross section:

Based on the example in Fig. 4-28a, the following applies:

for incoming air:	acceleration	1
	screen	0.75
	widening in cross section	0.55
	gradual change of direction	0.6
	R_1 =	2.9
for exhaust air:	acceleration	1
	right-angle bend	1.5
	slats	3
	R_2 =	5.5

If the exhaust air duct is 10 % larger than the incoming air duct, then

$$m = \frac{A_1}{A_2} = \frac{1}{1.1} = 0.91 \text{ and } m^2 = 0.83,$$

then $R = 2.9 + 0.83 \cdot 5.5 = 7.5$.

The ventilation ratios can be calculated with the formula

$$(\Delta \vartheta)^3 \cdot H = 13.2 \frac{P_V^2}{A_1^2} (R_1 + m^2 R_2).$$

numerical value equation with $\Delta \vartheta$ in K, H in m, P_V in kW and A_1 in m^2.

Example:

transformer losses $P_V = 10$ kW, $\Delta \vartheta = 12$ K, $R = 7.5$ and H = 6 m yield:

$$A_1 \approx 1 \text{ m}^2.$$

Practical experience has shown that the ventilation cross sections can be reduced if the transformer is not continuously operated at full load, the compartment is on the north side or there are other suitable intervals for cooling. A small part of the heat is also dissipated through the walls of the compartment. The accurate calculation can be done as per DIN 4701. For the design of transformer substations and fire-prevention measures, see Section 4.7.5 to 4.7.6.

Fans for switchgear and transformer rooms

Ventilation fans, in addition to their capacity, must compensate for the pressure losses in the air path and provide blow-out or dynamic pressure for the cooling air flow. This static and dynamic pressure can be applied with $\Delta p \approx 0.2 \ldots 0.4$ mbar.

Then the propulsion power of the fan is:

$$P_L = \frac{\dot{V} \cdot \Delta p}{\eta}, \qquad \eta = \text{efficiency}$$

Example:

For the cooling air requirement of the transformer in the example above, where $P_v = 30$ kW, with $\dot{V} = 2.4$ m^3/s, $\eta = 0.2$, $\Delta p = 0.35$ mbar = 35 Ws/m^3
the fan capacity is calculated as:

$$P_L = \frac{2.4 \cdot 0.35}{0.2} = 0.42 \text{ kW}.$$

Resistances in the ventilation ducts and supplementary system components, such as dust filters, must be considered separately in consultation with the supplier.

For sufficient air circulation, a minimum clearance between the equipment and the wall is required, depending on the heat output. For auxiliary transformers, this is about 0.4 m, for power transformers about 1 m.

4.4.3 Forced ventilation and air-conditioning of switchgear installations

Overview and selection

When planning switchgear installations, thermal loads resulting from heat dissipation from the installation and environmental conditions (local climate) must be taken into account. This is generally done by:

- designing the switchgear installation for increased temperature,
- reducing the thermal load by ventilating, cooling or air-conditioning installations (HVAC).

In compliance with relevant DIN and VDI requirements, the following simplified installation configuration can be used:

- *ventilation devices and installations* for ventilation and exhaust, e.g. when the permissible ambient temperature is higher than the (max.) outside temperature, see Fig. 4-29
- *refrigeration units and installations* for heat exhaust only, e.g. when the permissible ambient temperature is equal to or less than the (max.) outside temperature, see Fig. 4-30
- *air-condtioning units and installations* for air-conditioning, when in addition to heat removal specific ambient climate conditions are required (temperature, humidity, air quality, etc.), see Fig. 4-31.

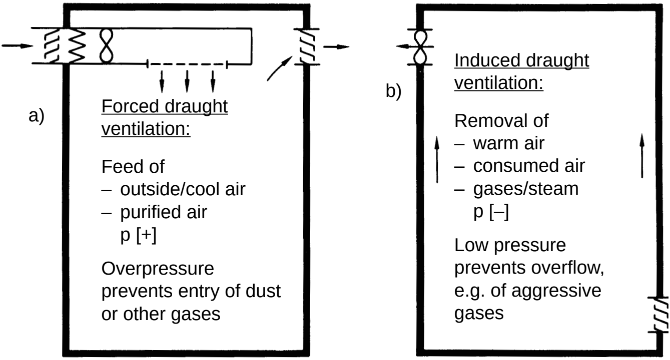

Fig. 4-29

Schematic view of a ventilation system: a) forced draught ventilation, b) Induced draught ventilation

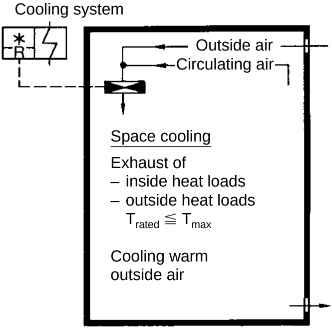

Fig. 4-30

Schematic view of a cooling system

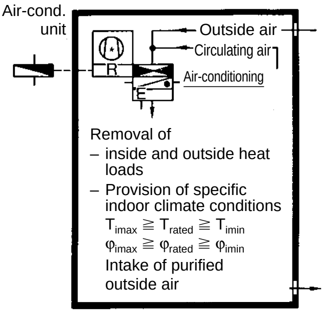

Fig. 4-31

Schematic view of an air-conditioning system

- *Permissible ambient temperatures* are the max. permissible compartment temperatures as specified in DIN VDE or other standards.
- Telecommunications and electronics modules require special *environmental conditions* and are specified in DIN 40040.
- In addition to the technical requirements, human (physiological) requirements may determine the *compartment climate*, e.g. the workplace regulations in Germany.
- The (max.) *outside temperature* is defined as the maximum outside temperatures occurring at the set-up area. It is selected from relevant climate tables, such as given in an encyclopedia or using information from meteorological organizations.
- *Space heating systems* in substation design is only relevant for occupied compartments. It is used almost exclusively in connection with ventilation or air-conditioning systems.
- Some of the most important and internationally accepted *regulations (standards) are listed below:*
  - *DIN 4701 – Calculating heat requirements –*
  - *DIN 1946 – Ventilation engineering –*
  - *VDI 2078 – Calculating cooling loads –*
  - *Ashrae Handbook (NEW YORK)*
  - *Carrier Handbook of air-conditioning system design (NEW YORK)*.

Basis for HVAC design is calculation of the thermal loads (Q_{th}) (heat balance).

$Q_{th} = Q_{tr} + Q_{str} + Q_i + Q_a$

Q_{tr} = heat transmission by the areas around the room (outside heat loads)

= A (m^2) · k (W/m^2 · K) · ΔT (K)

Q_{str} = radiation heat from exterior areas exposed to the sun

Q_i = installation and personnel heat (inside heat loads)

Q_a = heat from outside air, humidifiers and dehumidifiers (outside heat loads)

= $\dot{m}$ (kg/h) · c (W h / kg · K) · ΔT (K) (without dehumidifiers)

= $\dot{m}$ (kg/s) · Δh (kJ/kg) (with dehumidifiers)

A = *areas around the compartment (m^2)*
k = heat transmission coefficient (W/m^2)
ΔT = temperature difference
$\dot{m}$ = quantity of air flow/outside air flow (kg/h])
c = specific heat capacity of air (Wh/kg.K)
Δh = difference of the specific outside air enthalpy (Wh/kg)

This is calculated in compliance with various DIN, VDI or relevant international rules.

4.4.4 Temperature rise in enclosed busbars

Busbars in medium and low-voltage substation design are often installed in small compartments or in conduits. For this reason they are subject to different thermal conditions to busbar configurations installed in the open general compartment.

It is not possible to select the busbar cross sections directly from the load tables in Section 13.1.2. Because of the number of parameters influencing the temperature of enclosed busbars (such as position of the busbars in the conduit, conduit dimensions, ventilation conditions), the permissible current load must be calculated for the specific configuration.

The heat network method has proven useful for this calculation; Fig. 4-32 b.

Heat flows are generated by power dissipation.

Symbols used:

α	Heat transfer coefficient
A	Effective area
P	Heat output
R	Equivalent thermal resistance
$\Delta\vartheta$	Temperature difference
D	Throughput of circulating cooling medium (D = V/t)
C	*Radiant exchange number*
T	*Absolute temperature*
c_p	Specific heat
ρ	Density

Indices used:

D	Forced cooling
K	Convector
S	Radiation
O	Environment
1	Busbar
2	Inside air
3	Enclosure

Thermal transfer and thermal resistances
for radiation:

$$P_S = \alpha_S \cdot A_S \cdot \Delta\vartheta \text{ or } R_S = \frac{1}{\alpha_S \cdot A_S}$$

$$= C_{13} \cdot A_s \cdot (T_1^4 - T_3^4) \qquad \text{where } \alpha_s = \frac{C_{13}\,(T_1^4 - T_3^4)}{\Delta\vartheta}$$

for the convection:

$$P_K = \alpha_K \cdot A_K \cdot \Delta\vartheta \text{ or } R_K = \frac{1}{\alpha_K \cdot A_K}$$

for the circulating cooling medium:

$$P_D = c_p \cdot \rho \cdot D \cdot \Delta\vartheta \text{ or } R_D = \frac{1}{c_p \cdot \rho \cdot D}$$

For additional information, see Section 1.2.5.

For information on temperature rise of high-current busbars, see Section 9.2.

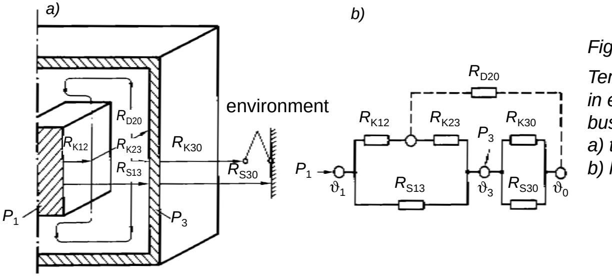

Fig. 4-32

Temperature rise in enclosed busbars
a) thermal flow,
b) heat network

4.4.5 Temperature rise in insulated conductors

Conductors have a real resistance. This causes current thermal losses by current flow. The conductors and the insulation around them become warmer.

One part of the heat quantity developed in the line (power dissipation):

$P_c = c \cdot \gamma \cdot A \dfrac{d}{d\,t} \Delta\vartheta$ is stored and the other part is

$P_A = \alpha \cdot U \cdot \Delta\vartheta$ dissipated to the environment.

The heat process can be described as follows:

$$\frac{c \cdot \gamma \cdot A}{\alpha \cdot U} \cdot \frac{d}{d\,t} \Delta\vartheta + \Delta\vartheta = \frac{A \cdot \rho}{\alpha \cdot U} \left(\frac{I}{A}\right)^2$$

Here:

$\Delta\vartheta$ = conductor overtemperature (K)

$\Delta\vartheta_e$ = end value of the conductor overtemperature (K)

α = heat transfer coefficient (9…40 W/(m^2 K)

c = specific heat (384.38 Ws/K · kg for copper)

γ = density (8.92 · 10^{-3} kg /cm^3 for copper)

ρ = specific resistance (0.0178 Ωmm^2/m at 20 °C for copper)

A = conductor cross section

U = conductor circumference

I = current in conductor (A)

The stationary state in the temperature rise occurs when all the power dissipation generated can be dissipated to the environment. This is the case when the temperature change is zero:

$$\Delta\vartheta_e = \frac{\rho \cdot A}{\alpha \cdot U} \left(\frac{I}{A}\right)^2.$$

The solution of the differential equation yields the overtemperature in relation to time:

$$\Delta\vartheta = \Delta\vartheta_e \cdot (1 - e^{-\frac{1}{T}}).$$

T is referred to as the time constant. It is the scale for the time in which the end temperature $\Delta\vartheta_e$ would be reached if the temperature rise were constant, therefore if the generated heat is completely stored in the conductor and the thermal dissipation is equal to zero. It is:

$$T = \frac{c \cdot \gamma \cdot A}{\alpha \cdot U} = \frac{\text{thermal storage capacity}}{\text{thermal dissipation capacity}}$$

The result of this is that T increases with the cross section of the conductor and by α also depends on the way it is laid and the accumulation of conductors. For example, multicore PVC copper conductors or cables laid well apart on the wall have the following heating time constants:

A	= 1.5	2.5	4	10	25	95	150	240	mm^2
T	= 0.7	1.0	1.5	3	6	16	23	32	min

Continuous operation occurs when the equilibrium temperature is reached. In practice, this is the case with 4 to 5 times the value of the time constants. A higher load may be approved for intermittent operation, so long as $t < 4 \cdot T$.

Excessively high conductor temperatures endanger the conductors and the environment. Care must be taken to ensure that non-permissible temperatures cannot occur. The limit temperature of the conductors for continuous load is:

- with rubber insulation 60 °C and
- with plastic insulation 70 °C
- with plastic insulation with increased heat resistance 100 °C.

In the event of a short circuit, the DIN VDE regulations allow a higher limit temperature for a brief period, see also Section 4.2.5.

The maximum load duration t_{Bmax} in which a conductor with the current carrying capacity I_z at higher load $I_a = a \cdot I_z$ has been heated to the still permissible limit temperature is:

$$t_{\mathrm{Bmax}} = T \cdot \ln\left(\frac{a^2}{a^2 - 1}\right)$$

Example:

Is a conductor of 1.5 mm² Cu for a three-phase a.c. motor ($I_{\mathrm{start}} = 6 \cdot I_{\mathrm{n\,Mot}}$) sufficiently protected against overload with the motor protection switch when the rotor is blocked?

The current-carrying capacity of the conductor is $I_{\mathrm{n\,Mot}} \cdot 0.8$.

$$a = 0.8 \cdot 6 = 4{,}8$$
$$T = 0.7\ \mathrm{min} = 42\ \mathrm{s}$$
$$t_{\mathrm{Bmax}} = 42\ \mathrm{s} \cdot \ln\left(\frac{4.8^2}{4.8^2 - 1}\right) = 1.86\ \mathrm{s}$$

Because the overload protection device only responds after about 6 s at 6 times current value, a 1.5 mm² Cu is not sufficiently protected. After 6 s this wire already reaches 152 °C. A larger conductor cross section must be selected.

A 2.5 mm² Cu wire (utilization 0.53) only reaches the limit temperature after 6.2 s.

4.4.6 Longitudinal expansion of busbars

Operational temperature variations result in longitudinal expansion or contraction of the busbars. This is calculated from

$$\Delta l = l_o\, \alpha\, \Delta \vartheta.$$

For a busbar of 10 m in length at 50 K temperature difference, the following typical values are obtained:

with Cu: $\Delta l = 10 \cdot 0.000017 \cdot 50 = 0.0085\ \mathrm{m} = 8.5\ \mathrm{mm}$,
with Al: $\Delta l = 10 \cdot 0.000023 \cdot 50 = 0.0115\ \mathrm{m} = 11.5\ \mathrm{mm}$.

These temperature-caused longitudinal changes may cause significant mechanical stresses on the conductors, on their supports and on connections to apparatus if there are no expansion sections installed in long line segments.

The forces generated are very easy to calculate if the longitudinal change caused by the difference in temperature $(\vartheta - \vartheta_0) = \Delta\vartheta$ is assumed to be equal to the longitudinal change that would be caused by a mechanical force F, which means:

$$\Delta l = l_o\, \alpha\, \Delta \vartheta = \frac{F\, l_o}{E\, A}$$

Where:

l_0 length of the conductor at temperature at which it was laid ϑ_o
$\Delta\,\vartheta$ temperature difference
F mechanical stress
A conductor cross section
α linear coefficient of thermal expansion, for Cu = $0.000017 \cdot K^{-1}$, for Al = $0.000023 \cdot K^{-1}$
E module of elasticity, for Cu = 110 000 N/mm^2, for Al = 65 000 N /mm^2.

The above equation gives the mechanical stress as:

$$F = \alpha \cdot E \cdot A \cdot \Delta\,\vartheta$$

and for $\Delta\,\vartheta$ = 1 K and A = 1 mm^2 the specific stress:

$$F' = \alpha \cdot E.$$

Therefore, for copper conductors:

$$F'_{Cu} = 0.000017 \cdot 110\,000 = \approx 1.87 \text{ N/(K} \cdot \text{mm}^2)$$

and for aluminium conductors:

$$F'_{Al} = 0.000023 \cdot 65\,000 = \approx 1.5 \text{ N/(K} \cdot \text{mm}^2).$$

4.5 Rating power systems for earthquake safety

4.5.1 General principles

Earthquakes in 95 of 100 cases originate from faults at the edges of the tectonic plates. The remainder are caused by volcanic action and landslides. The tectonic plates float on the surface of the viscous mantle of the earth and are subject to strong convection currents. The relative motion of the rigid plates in relation to one another generates local mechanical tension peaks at their edges, which from time to time are released by sudden deformations. These vibrations are spread by seismic waves, which propagate in accordance with the laws of wave propagation by reflection and refraction in complex waveforms and occur primarily as energetic surface waves in the frequency range of 0.1 Hz to 30 Hz with strong horizontal acceleration at the surface of the earth. The most energetic waves are therefore in the range of the natural frequencies of devices and components in high-voltage substations, but they must not adversely affect their functioning in the preset limits. The ground acceleration amplitudes are mostly in the range of 0.3 to 0.7 g. The strong earthquake phase only lasts a few seconds. In total, an earthquake rarely lasts more than 1 to 2 minutes.
The edges of the plates subject to earthquakes are primarily found in line reaching from south-eastern Europe through central Asia to Indonesia and around the Pacific Ocean. Even in central Europe earthquakes of moderate power occur occasionally. For this reason, even here nuclear installations also require verification of earthquake safety for all important components. This is also required for high-voltage power systems.

The most important parameters of an earthquake with respect to the mechanical stress on equipment and installations is the limit value of the acceleration of the ground at the installation site.

Characteristic values are:

– 5 m/s^2 (≈ 0.5 g, qualification class AF5),
– 3 m/s^2 (≈ 0.3 g, qualification class AF3) and
– 2 m/s^2 (≈ 0.2 g, qualification class AF2)

Where:

l_0 length of the conductor at temperature at which it was laid ϑ_o
$\Delta\,\vartheta$ temperature difference
F mechanical stress
A conductor cross section
α linear coefficient of thermal expansion, for Cu = $0.000017 \cdot \mathrm{K}^{-1}$, for Al = $0.000023 \cdot \mathrm{K}^{-1}$
E module of elasticity, for Cu = 110 000 N/mm^2, for Al = 65 000 N /mm^2.

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Characteristic values are:

– 5 m/s^2 (≈ 0.5 g, qualification class AF5),
– 3 m/s^2 (≈ 0.3 g, qualification class AF3) and
– 2 m/s^2 (≈ 0.2 g, qualification class AF2)

For the oscillation in the horizontal direction (x and y component). The vertical stress is calculated with half that value for every case. Of primary importance for the mechanical stress of equipment and device combinations is their mechanical natural frequencies, which are generally in the frequency spectrum of the seismic excitation. When verifying earthquake safety, the excitation with the natural frequency values of the equipment must be regarded as the "worst case".

The temporal process of the seismic excitation, i.e. the process of the oscillation of the ground at the installation site, can be selected differently for the verification. The following options are available:

- Continuous sine wave with natural frequencies
- Several (5) groups of 5 sinusoidal increasing and decreasing load cycle oscillations with natural frequency (5-sine beat, Fig. 4-33) separated by pauses
- Exponentially damped decaying load cycle oscillations with natural frequency (e-beat, Fig. 4-34)
- Simulation of an earthquake sequence typical for the installation site (Fig. 4-35)

The earthquake safety of equipment and installations (DIN EN 61166 (VDE 0670 Part 111), IEC 60068-3-3) can be verified in different ways, i.e.

- by testing,
- by a combination of testing and calculation or
- by calculation alone.

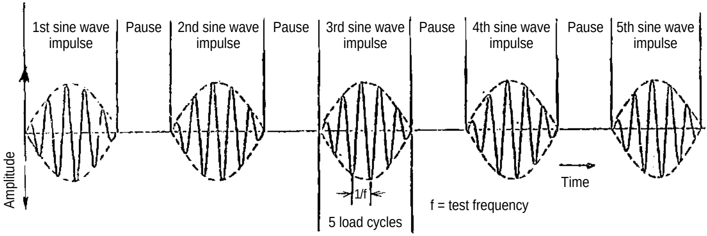
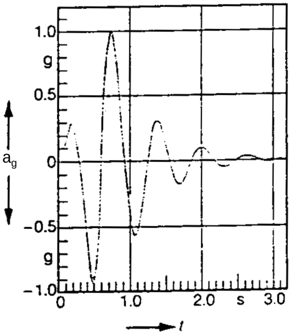


Fig. 4-33

Result of 5 sine wave impulses with 5 load cycles each

Fig. 4-34

a_g ground acceleration



Exponential beat,
"e-beat" for short,
as excitation function for simulation
of an earthquake shock

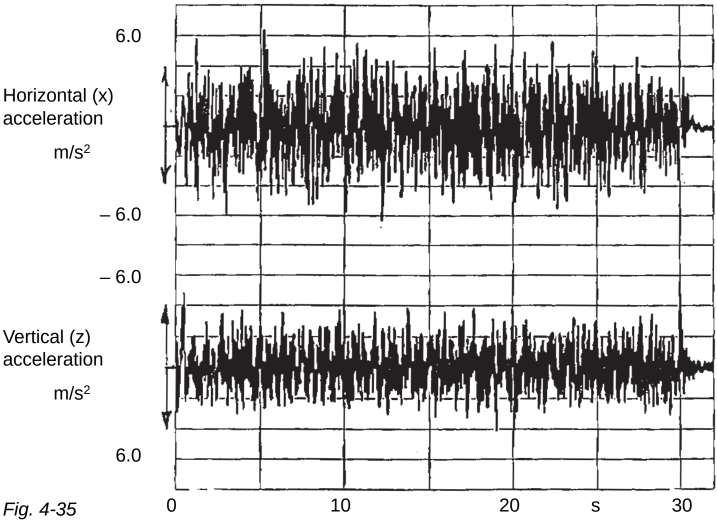


Fig. 4-35

Process of acceleration of the test table during a simulated earthquake
$1\ \mathrm{m/s^2} \approx 0.1\ \mathrm{g}$

Medium-voltage switchgear installations and equipment, are difficult to handle by calculation because of their complex design, but their compact dimensions make it quite easy to test them fully in existing test installations. High-voltage equipment can also be tested, but particularly in the development phase and with spatially extended installations a calculated verification of earthquake safety is preferred, particularly when dealing with rotation-symmetrical configurations.

4.5.2 Experimental verification

Very complex test installations are required for these tests, such as a vibration table with an area of 5 x 5 m and a mass of up to 25 t, which can vibrate with the above parameters.

Before the actual qualification test, the natural mechanical frequencies of the test object are determined in a resonance search run. A continuous sine wave with which the relevant frequency range of 0.5 – 35 Hz with a speed increase of 1 octave/min in all 3 axes running through in succession is selected as the test excitation. The acceleration here is only about 0.1 g.

During the qualification test, one of three different processes of the excitation of oscillations can be selected:

- Continuous sine wave method

  The relevant frequency range is run corresponding to the resonance search run procedure, with the difference that the amplitude is increased to the required value.

This test procedure only reproduces the stresses poorly in practice and represents an unrealistically sharp stress for the test object.

- Sine beat method (5-sine beat)

  The vibration table is excited with several sine impulses separated by pauses in this test procedure, as shown in Fig. 4-33. The frequency of the load cycle oscillation corresponds to the natural frequencies, i.e. the test is run in all natural frequencies of the installation in 2 axes, with generally one horizontal axis being combined with one vertical axis.

  A test with sine impulses yields quite useful conclusions respecting the response of the installation to an earthquake and is particularly useful if there is no accurate seismic information available for the installation site. However, the test takes time if the installation has many natural frequencies.

- Time history method

  This process simulates an actual earthquake. It lasts for about 30 s and the excitation is on 2 or 3 axes. An example of a synthetic earthquake time characteristic is shown in Fig. 4-35.

  This procedure simulates an earthquake very well if accurate information on ground acceleration is available. It also enables safety-relevant functions such as secure contact of conducting paths or tripping and reclosing the switchgear to be checked during the test. For this reason this test is often required for nuclear installations.

After the qualification test, the resonance search run is generally repeated to check whether the test object has deteriorated because of the test. If the natural frequencies have changed significantly, this indicates damage.

The greater part of the current medium-voltage switchgear range from ABB Calor Emag has been verified for earthquake safety by testing, in some cases with the 5-sine-beat method, in part while using the time history method with excitation accelerations to 0.7 g.

4.5.3 Verification by calculation

In the past, the dynamic load resulting from earthquakes was generally only roughly estimated with static loads. The dynamics of the process were simulated with correction and damping factors. The development of powerful computers now makes it possible to use mathematical simulation with the finite-element method (FEM), which has been in use around the world for some years as a tool for investigating complex processes of any type. Its application to the stress on switchgear, modules and complete switchbays caused by earthquakes is possible in principle, but the expense of modelling still limits the testing to individual components and device combinations. However, it is easier to analyse variations than use the vibration test. Natural frequencies, stiffness and the maximum permissible mechanical basic data are input into the computer as starting parameters. The excitation of oscillations by the earthquake is best simulated here by the exponentially decaying load cycle surge, the e-beat (Fig. 4-34).

The FEM was initially successfully used by ABB to determine the stress caused by earthquakes in the finely structured model for some ABB switchgear, such as the 550-kV circuit-breakers of the ELF SP 7-2 type including device table, the 245-kV pantograph disconnector of the TFB 245 type, the 123 kV rotary disconnector of the SGF 123 type and a 245-kV switchbay with pantograph disconnector, current transformer, circuit-breaker and rotary disconnector. Simpler approximate solutions are currently being developed in two directions, in one case an FEM with a roughly structured model and in the other case an alternative calculation procedure with statically equivalent loads derived from the dynamic process with earthquakes.

4.6 Minimum clearances, protective barrier clearances and widths of gangways

Key to symbols used

U_m	(kV)	maximum voltage for apparatus
U_n	(kV)	nominal voltage
U_{rB}	(kV)	rated lightning impulse withstand voltage
U_{rS}	(kV)	rated switching impulse withstand voltage
N	(mm)	minimum clearance (Table 4-10)
B_1	(mm)	protective barrier clearances for solid-panel walls (≥ 1800 mm high) with no openings. The dimension applies from the interior of the solid wall. $B_1 = N$
B_2	(mm)	protective barrier clearances with wire mesh, screens or solid walls (≥ 1800 mm high) ≤ 52 kv: $B_2 = N$ + 80 mm and protection class IP2X, > 52 kV: $B_2 = N$ + 100 mm and protection class IP1XB.
O_1, O_2	(mm)	protective barrier clearances for obstacles, such as rails, chains, wires, screens, walls (< 1800 mm high) for indoor installations: $O_1 = N$ + 200 mm (minimum 500 mm), for outdoor installations: $O_2 = N$ + 300 mm (minimum 600 mm). rails, chains and wires must be placed at a height of 1200 mm to 1400 mm. With chains or wires, the protective barrier clearance must be increased by the sag.
C, E	(mm)	protective barrier clearances at the outer fence (≥ 1800 mm high) with solid walls C = N + 1000 mm, with wire mesh, screens (mesh size ≤ 50 mm) E = N + 1500 mm
H	(mm)	minimum height of live parts (without protective barrier) above accessible areas H = N + 2250 mm (minimum 2500 mm)
H'	(mm)	minimum height of overhead lines at the outer fencing. ≤ 52 kv: H' = 4300 mm > 52 kV: H' = N + 4500 mm (minimum 6000 mm)
T	(mm)	minimum transport clearance for vehicles T = N + 100 mm (minimum 500 mm)

4.6.1 Minimum clearances and protective barrier clearances in power systems with rated voltages over 1 kV (DIN VDE 0101)

Minimum clearances

The clearances of live parts of a system from one another and from earthed parts must at least comply with Table 4-10. This table lists the minimum clearances for the maximum apparatus voltages assigned to the associated insulation levels as per DIN EN 60071-1 (VDE 0111 Part 1). The various insulation levels available should be selected in accordance with the insulation coordination as per this standard.

Table 4-10

Minimum clearances of live parts of a system from one another and from earth as per DIN VDE 0101 (HD 637 S1).

In the areas of 1 kV < U_m < 300 kV, the rated lightning impulse withstand voltage is the basis for the rating.

In the area of 1 kV < U_m < 52 kV

Nominal voltage	Maximum voltage for apparatus	Short-duration power frequency withstand voltage	Rated lightning impulse withstand voltage 1.2/50 µs U_{rB}	Minimum clearance (*N*) phase-to-earth and phase-to-phase	
				Indoor installation	Outdoor installation
U_n kV	U_m kV	kV	kV	mm	mm
3	3.6	10	20	60	120
			40	60	120
6	7.2	20	40	60	120
			60	90	120
10	12	28	60	90	150
			75	120	150
15 [1]	17.5	38	75	120	160
			95	160	160
20	24	50	95	160	
			125	220	
30	36	70	145	270	
			170	320	
36 [2]	41.5	80	170	320	
			200	360	

[1] These nominal voltages are not recommended for planning of new networks.
[2] This voltage value is not included in DIN EN 60071-1.

In the area of 52 kV < U_m < 300 kV

Nominal voltage U_n kV	Maximum voltage for apparatus U_m kV	Short-duration power frequency withstand voltage kV	Rated lightning impulse withstand voltage 1.2/50 µs U_{rB} kV	Minimum clearance (*N*) phase-to-earth and phase-to-phase mm
45 1)	52	95	250	480
66 2)	72.5	140	325	630
70 6)	82.5	150	380	750
110 3)	123	185 4)	450	900
		230	550	1100
132	145	185 4)	450	900
		230	550	1100
		275	650	1300
150 1)	170	230 4)	550	1100
		275	650	1300
		325	750	1500
220	245 5)	325 4)	750	1500
		360	850	1700
		395	950	1900
		460	1050	2100

1) These nominal voltages are not recommended for planning of new networks.
2) For U_n = 60 KV the values for U_n = 66 kV are recommended.
3) For U_n = 90 KV / U_n = 100 kV the lower values are recommended.
4) The values in this line should only be considered for application in special cases.
5) A fifth (even lower) level for 245 kV is given in EN 60071-1.
6) This voltage value is not included in DIN EN 60071-1.

In the area of U_m > 300 kV, the rated switching impulse withstand voltage is the basis for the rating

Nominal voltage	Maximum voltage for apparatus	Rated switching impulse withstand voltage phase-to-earth 250/2500 µs	Minimum clearance (*N*) phase-to-earth		Rated switching impulse withstand voltage phase-to-phase 250/2500 µs	Minimum clearance phase-to-phase	
			Conductor/ design	Bar/ design		Conductor	Bar/ conductor
U_n kV	U_m kV	U_{rS} kV	mm		kV	mm	
275	300	750	1600	1900	1125	2300	2600
		850	1800	2400	1275	2600	3100
380	420	950	2200	2900	1425	3100	3600
		1050	2600	3400	1575	3600	4200
480	525	1050	2600	3400	1680	3900	4600
		1175	3100	4100	1763	4200	5000
700	765	1425	4200	5600	2423	7200	9000
		1550	4900	6400	2480	7600	9400

Protective barrier clearances

As per DIN VDE 0105-100 (VDE 0105 Part 100), bare live parts are surrounded by a danger zone whose dimensions comply with the maximum values of the minimum clearances *N* given in Table 4-10. (Exception: U_m = 380 kV, both values are applicable there). Being in the vicinity of the outer limit of the danger zone and its penetration by body parts or objects are treated as work on electrically energized systems.

Protection against direct contact in installations as per DIN VDE 0101 (HD 637 S1) must therefore prevent such a hazardous proximity to live parts. In closed electrical premises, protection against accidental contact is sufficient. This can be done by installing protective barriers, e.g. solid walls, doors, screens, arc screens, rails, chains or ropes. An additional safety clearance is required corresponding to the possibilities of reaching through between the danger zone (minimum clearance *N*) and the protective barrier (Fig. 4-36).

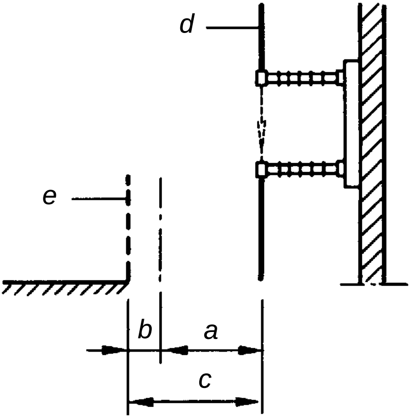


Fig. 4-36

Minimum clearance + safety clearance = protective barrier clearance:
a = minimum clearance,
b = safety clearance,
c = protective barrier clearance,
d = live part,
e = protective barrier

The position of abbreviations and explanations at the beginning of this section meets the requirements of DIN VDE 0101 (HD 637 S1) with reference to the minimum clearances from the various types of obstacles. Tables 4-11 and 4-12 list the maximum values of the assigned minimum clearances *N* listed in Table 4-10 and the associated protective barrier minimum clearances for all standard-nominal system voltages as guidance values.

Protection against accidental contact is then assured when live parts above walkways, where they are not behind barriers, are installed at the minimum heights *H* or *H'* given in Tables 4-11 and 4-12 (Fig. 4-37), where the greatest conductor sag must be considered. With transport paths, the height of the transport units may make it necessary to increase the height requirements.

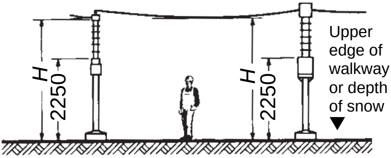
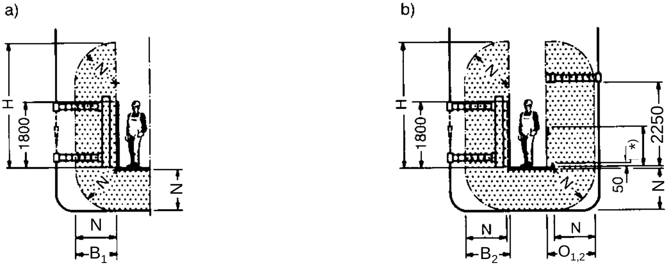


Fig. 4-37

Minimum heights of live parts over walkways

The upper edge of an insulator base must be at least 2250 mm over walkways if there is no protective barrier installed.

If the protective barrier clearance is partly or completely bridged by insulators, protection against direct contact must be assured by panel walls, panel doors, screens or screen doors with a minimum height of 1800 mm (Fig. 4-38). Where the insulators are installed above 2250 mm, rails, chains or wires are sufficient (Fig. 4-38 b).



Panel wall or panel door

Screen or screen door

Rail, chain or wire

Fig. 4-38

Minimum clearance bridged by insulators and design of walkways over live parts (dimensions in mm):

a) panel wall or panel door, b) screen or screen door, rail, chain or wire

**) min. 1200 mm, max. 1400 mm*

Walkways over live parts accessible during operation must be of solid plate. If rails, chains or wires are installed as protective barriers, they must be widened by the safety clearance and a minimum 50 mm high edge must be installed as a limit (see Fig. 4-38b). This is intended to prevent objects from falling on live parts.

4.6.2 Walkways and gangways in power installations with rated voltages over 1 kV (DIN VDE 0101)

The minimum width of walkways within outdoor installations should be a minimum of 1000 mm, the minimum width of gangways in indoor installations should be 800 mm. For safety reasons these dimensions must not be reduced. Service aisles behind metall-enclosed installations may be an exception; a minimum gangway width of 500 mm is permissible here.

The minimum width of walkways and gangways must not be reduced, not even by projecting parts such as fixed drives, control cabinets, switchgear truck in isolated position. When measuring the gangway width of indoor switchgear installations, the open position of the cubicle door must be taken into account. Cubicle doors must slam shut in the escape direction. When the door is open, the gangway width must still be 500 mm.

In the case of transport paths inside enclosed electrical premises, the dimensions for the transport unit must be agreed between the installer and the operator. The following regulations are applicable (Fig. 4-39):

Vehicles and similar may pass below live parts (without protection devices) or in their vicinity when

- the vehicle, even with its doors open, and its load do not come into the danger zone (minimum transport clearance *T* = *N* + 100 mm; minimum 500 mm) and
- the minimum height *H* of live parts over walkways is maintained.

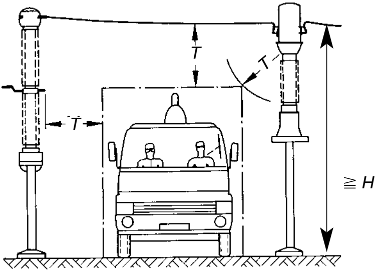


Fig. 4-39

Limit of the transport path in outdoor switchgear installations

Table 4-11

Minimum height and protective barrier clearances in outdoor installations as per DIN VDE 0101

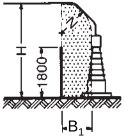
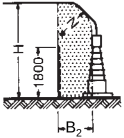
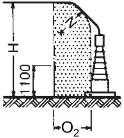
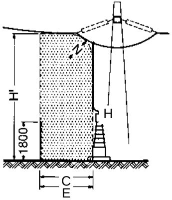
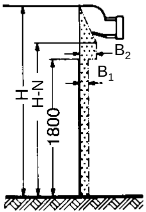
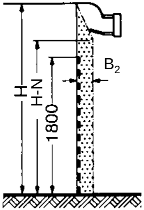
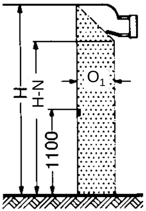
Nominal voltage	Maximum voltage for equipment	Minimum clearances *N* as per Table 4-10	Minimum height	Protective barrier clearances of live parts inside the installation			at the outer fence			Transport clearances as per Fig. 4-39
				 Solid-panel wall	 Wire mesh, screen	 Rail, chain, rope		Solid wall	Screen	
U_n kV	U_m kV	N mm	H mm	B_1 mm	B_2 mm	O_2 mm	H' mm	C mm	E mm	T mm
3	3.6	120	2 500	120	200	600	4 300	1 120	1 620	500
6	7.2	120	2 500	120	200	600	4 300	1 120	1 620	500
10	12	150	2 500	150	230	600	4 300	1 150	1 650	500
20	24	220	2 500	220	300	600	4 300	1 220	1 720	500
30	36	320	2 570	320	400	620	4 300	1 320	1 820	500
45	52	480	2 730	480	560	780	4 300	1 480	1 980	580
60	72.5	630	2 880	630	730	930	6 000	1 630	2 130	730
110	123	1 100	3 350	1 100	1 200	1 400	6 000	2 100	2 600	1 200
150	170	1 500	3 750	1 500	1 600	1 800	6 000	2 500	3 000	1 600
220	245	2 100	4 350	2 100	2 200	2 400	6 600	3 100	3 600	2 200
380	420	3 400	5 650	3 400	3 500	3 700	7 900	4 400	4 900	3 500
480	525	4 100	6 350	4 100	4 200	4 400	8 600	5 100	5 600	4 200
700	765	6 400	8 650	6 400	6 500	6 700	10 900	7 400	7 900	6 500

Table 4-12

Minimum height and protective barrier clearances in indoor installations as per DIN VDE 0101

Nominal voltage	Maximum voltage for equipment	Minimum clearances *N* as per Table 4-10		Minimum height	Protective barrier clearances of live parts	
				 Solid-panel wall	 Wire mesh, screen	 Rail, chain or rope
U_n kV	U_m kV	*N* mm	*H* mm	B_1 mm	B_2 mm	O_1 mm
3	3.6	60	2 500	60	140	500
6	7.2	90	2 500	90	170	500
10	12	120	2 500	120	200	500
20	24	220	2 500	220	300	500
30	36	320	2 570	320	400	520
45	52	430	2 730	480	560	680
60	72.5	630	2 880	630	730	830
110	123	1 100	3 350	1 100	1 200	1 300

4.6.3 Gangway widths in power installations with rated voltages of up to 1 kV (DIN VDE 0100 Part 729)

Specifications for the arrangement of switchgear installations

They apply for both type-tested and partially type-tested switchgear installations and switchboards

Control and service gangways

Switchgear installations and distribution boards must be configured and installed so the width and height of gangways are not less than the dimensions shown in Fig. 4-40. The exits must also be accessible in emergencies even when the panel and housing doors are open. These conditions are considered fulfilled if doors slam shut in the escape direction or open completely. The remaining minimum accesses may not be less than 500 mm.

Service and operational accesses with a length of more than 20 m must be accessible from both ends. Access from both ends is also recommended for gangways that are longer than 6 m. Exits must be placed so that the escape path inside a room of electrical or enclosed electrical premises is no more than 40 m long.

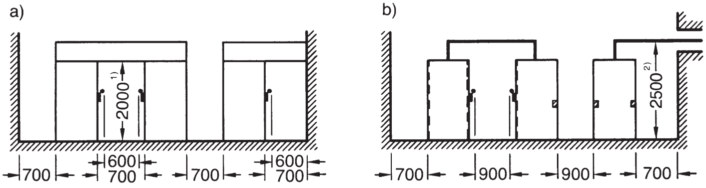


Fig. 4-40

Minimum dimensions for gangways

a) gangways for low-voltage installations with the minimum degree of protection IP 2X as per DIN 40 050.

b) gangways for low-voltage installations with degrees of protection below IP 2X.

1) minimum passage height under obstacles, such as barriers
2) minimum passage height under bare live parts

See Section 5.7 for degrees of protection

The values of DIN VDE 0101 as the dimension for gangways are applicable for the gangway widths where low-voltage and high-voltage device combinations are installed front-to-front in the same room (see Section 4.6.2).

Protective clearances DIN VDE 0660

Removable parts that are intended to prevent direct contact with live parts may only be removable with a tool or key.

Fig. 4-40a shows the minimum dimensions for closed installations. The minimum dimensions in Fig. 4-40b are applicable for open installations in locked electrical premisses only.

In the case of barriers, such as wooden railings, the gangway widths must meet the minimum dimensions for operating handles (900 or 700 mm) listed in Fig. 4-40b and also the additional minimum clearance of 200 mm between barrier and live part given in Fig. 4-41.

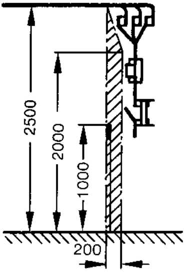


Fig. 4-41

Minimum dimensions for barriers

4.7 Civil construction requirements

The civil engineering consultant must determine a large quantity of information and details for the structural drawings required to design switchgear installations. The structural drawings are the basis for producing the structural design plans (foundation, shell and reinforcement plans, equipment plans). In Germany the Arbeitsgemeinschaft Industriebau e. V. (AGI) has issued the following datasheets:

datasheet J11 for transformer compartments
datasheet J12 for indoor switchgear
datasheet J21 for outdoor transformers
datasheet J31 for battery compartments

The structural information includes the following data:

- spatial configuration of the installation components
- aisle widths for control, transport and assembly
- main dimensions of the station components
- load specifications
- doors, gates, windows with type of opening and type of fire-preventive or fire-resistant design
- ceiling and wall openings for cables, pipes or conduits
- information on compartments with special equipment
- information on building services
- ventilation, air-conditioning information
- floors including steel base frames
- foundation and building earth switches
- lightning protection
- drainage.

The following design details must be observed:

Fig. 4-40a shows the minimum dimensions for closed installations. The minimum dimensions in Fig. 4-40b are applicable for open installations in locked electrical premisses only.

In the case of barriers, such as wooden railings, the gangway widths must meet the minimum dimensions for operating handles (900 or 700 mm) listed in Fig. 4-40b and also the additional minimum clearance of 200 mm between barrier and live part given in Fig. 4-41.

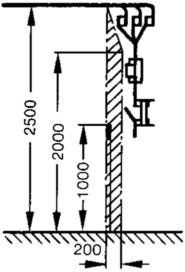


Fig. 4-41

Minimum dimensions for barriers

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- ceiling and wall openings for cables, pipes or conduits
- information on compartments with special equipment
- information on building services
- ventilation, air-conditioning information
- floors including steel base frames
- foundation and building earth switches
- lightning protection
- drainage.

The following design details must be observed:

4.7.1 Indoor installations

When planning indoor installations (substation buildings and switchboard rooms), in addition to configuration to meet operational requirements, ensure that the selected compartments are not affected by groundwater and flooding and are also easily accessible for control and transport equipment and also for firefighting. The current applicable construction codes, regulations and directives must be observed. Construction laws include regulations that must be observed and in addition, the generally accepted engineering requirements apply.

Walls, ceilings and floors must be dry. Pipes carrying liquids, steam and flammable gases must not be laid in, above or under rooms intended for switchgear installations. If, however, necessary, structural measures for protection of the electrical installations are required.

The clearance dimensions of an equipment room depend on the type, size and configuration of the switchbays, on their number and on the operating conditions. The required minimum aisle widths and safety clearances are specified in DIN VDE 0101 or DIN VDE 0105 Part 1.

The exits must be laid out so the escape route from the installation is no more than 40 m for rated voltages over 52 kV and no more than 20 m for rated voltages of up to 52 kV. A servicel aisle more than 10 m long must have two exits, one of which may be an emergency exit.

The interiors of the switchgear house walls must be as smooth as possible to prevent dust from accumulating. The brickwork must be plastered, but not ceilings in the area of open installations, so switchgear parts are not subject to falling plaster.

The floor covering must be easy to clean, pressure-resistant, non-slippery and abrasion-proof (e.g. stoneware tiles, plastic covering, gravel set in concrete with abrasion-resistant protective coating to reduce dust formation); the pressure load on the floor from transport of station components must be considered.

Steps or sloping floor areas must always be avoided in switchgear compartments.

Opening windows must be positioned so they can be operated. In open areas, this must not place personnel in danger of contacting live parts.

Windows in locked electrical premises must be secured to prevent access. This condition is considered to be met by one of the following measures:

- The window consists of unbreakable materials.
- The window is barred.
- The bottom edge of the window is at least 1.8 m above the access level.
- The building is surrounded by a fence at least 1.8 m high.

Ventilation and pressure relief

The compartments should be ventilated sufficiently to prevent the formation of condensation. To prevent corrosion and reduction of the creepage distance by high humidity and condensation, it is recommended that the typical values for climate stress listed in DIN VDE 0101 be observed in switchgear rooms. The following apply:

- the maximum relative humidity is 95 % in the 24 hour average,
- the highest and lowest ambient temperature in the 24 hour average is 35 °C and – 5 °C with “Minus 5 Indoor” class.

In areas of high pollution, the compartments must be kept at a low level of overpressure with filtered air. The air vents required for this must prevent the entry of rain, spray water and small animals. Sheetmetal covers must also be installed over the vents at heights to about 2.50 m above ground. See Sections 4.4.2 and 4.4.3 for additional information on ventilation.

SF_6 installations

For SF_6 installations, it is recommended that the building be extended by the length of one bay for installation and renovation purposes and that a hoist system with a lifting capacity equal to the heaviest installation components be installed.

Natural cross-ventilation in above-ground compartments is sufficient to remove the SF_6 gas that escapes because of leakage losses. This requires about half of the required ventilation cross section to be close to the floor.

It must be possible to ventilate compartments, conduits and the like under compartments with SF_6 installations.

Mechanical ventilation is not necessary so long as the gas content of the largest contiguous gas space including the content of all connected SF_6 tanks (based on atmospheric pressure) does not exceed 10% of the volume of the compartment receiving the leakage gas.

Mechanical ventilation may be required in the event of faults with arcing.

Reference is also made to the requirement to observe the code of practice "SF_6 Installations" (Edition 10/92) of the professional association for precision engineering and electrical engineering (BGFE, Germany).

Pressure relief

In the event of an accidental internal arc in a switchgear installation, significant overpressure occurs in switchgear compartments, in particular in those with conventional air insulation with high arc lengths. Damage to walls and ceilings caused by unacceptably high pressure load can be prevented by appropriate pressure relief vents. Floor plates must be properly secured. Pressure relief facilities in switchgear rooms should meet the following criteria:

– they should normally be closed to prevent the entry of small animals, snow, rain etc.; light, self-actuating opening of the facility at an overpressure of less than 10 mbar;
– pressure relief in an area where there are usually no personnel;
– no parts should become detached during pressure relief.

Cable laying

The options listed below are available for cable laying:

Tubes or cable conduit forms, covered cable conduits, cable conduits accessible as crawl space and cable floors, accessible cable levels.

Tubes or cable conduit forms are used to lay single cables. To avoid water damage when laid outside they should be sloped. The bending radius of the cable used should be observed for proper cable layout.

Covered cable conduits are intended when several cables are laid together, with the width and depth of the conduit depending on the number of cables. The covers of the conduits should be fireproof, non-slip and non-rattling and should not have a raised edge. They must able to take the weight of transport vehicles carrying electrical equipment during installation. The conduits should be placed before the compartments to allow cable work to be done at any time without having to disconnect equipment.

Cable conduits accessible as crawl spaces and cable floors should be at least 1.50 m wide; the overhead clearance should not be less than 1.00 m to allow for any cable crossings. Access and ventilation openings and the required cable accesses must be taken into account.

Accessible cable conduits and cable levels are required for a large accumulation of cables in larger installations. A height of 2.10 m (to the lower edge of the support girder) is recommended to provide space for the required lighting and suspended cables. The cables can be laid on cable racks and also fastened to supports using cable clamps. Escape paths (emergency exits) must be available. Access doors must open outwards, should be airtight when closed, must be fire-resistant and have a panic lock.

Auxiliary cables are laid on separate cable racks or on supports beneath the ceiling.

The VDEW directives "Empfehlungen für Maßnahmen zur Herabsetzung von transienten Überspannungen" (recommendations for measures to reduce transient overvoltages) in secondary lines are particularly important in the selection and laying of cables; for this reason power cables should be laid apart from control cables. Separate conduits should be provided for cable laying where possible.

The cable conduits, particularly for the power cables, must be dimensioned to provide sufficient space for the heat from power dissipation.

4.7.2 Outdoor installations

Foundations

Foundations for portals, supports (for equipment) and similar and also for transformers are constructed as simple concrete foundations.

As well as the static loads, they must be able to resist operational loads, such as the effects of switching forces, short-circuit forces, tension caused by temperature variations and wind and ice load. The foundation types, such as slab or individual, depend on the soil quality or other installation-specific criteria.

Foundation design is determined by the installation structure and the steel structure design.

The base of the foundation must be frost-free, i.e. at a depth of around 0.8 – 1.2 m. The foundations must have the appropriate openings for earth wires and any necessary cables.

The relevant regulations for outdoor construction specified in DIN VDE 0210 apply for the mechanical strength analyses.

Access roads

The type, design, surveying and layout of access roads is determined by the purpose of the roads and the installation design:

- for transport of switchgear (up to approx. 123 kV) roads are provided only in specially extended installations, (otherwise possible for higher voltage levels) min. 2.50 m wide and with a load rating corresponding to the maximum transport component;
- for transport of transformers, min. 5 m wide, load capacity corresponding to the transport conditions. When laying out the road, the radius of the curves should be suitable for multi-axle transport vehicles.

When planning the roads, the required cable conduits, such as for earthing conductors or cable connections that cross the road, must be taken into account.

The height of live parts over access roads depends on the height of the transport units (this must be agreed between the contractor and the operator) and the required minimum clearances T as shown in Fig. 4-39.

Design and rating must be suited for transport of the heaviest station components.

Cable trenches

Covered cable trenches are planned for cables in outdoor installations. In large installations with conventional secondary technology, an accessible cable trench with single or double-sided cable racks may be required for most of the control cables.

Main trenches should not be more than 100 cm wide because of the weight of the cover plates. The depth depends on the number of cables. Cable racks are installed on the sides.

Branch ducts, which can be designed as finished parts, run from the control cabinets or relay compartments to the high-voltage equipment. The upper part of the main conduits and branch ducts is placed a little above ground level to keep the trench dry even in heavy rain.

Cables to individual devices can also be laid in prefabricated cable ducts or directly in the ground and covered with bricks or similar material.

Otherwise refer to the information given in Section 4.7.1 on laying cables as applicable. For preferred cable trench designs, see Section 11.3.2 Fig. 11-17.

4.7.3 Installations subject to special conditions

Electrical installations subject to special conditions include:

- installations in equipment rooms that are subject to the German Elt-Bau-VO,
- installations in enclosed design outside locked electrical premises,
- mast and tower substations to 30 kV nominal voltage,
- installations in premises subject to fire hazard.

Installations that are subject to the Elt-Bau-VO are subject to the implementation regulations for Elt-Bau-VO issued by the various German states with respect to their structural design. This particularly covers structural measures required for fire prevention.

The other installations subject to special conditions are subject to the structural requirements as in Section 4.6.1.

4.7.4 Battery compartments

The following specifications must be observed for the structural design:

The *layout of the compartments* should be such that they are easily accessible for transporting batteries. In addition, the compartments should be proof against groundwater and flooding, well ventilated – either natural or forced ventilation –, well lit, dry, cool, frost-free and free from vibrations. Temperature variations and direct solar radiation should be avoided. The room temperature should not fall below 0 °C and not exceed 35 °C so far as possible.

The *floor* must be rated for the anticipated load, including any point loads that might occur. It must be resistant to the effects of electrolytes and should be sloping. Very large compartments may require the installation of a drain for cleaning the floor. This will require a sloping floor leading to the drain. A neutralization trap must be installed between the drain outlet and the sewer system. The ground leakage resistance of the soil must comply with DIN 51953 $\leq 10^8\ \Omega$.

Ceilings and walls must be smooth and abrasion-resistant; they should be painted with an acid-resistant coating that does not release toxic vapours.

Windows are not required in a battery room with forced ventilation. If there are any, they should be resistant to corrosion by electrolyte. If the compartment has natural ventilation, aluminium windows should not be used. The windows should have vents that cannot be closed to ensure a continuous circulation of air.

The VDE standards do not require *gas or air locks*. However, if they are planned, they must be ventilated and fitted with a water connection and drain, unless these are already provided in the battery room. The outlet must pass though a neutralization system.

Battery compartments must have *natural* or forced ventilation.

The fresh air should enter near ground level and be sucked out below the ceiling so far as possible. This ensures that the fresh air passes over the cells.

Natural ventilation is preferable. This can be done with windows, air ducts or chimneys. Air ducts must be of acid-resistant material. Chimneys must not be connected to any sources of fire because of the danger of explosion.

With forced ventilation, the fan motors must be designed for protection against explosion and acid-resistant or they must be installed outside the hazard zone. The fan blades must be manufactured of material that does not take a static charge and does not generate sparks on contact with foreign bodies.

The forced ventilation should include extractor fans. The installation of forced-air fans is not advisable for reasons of ventilation technology.

As per DIN VDE 0510 Part 2, the ventilation is considered satisfactory when the measured air-flow volume complies with the numerical comparison below. This information is applicable for ventilation of rooms, containers or cabinets in which batteries are operated:

$$Q = 0{,}05 \cdot n \cdot I \ [\mathrm{m^3/h}]$$

where n = number of cells,

I = current value in A as per DIN VDE 0510 that initiates the development of hydrogen.

The requirements for the installation of batteries are dealt with in Section 15.3.5.

Additional information on the subject of ventilation can be found in Section 4.4.3.

Electrical equipment should meet the degree of protection IPX2 as per DIN 40050 as a minimum.

4.7.5 Transformer installation

The transformers and switchgear compartments should be configured for easy access, because the power supply components in the transformer substation must be quickly and safely accessible from outside at all times.

The compartment dimensions must be determined from the point of view of temperature rise, noise generation, transmission of structural noise, fire hazard and replacement of equipment. The structure must be planned subject to these criteria. See Section 1.2.6 for information on measuring noise and noise reduction.

Oil-insulated transformers may be installed in large buildings only with specified structural and electrical requirements satisfied.

Indoor and outdoor oil-insulated transformers do not require special protection against environmental influences. Cast-resin transformers in the IP00 design (without housing) may be installed in dry indoor rooms. Outdoor installation of cast-resin transformers requires a housing complying with the degree of protection of minimum IP23 with a roof protecting them against rain.

The requirements of DIN VDE 0100, 0101 and 0108 must be observed for the installation and connection of transformers. The installation of surge arrestors is recommended as protection against overvoltages caused by lightning and switching operations (Section 10.6).

If transformers are installed in indoor compartments for natural cooling, sufficiently large cooling vents above and below the transformers must be provided for venting the heat dissipation. If natural ventilation is not sufficient, forced ventilation is required, see Section 4.4.2, Fig. 4-28.

In detail, the following requirements for installation of transformers must be observed:

- clearances
- safety distances
- design of high-voltage connections
- accessibility for operation and maintenance
- transport paths
- cooling/ventilation (see Section 4.4.3)
- fire prevention (see Section 4.7.6)
- auxiliary equipment
- setup
- withdrawal for future replacement of transformers.

For construction details see AG datasheet J21, Arbeitsgemeinschaft Industriebau (industrial construction workgroup).

Catchment pans, sumps and sump groups must be installed under transformers with liquid insulation (cooling types O and L) for fire and water protection. Their design must prevent the insulation fluid from leaking into the soil.

Connection lines between catchment pans and sumps must be designed to prevent insulation fluid from continuing to burn in the collection sumps (longer pipes or gravel system).

Catchment or collection sumps must be large enough to catch water flowing in (rain, extinguishing and washing water) as well as insulation fluid.

Water flows must be directed to an oil separator, or otherwise it must be possible to pump out the contents of the catchment sump.

The local water authority may allow concessions in accordance with DIN VDE 0101 for specified local conditions (soil characteristics) and transformers with less than 1000 l of insulation fluid .

Fig. 4-42 shows the preferred configuration of oil catchment equipment.

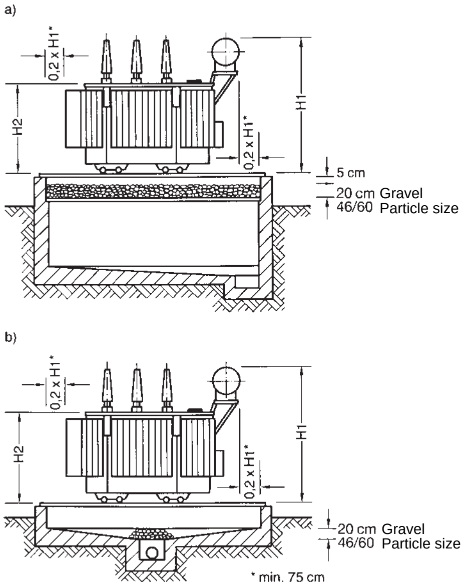


Fig. 4-42

Configuration of oil sumps a) and oil catchment pans b)

4.7.6 Fire prevention

The possibility of fire in switchgear and transformer rooms cannot be excluded. The seriousness of the fire risk depends on the type of installation, the structure, the installation components (devices, apparatus etc.) and on the fire load.

Targeted structural fire prevention measures (e.g. small fire compartments, fire-reducing and fire-resistant barriers, cable and conductor compartmentalization) can significantly reduce the risk of a fire spreading.

Fires caused by electrical equipment may occur due to: short-circuit arcing, unacceptable temperature rise caused by operational overload or short-circuit currents.

Fire load, effects of fire

The fire load corresponds to the theoretical energy that can be released from all flammable material with reference to a defined area. It is expressed in kWh per m^2 of fire compartment area. Data from the association of insurers (VdS) provides guidance values on the combustion heat of cables and wires.

Measures

The following measures for protection of installations emphasize cable compartments, cable ducts and transformers:

a) partitioning of cable feeds by ceilings and walls, see Fig. 4-43

b) partitioning of cable infeeds in switchgear cubicles or bays, see Fig. 4-44

c) cable sheathing – insulation layer formation

d) fire-resistant sheathing of cable racks and supports

e) compartmentalization of cable ducts, use of small fire compartments, see Fig. 4-45, installation of fire-protection valves in inlet and outlet air ducts

f) sprinkler systems in buildings

g) installation of venting and smoke removal systems

h) fire-protection walls for transformers, see Fig. 4-46

i) oil catchment systems for transformers, see Section 4.7.5, Fig. 4-42

k) water spray extinguishing systems for transformers, see Fig. 4-47, for preventing fires in leaked flammable insulation and cooling fluids

l) fire alarms, see Section 15.4.4.

If cables and conductors are run through walls and ceilings with planned fire resistance class (e.g. F 30, F 90), the openings must be closed with tested cable barrier systems in accordance with DIN 4102, Part 9, corresponding to the fire-resistance class (e.g. S 30, S 90) of the component.

Functional endurance of cable and wiring systems

On the basis of DIN VDE 0108 and in accordance with DIN 4102 Part 12, there are special fire-prevention requirements for the functioning of cables and wires for “buildings of special types or usage”. Various German states have introduced corresponding administrative regulations covering the above structural standards. These requirements specifically cover government-supported safety equipment.

DIN 4102 is divided into the functional classes E 30, E 60 and E 90 corresponding to the fire resistance class. It can be satisfied by laying cables under plaster, in tested cables ducts or by the electrical lines themselves.

The functional duration for government-supported and required safety equipment must be at least:

- 30 minutes with
    - Fire alarm systems
    - Installations for alarming and distributing instructions to visitors and employees
    - Safety lighting and other emergency electric lighting, except for branch circuits
    - Lift systems with evacuation setting
- 90 minutes with
    - Water pressure-lifting systems for water supply for extinguishing fires
    - Ventilation systems for safety stairwells, interior stairwells
    - Lift shafts and machinery compartments for firefighting lifts
    - Smoke and heat removal systems
    - Firefighting lifts

Escape routes

All installations must have escape routes leading outside. They must be protected by fire-preventive and fire-resistant structures. The safest escape route length in accordance with the German sample construction code is 40 m or in accordance with the workplace regulations 35 m.

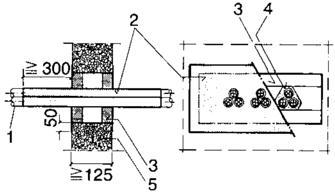


Fig. 4-43

Partition construction
of a cable feed for wall or ceiling:

1 cable, 2 sheath of fire-resistant insulation material, 3 mineral fibre plates, 4 mineral wool stuffing, 5 firewall

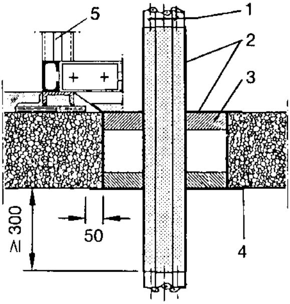


Fig. 4-44

Partition construction
of a switchgear cubicle infeed:

1 cable, 2 sheath of fire-resistant insulation material, 3 mineral fibre plates, 4 fire ceiling, 5 base frame of cubicle

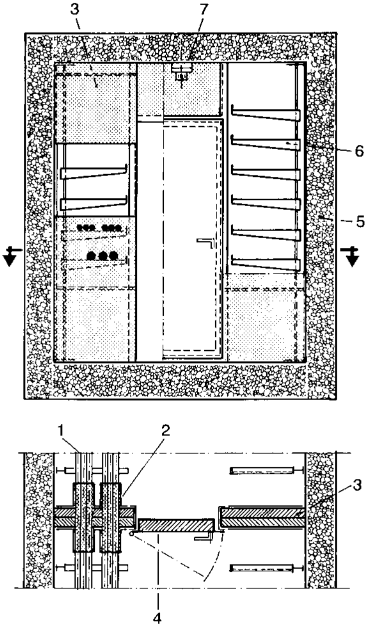
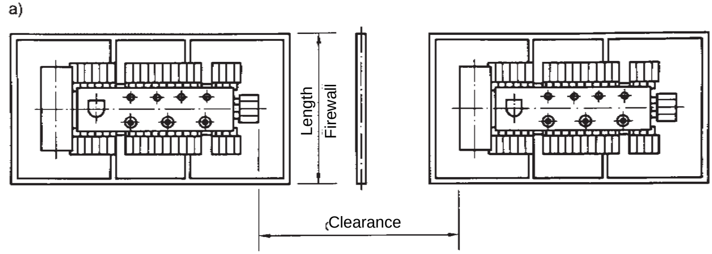
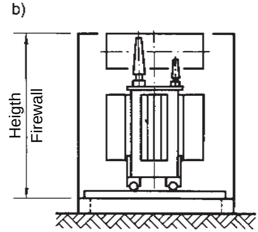


Fig. 4-45

Partition construction
of an accessible cable duct:

1 cable, 2 sheath of fire-resistant insulation material, 3 mineral fibre plates, 4 fire-protection door, 5 concrete or brickwork, 6 cable rack, 7 smoke alarm





c)

Transformer output over	Clearances less than
1 MVA	3 m
10 MVA	5 m
40 MVA	10 m
200 MVA	15 m

Fig. 4-46

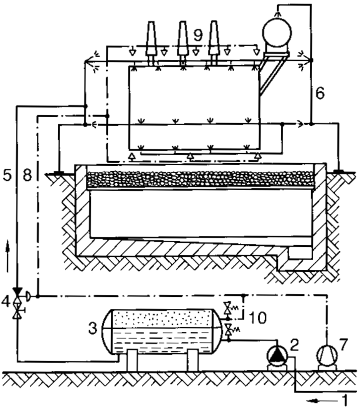
Configuration of firewall for transformers:

a) Top view b) Side view c) Typical value table for installation of firewalls, dependent on transformer output and clearance

Fig. 4-47

Spray fire-extinguishing system (sprinkler) for a transformer with the following functional elements:

1 *Water supply*
2 *Filler pump*
3 *Air/Water pressure vessel*
4 *Valve block*
5 *Water feed*
6 *Pipe cage with spray nozzles*
7 *Compressor*
8 *Detector line*
9 *Pipe cage with detectors*
10 *Safety valves*



4.7.7 Shipping dimensions

Table 4-13

Container for land, sea and air freight, general data.

Type (' foot, " inch) ft. in. weight	External dimensions			Internal dimensions – minimum dimension –			Clearance dimension of door – minimum –		Volume	Weights permitted Total weight 1)	Tare	max. cargo weight
	Length mm	Width mm	Height mm	Length mm	Width mm	Height mm	Width nm	Height mm	m^3	kg	from to kg	from to kg
20' × 8' × 8'	6 058	2 438	2 438	5 935	2 370	2 248	2 280	2 135	31.6	20 320	2 030 1 950	18 290 18 370
20' × 8' × 8'6"	6 058	2 438	2 591	5 880	2 330	2 340	2 330	2 270	32.7	20 320	2 450 2 080	17 870 18 240
40' × 8' × 8'6"	12 192	2 438	2 591	12 010	2 330	2 365	2 335	2 280	66.4	30 480	4 200 3 490	26 280 26 990
40' × 8' × 9'6" 2) (High Cube)	12 192	2 438	2 895	12 069	2 773	2 709	2 335	2 587	77.5	30 480	3 820	26 660

1) Observe permissible load limit for road and rail vehicles.

2) Observe overheight for road and rail transport.

5 Protective Measures for Persons and Installations

5.1 Electric shock protection in installations up to 1000 V as per DIN VDE 0100

5.1.1 Protection against direct contact (basic protection)

The danger of touching live parts is particularly great with this kind of switchgear, because in locked electrical premises this equipment does not require any electric shock protection by an enclosure (IP 00), or the electric shock protection can be become ineffective on opening the cubicle doors.

According to DIN VDE 0100-410 (VDE 0100 Part 410), protection against direct contact is always required regardless of the voltage. Exception: the voltage is generated in accordance with the regulations for extra low voltage SELV and does not exceed 25 V AC or 60 V DC (cf. Section 5.1.3!).

Protection against direct contact is assured by insulating, enclosing or covering the live parts and is essential for operation by electrically untrained personnel. This kind of protection should be chosen wherever possible. However, with switchgear, intervention is sometimes required to restore things to the normal conditions, e.g. actuate miniature circuit-breakers or replace indicator lamps, in areas where there is only partial protection against direct contact. Such activities may only be carried out by at least electrically instructed personnel. DIN 57106-100 (VDE 0106 Part 100) specifies the areas in which controls for restoring normal conditions may be installed (Fig. 5-1), and the clearances to bare live parts required in front of the controls (protected zone, Fig. 5-2). The rules for minimum clearance do not apply in the case of finger-proof equipment (Fig. 5-3) and for devices that cannot be contacted by the back of the hand (Fig. 5-4), within the protected zone or when mounted in substation doors.

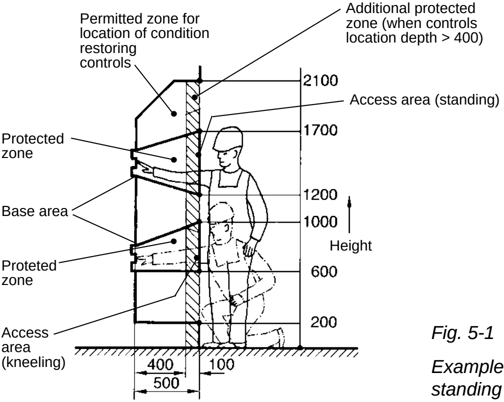


Fig. 5-1

Examples for protected zones for standing or kneeling positions

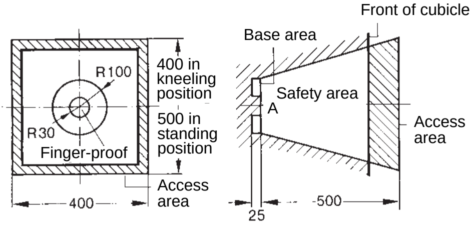
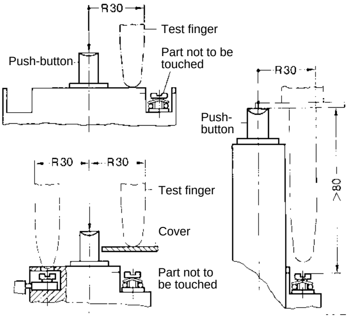


Fig. 5-2

Example for protected zone for push-button operation (A)



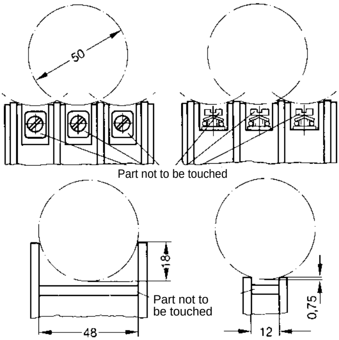


Fig. 5-3

Examples for finger-proof arrangement of shock-hazard parts

Fig. 5-4

Examples for arrangement of shock-hazard parts to prevent contact with the back of the hand

The standard VDE 0106 Part 100 applies for all switchgear, including those in locked electrical premises. It does not apply for installations that are operated at voltages of up to 50 V AC or 120 V DC, so long as these voltages are not generated by equipment such as autotransformers, potentiometers, semiconductor elements or similar.

Provisions of this standard do not apply for work on switchgear in accordance with DIN EN 50110-1 (VDE 0105 Part 1), and therefore also not to the replacement of HRC fuse links.

Additional protection in case of direct contact

The purpose of additional protection is to ensure that potentially fatal currents cannot flow through the body in the event of direct contact of live parts. The additional protection is provided by the use of highly sensitive residual current protective devices (RCDs), each with a rated fault current ≤ 30 mA. DIN VDE 0100 Part 701ff specifies which protection device is to be used in which special installations. The additional protection in case of direct contact is not permissible as the sole form of protection; the requirements for protection against direct contact must always be met.

5.1.2 Protection in case of indirect contact (fault protection)

The hazard from touch voltages in the event of a malfunction (earth fault to frame) can be avoided as per DIN VDE 0100-410 (VDE 0100 Part 410) by several different protection concepts. The two concepts that are most commonly used in switchgear installation design are discussed here.

Protection by automatic tripping of the power supply

The following are specified as limit values for the touch voltage:

50 V AC
120 V DC

Lower values are required for certain applications.

Protection by tripping ensures that in the event of faults, hazardous touch voltages are automatically prevented from persisting by protection devices. These protective measures require coordination of the earthing of the system and the protection device (Fig. 5-5), which has to trip the faulty component within the set break time (between 0.1 s and 5 s) (Table 5-1). The metallic enclosures of the equipment must be connected with a protective conductor.

Protection by tripping requires a main equipotential bonding conductor, which connects all conductive parts in the building, such as main protective conductor, main earthing conductor, lightning protection earth, main water and gas pipes and other metallic pipe and building construction systems.

If only one fault occurs in the IT system (enclosure or earth fault), tripping is not necessary if the break conditions listed in Table 5-1 are not reached. In the event of a second fault, depending on the earthing of the enclosure, the break conditions apply as in the TT system (single or group earthing) or the TN system (one common protective conductor).

Supplementary equipotential bonding may be required if the specified break conditions cannot be reached or if it is specified in the standards for special installations, e.g. rooms with a shower or bath. All metallic enclosures of equipment, which can be touched simultaneously, protective conductors, other conductive parts and the concrete-reinforcing steel rods (so far as possible) have to be included in the supplementary equipotential bonding system.

TN system

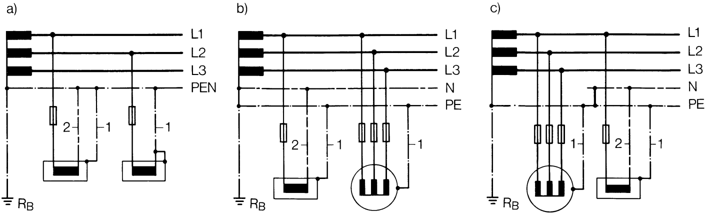


Fig. 5-5 (Part 1)

Overview of the types of earthing for systems:

a) TN-C system: Neutral conductor and protective conductor combined;
b) TN-S system: Neutral conductor and protective conductor separate;
c) TN-C-S system: Combination of layouts a) and b).
1 wire colour green/yellow, 2 wire colour light blue.

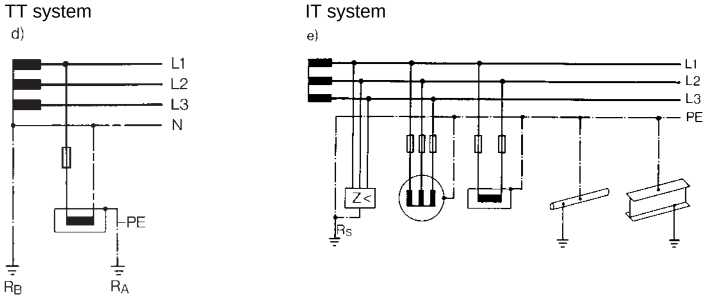


Fig. 5-5 (Part 2)

Overview of the types of earthing for systems:

d) TT system, neutral conductor and protective conductor (exposed conductive part) separately earthed, e) IT system, system not earthed or high-resistance earthed, metallic enclosures, earthed in groups or individually, Z<: insulation monitoring device.

Table 5-1

Coordination of the type of earthing of the systems and protection devices

System	Protection devices	Application	Break condition
TN-S and TN-C-S	Overcurrent Fault current		$Z_S \cdot I_a \leq U_0$
TN-C	Overcurrent		
TT	Overcurrent Fault current Insulation monitoring	not always	$R_A \cdot I_a \leq 50$ V
IT	Overcurrent Fault current Insulation monitoring	not always	$R_A \cdot I_d \leq 50$ V

Z_S Impedance of fault loop
Note: Z_S can be found by calculation, measurement or with network analyser.

R_A Earth resistance of earth of metallic enclosures

I_a Current automatically tripping the protection device within

- 0.4 s at rated alternating voltage (effective) ≤ 230 V
- 0.2 s at rated alternating voltage (effective) ≤ 400 V
- 0.1 s at rated alternating voltage (effective) > 400 V

in circuits supplying via socket-outlets or fixed connections handheld devices of safety class I or portable equipment of safety class I. In all other current circuits a break time up to a maximum of 5 s can be agreed.

When a residual current protective device is used, I_a is the rated fault current $I_{\Delta N}$.

I_d Fault current in the event of the first fault with negligible impedance between a phase and the protective conductor or a metallic enclosure connected to it. The value of I_d considers the leakage currents and the total impedance of the electrical installation against earth.

U_0 Rated voltage (r.m.s.) against earth.

The following are used as protection devices:

Overcurrent protection devices
- low-voltage fuses according to VDE 0636 Part 10 ff.
- miniature fuses according to VDE 0820 Part 1 ff.

Miniature circuit-breakers according to VDE 0641 Part 2 ff.
Circuit-breaker according to VDE 0660 Part 100 ff.
Residual current-operated circuit-breakers according to VDE 0664 Part 10 ff.
Insulation monitoring device according to VDE 0413 Part 2, Part 8, Part 9.

In TN or TT systems, the total earthing resistance of all functional earths should be as low as possible to limit the voltage rise against earth of all other conductors, particularly the protection or PEN conductor in the TN network if an earth fault occurs on a phase. A value of 2 Ω is considered sufficient in TN systems. If the value of 2 Ω cannot be reached in soils of low conductivity, the following condition must be met:

$$\frac{R_B}{R_E} \leq \frac{50\ \text{V}}{U_0 - 50\ \text{V}}$$

R_B total earthing resistance of all parallel earths of the system

R_E assumed lowest earth resistance of conductive parts not connected to a protective conductor over which an earth fault can occur

U_0 rated voltage (r.m.s.) against earth.

In the TT system, the implementation of overcurrent protection devices is problematic because of the required very low continuous earth resistance. In the IT system an earth resistance of ≤ 15 Ω is generally sufficient when all metallic enclosures of equipment are connected to a common earthing system.

If a supplementary equipotential bonding is required in an electrical installation, its effectiveness must be verified by the following condition:

$$R \leq \frac{50\ \text{V}}{I_a}$$

R Resistance between metallic enclosures and other conductive parts that can be touched at the same time.

I_a Current that effects the automatic tripping of the protection device within the set time.

When a residual current-operated device is used, I_a is the rated fault current $I_{\Delta N}$.

Protection by equipment of safety class II

Another common measure, against the occurrence of hazardous touch voltages that is also used in switchgear installation design is protection by equipment of safety class II (equipment of safety class II as per DIN VDE 0106 Part 1) or by type-tested assemblies with total insulation (type-tested assemblies with total insulation as per DIN EN 60439-1 (VDE 0660 Part 500)) or by application of an equivalent insulation.

Equipment of safety class II and type-tested assemblies with total insulation are identified with the symbol ⧈ as per DIN 40014.

Conductive parts within the enclosure must not be connected to the protective conductor, otherwise it will be a device in safety class I. If protective conductors must be routed through insulated equipment, they must be insulated like live conductors.

Exceptions

Measures for protection in case of indirect contact are not required for the following equipment:

- lower parts of overhead line insulators (except when they are within reach)
- steel towers, steel-concrete towers, packing stands
- equipment that is not likely to come into contact by any part of the human body because of its small dimensions (e.g. 50 mm x 50 mm) or because of its configuration,
- metal enclosures for protection of equipment of safety class II or equivalent.

5.1.3 Protection by extra low voltage

As per DIN VDE 0100-410 (VDE 0100 Part 410) the use of the SELV and PELV extra low-voltage systems (Fig. 5-6) can offer protection in case of direct and indirect contact. Extra low voltages in accordance with these specifications are AC voltages ≤ 50 V and DC voltages ≤ 120 V. Corresponding specifications for current circuits with limited discharge energy (≤ 350 m J) are in preparation.

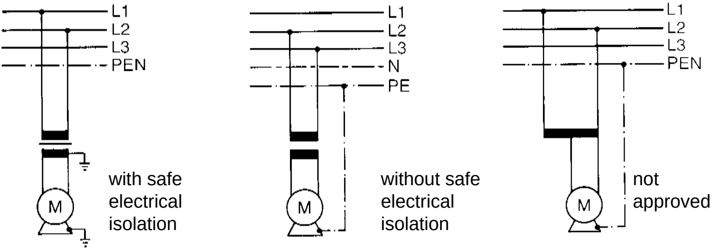
Current sources for supplying extra low-voltage systems of the SELV and PELV types must be safely separated from the infeed system, e.g. as isolating transformer with shielding (DIN EN 60742 (VDE 0551) or as motor generators (DIN VDE 0530), but not as autotransformer, potentiometer and the like.

The SELV extra low voltage, apart from secure separation of the current circuits, requires that neither live parts nor metallic enclosures must be earthed. Protective measures to prevent direct contact, such as barriers, enclosures or insulation are not necessary here if the rated voltage does not exceed AC 25 V and DC 60 V.

Live parts and metallic enclosures may be earthed with the PELV extra low voltage. Protective measures against direct contact are also not necessary here with rated voltages below AC 25 V and DC 60 V, if metallic enclosures, which can be touched simultaneously, and other conductive parts are connected to the same earthing system.

The FELV extra low voltage is supplied by a power source without a safe isolation. Earthing the current circuits is permitted. Metallic enclosures must be connected to the protective conductor on the primary side of the power source. Protection against direct contact and in case of indirect contact is generally required (DIN VDE 0100-470 (VDE 0100 Part 470).

Auxiliary circuits in switchgear installations are often operated with extra low voltage. With reference to protection in case of indirect contact, the systems with safe isolation (SELV, PELV) are to be recommended, particularly with small direct cross sections, because in contrast to the FELV system, no additional measures are required. Consistent safe isolation from the supply network must be assured by the selection of the equipment in the entire current circuit.



extra low voltages SELV and PELV

extra low voltage FELV

autotransformer

Fig. 5-6 Power sources for extra low voltages

5.1.4 Protective conductors, PEN conductors and equipotential bonding conductors

Requirements as specified by VDE 0100 Part 540

The following may be used as protective conductors:

- conductors in multicore cables and wires,
- insulated or bare conductors in the same covering together with phase conductors and the neutral conductor, e.g. in pipes or electrical conduits,
- permanently installed bare or insulated conductors,
- metallic enclosures, such as sheaths, shields and concentric conductors of cables and wires,
- metal pipes or other metallic coverings, such as electrical conduits, housings for busbar systems,
- external conductive parts,
- mounting channels, also when carrying terminals and/or devices.

If structural components or external conductive parts are used as protective conductors, their conductivity must correspond to the specified minimum cross section, and their continuous electrical connection must not be interrupted by temporary structures or affected by mechanical, chemical or electrochemical influences. Guy wires, suspension wires, metal hoses and similar must not be used as protective conductors.

The cross sections for protective conductors must be selected from Table 5-2 or calculated by the following formula for break times up to max. 5 s

$$S = \frac{\sqrt{I^2 t}}{k}$$

Here:

S minimum cross section in mm^2,

I r.m.s. value of the fault current in A, which can flow through the protective device in the event of a dead short circuit,

t response time in s for the tripping device,

k material coefficient, which depends on
  - the conductor material of the protective conductor,
  - the material of the insulation,
  - the material of other parts,
  - the initial and final temperature of the protective conductor, see Tables 5-3 and 5-4.

PEN conductors, a combination of protective and neutral conductors, are permitted in TN networks if they are permanently laid and have a minimum conductor cross section of 10 mm^2 Cu. The protective conductor function has priority with PEN conductors. If the concentric conductor of cables or wires is used as a PEN conductor, the minimum cross section can be 4 mm^2 Cu if all connections and joints are duplicated for the course of the concentric conductor. PEN conductors must be insulated for the highest expected voltage; except within switchgear installations.

Table 5-2

Minimum cross sections of protective conductors to the cross section of the phase conductors (as per DIN VDE 0100-540/05.86 – superseded by edition 11.91)

1	2	3	4		5
Nominal cross sections					
Phase conductor4) 5)	protective conductor or PEN conductor1)		protective conductor3) laid separately		
	Insulated power cables	0.6/1-kV cable with 4 conductors	protected mm^2		unprotected2) mm^2
mm^2	mm^2	mm^2	Cu	Al	Cu
to 0.5	0.5	–	2.5	–	4
0.75	0.75	–	2.5	–	4
1	1	–	2.5	–	4
1.5	1.5	1.5	2.5	–	4
2.5	2.5	2.5	2.5	–	4
4	4	4	4	–	4
6	6	6	6	–	6
10	10	10	10	–	10
16	16	16	16	16	16
25	16	16	16	16	16
35	16	16	16	16	16
50	25	25	25	25	25
70	35	35	35	35	35
95	50	50	50	50	50
120	70	70	70	70	70
150	95	95	95	95	95
185	95	95	95	95	95
240	–	120	120	120	120
300	–	150	150	150	150
400	–	240	240	240	240

1) PEN conductor ≥ 10 mm^2 Cu or ≥ 16 mm^2 Al.

2) Unprotected aluminium conductors may not be laid.

3) From an outside conductor cross section of ≥ 95 mm^{2,} bare conductors are preferred.

4) Minimum cross section for aluminium conductors: 16 mm^2.

5) For minimum conductor cross sections for phase conductors and other conductors, see also DIN VDE 0100 Part 520.

After a PEN conductor has been split into protective and neutral conductor, they must not be joined again and the neutral conductor must not be earthed. The PEN conductor must be connected to the protective conductor terminal.

The conductor cross sections for equipotential bonding conductors can be found in Table 5-5.

When insulated conductors are used as protective or PEN conductors they must be coloured green-yellow throughout their length. The insulated conductors of single-core cables and sheathed cables are an exception. They must have durable green-yellow markings at the ends.

Equipotential bonding conductors may be marked green-yellow.

Non-insulated conductors do not require the green-yellow marking.

Green-yellow markings are not approved for anything other than the above conductors.

Table 5-3

Material coefficients *k*

	Protective conductor							
	Group 1				Group 2			
	G	PVC	VPE, EPR	IIK	G	PVC	VPE, EPR	IIK
ϑ_i in °C	30	30	30	30	60	70	90	85
ϑ_f in °C	200	160	250	220	200	160	250	220
	k in $A\sqrt{s}/\text{mm}^2$				*k* in $A\sqrt{s}/\text{mm}^2$			
Cu	159	143	176	166	141	115	143	134
Al	—	95	116	110	87	76	94	89
Fe	—	52	64	60	—	—	—	—
Pb	—	—	—	—	—	—	—	—
	Group 3							
	G	PVC	XLPE, EPR	IIK				
ϑ_i in °C	50	60	80	75				
ϑ_f in °C	200	160	250	220				
	k in $A\sqrt{s}/\text{mm}^2$							
Cu	—	—	—	—				
Al	97	81	98	93				
Fe	53	44	54	51				
Pb	27	22	27	26				

Group 1:	insulated protective conductors outside cables, bare protective conductors in contact with cable sheaths
Group 2	insulated protective conductors in cables
Group 3:	protective conductors as sheath or armouring of cables

See notes to Table 5-4!

Table 5-4

Material coefficients k for bare conductors in cases where there is no danger to the materials of adjacent parts from the temperatures given in the table

Conductor material	Conditions	Visible and in delimited areas*)	Normal conditions	If fire hazard
Cu	ϑ_f in °C	500	200	150
	k in A $\sqrt{s}$/mm^2	228	159	138
Al	ϑ_f in °C	300	200	150
	k in A $\sqrt{s}$/mm^2	125	105	91
Fe	ϑ_f in °C	500	200	150
	k in A $\sqrt{s}$/mm^2	82	58	50

Note: The initial temperature ϑ_i on the conductor is assumed to be 30 °C.

*) The given temperatures only apply if the temperature of the joint does not impair the quality of the connection.

Symbols used in Tables 5-3 and 5-4:

ϑ_i	Initial temperature at conductor
ϑ_f	Max. permitted temperature at conductor
G	Rubber insulation
PVC	Insulation of polyvinyl chloride
VPE	Insulation of cross-linked polyethylene
EPR	Insulation of ethylene propylene rubber
IIK	Insulation of butyl rubber

Table 5-5

Cross-sections for equipotential bonding conductors

	Main equipotential bonding	Additional equipotential bonding	
normal	≥ 0.5 × cross-section of the largest protective conductor of the installation	between two exposed conductive parts	≥ 1 × cross-section of the smaller protective conductor
		between a metallic enclosure and an external conductive part	≥ 0.5 × cross-section of the protective conductor
at least	6 mm^2 Cu or equivalent conductivity1)	with mechanical protection	2.5 mm^2 Cu 4 mm^2 Al
		without mechanical protection	4 mm^2 Cu
possible limitation	25 mm^2 or equivalent conductivity1)	—	—

1) Unprotected aluminium conductors may not be laid.

5.2 Protection against contact in installations above 1000 V as per DIN VDE 0101

5.2.1 Protection against direct contact

To provide protection against direct contact, measures are required to prevent people from coming dangerously close, indirectly or directly with tools or objects to the following system components:

- live parts
- conductor insulation of cables and wires from whose ends the conductive covering has been removed
- termination parts and conductive coverings on the ends of single-core cables if hazardous touch voltages are possible
- insulating bodies of insulators and other equipment
- windings of electrical machines
- converters, converter transformers and capacitors having live enclosures in fault-free operation
- installations with insulated enclosures and electric shock protection A
  as per IEC 60466 (formerly DIN VDE 0670 Part 7)

Depending on the location of the electrical installation, the following is required:

- complete protection against direct contact for installations outside locked premises,
- non-complete protection against direct contact for installations inside locked premises.

Protective measures against direct contact:

- protection by covering (complete protection)
- protection by distance (non-complete protection)
- the vertical distance between walkways and the parts to be guarded against direct contact must correspond at least to the values in the tables in Section 4.6.
- protection by partition (non-complete protection)
  solid walls without openings, minimum height 1800 mm,
  wire mesh, screens, minimum height 1800 mm
- protection by obstacle (non-complete protection)
  solid walls, height < 1800 mm,
  wire mesh, screens, height < 1800 mm,
  rails, chains or ropes

Protective barriers must meet the following requirements:

- mechanically robust and reliably fastened (in installations outside locked electrical premises they must be removable only with tools). Guard rails that can be removed without tools must be of non-conductive materials or wood.
- solid or wire mesh doors (40 mm mesh) may be opened only with keys, including socket-type keys. Safety locks are required for installations outside locked electrical premises.
- rails, chains or ropes must be installed at a height of 1200 to 1400 mm; in the case of chains and ropes, the clearance to the protective barrier must be greater depending on the amount of sag.
- walkways above live conductors must be of solid material and have a 50 mm high lip. They must also extend 300 mm beyond this in outside installations and 200 mm in indoor installations.

5.2.2 Protection in case of indirect contact

Measures as specified in DIN VDE 0141 must be implemented.

In the event of a short circuit in the system with earth contact, the earth carries at least part of the short-circuit current. Voltage drops that could result in potential differences are associated with this partial short-circuit current. The potential differences may be bridged by humans; they represent a danger to personnel, particularly in the form of touch voltage.

The protective earth system must be designed so that the earth fault current flows over the protective earthing in the event of an earth fault in the system.

When using protective earthing, all non-live equipment parts and installations must be earthed if they can come into contact with live parts as a result of creepage paths, arcing or direct contact. Metallic sheathing, armouring and screening of cables must be connected to one another at the joints and with the metallic joint boxes and earthed at the end seals. Earthing of sheathing at only one end is permissible if an unacceptable touch voltage cannot occur at the exposed metal parts of the cable installation under normal operation or in the event of faults. It may be desirable to earth three-core sheathed and single-conductor cables at one end only because of inductive effects in the sheaths. In this case, the end seals must be insulated. In long cable units, the touch voltage may be too high because of the induced voltage in the cable sheath, so these cables must be earthed at both ends. Low-voltage circuits of instrument transformers and surge arresters must also be connected to the protective earthing.

Certain resistance values are not required for protective earth systems in the relevant regulations. If earth voltages that are not greater than 65 V occur at a protective earth system, the approved touch voltages will be deemed to be met without verification.

In high-voltage installations with low-resistance neutral earthing, the permissible limit value for touch voltages depends on the duration of the fault current. The shorter the fault current duration, the higher the permissible limit value for the touch voltages occurring in the installation. Fig. 5-7 shows this relationship.

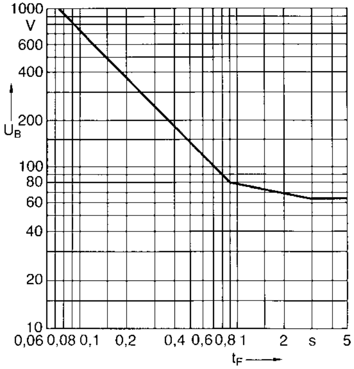


Fig. 5-7

Touch voltage U_B *in relationship to the duration* t_F *of the fault current.*

The requirement that the flow of electricity does not exceed Q = 70 mAs is met at every point on the curve in Fig. 5-7. This value is taken as the criterion, because studies have shown that no fatal accidents have occurred with this quantity of electricity. The lower value of 1000 Ω is taken as the body's resistance.

Conditions for the value of the permissible touch voltages, requirements according to which the conditions for complying with the touch voltages are met or measures to be taken 1) if the conditions are not met are described in DIN VDE 0141.

1) Voltage grading, insulation

5.3 Earthing

5.3.1 Fundamentals, definitions and specifications

Earthing systems have the following general purpose:

Protection of life and property in the event of

- 50-Hz-faults (short circuits and earth faults)
- transient phenomena (lightning, switching operations)

The general layout of a complete earthing system with sections for low voltage, high voltage and buildings and building services is shown in Fig. 5-8.

The most important definitions related to earthing are grouped below.

Earth is the term for the earth as a location and for the earth as material, e.g. the soil types of humus, clay, sand, gravel, rock.

Reference earth (neutral earth) is that part of the earth, particularly the surface outside the area of influence of an earth electrode or an earthing system, in which there are no detectable voltages resulting from the earthing current between any two random points.

Earth electrode is a conductor embedded in the ground and electrically connected to it, or a conductor embedded in concrete that is in contact with the earth over a large area (e.g. foundation earth).

Earthing conductor is a conductor connecting a system part to be earthed to an earth electrode, so long as it is laid out of contact with the ground or is insulated in the ground.

If the connection between a neutral or phase conductor and the earth electrode includes an isolating link, a disconnector switch or an earth-fault coil, only the connection between the earth electrode and the earth-side terminal of the nearest of the above devices is deemed to be an earthing conductor.

Main earthing conductor is an earthing conductor to which a number of earthing conductors are connected.

It does not include:

a) Earthing conductors joining the earthed parts of the single units of three-phase assemblies (3 instrument transformers, 3 potheads, 3 post insulators etc.),

b) with compartment-type installations: earthing conductors that connect the earthed parts of several devices of a compartment and are connected to a (continuous) main earthing conductor within this compartment.

Earthing system is a locally limited assembly of conductively interconnected earth electrodes or metal parts operating in the same way (e.g. tower feet, armouring, metal cable sheaths) and earthing conductors.

To earth means to connect an electrically conductive part to the ground via an earthing system.

Earthing is the total of all measures used for earthing.

Specific earth resistivity ρ_E is the specific electrical resistivity of the ground. It is generally stated in Ω m^2/m = Ω m and indicates the resistance between two opposite cube faces of a cube of soil with sides of 1 m.

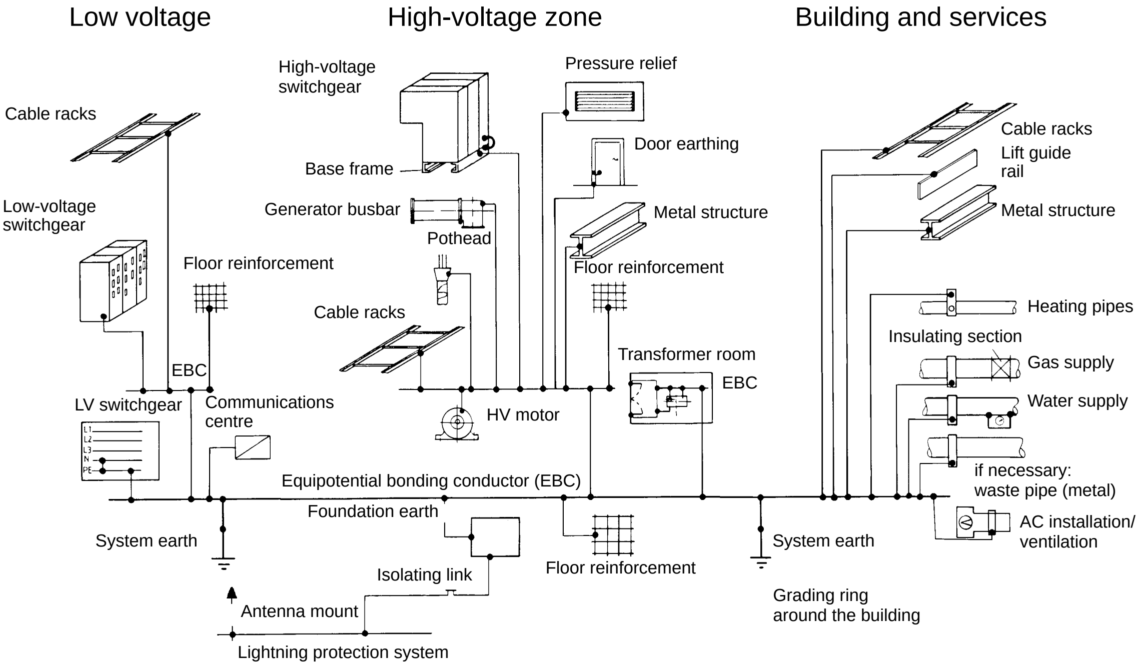


Fig. 5-8

Earthing system with equipotential bonding between HV/LV indoor switchgear and building/building services

Dissipation resistance R_A of an earth electrode is the resistance of the earth between the earth electrode and the reference earth.
R_A is in practice a real resistance.

Earthing impedance Z_E is the AC impedance between an earthing system and the reference earth at operating frequency. The value of the earthing impedance is derived from parallelling the dissipation resistances of the earth electrodes and the impedances of connected conductor strings, e.g. the overhead earth wire and cables acting as earth electrodes.

Impulse earthing resistance R_{st} is the resistance presented to the passage of lightning currents between a point of an earthing system and the reference earth.

Protective earthing is *the* earthing of a conductive component that is not part of the main circuit for the protection of persons against unacceptable touch voltages.

System earthing is the earthing of a point of the main circuit necessary for proper operation of devices or installations.

It is termed:

a) direct, if it includes no resistances other than the earthing impedance.
b) indirect, if it is established via additional resistive, inductive or capacitive resistances.

Lightning protection earthing is the earthing of a conductive component that is not part of the main circuit to avoid flashovers to the operational live conductors resulting from lightning as much as possible (back flashovers).

Earthing voltage U_E is the voltage occurring between an earthing system and the reference earth.

Earth surface potential φ is the voltage between a point on the surface of the earth and the reference earth.

Touch voltage U_B is the part of the earthing voltage that can be shunted through the human body, the current path being through the human body from hand to foot (horizontal distance from exposed part about 1 m) or from hand to hand.

Step voltage U_S is that part of the earthing voltage that can be shunted by a person with a stride of 1 m, with the current path being through the human body from foot to foot.

In contrast to the IEEE, DIN VDE 0101 does not set any limit values for the size of the step voltage.

Potential control consists in influencing the earth potential, particularly the earth surface potential, by earth electrodes to reduce the step and touch voltage in the outer area of the earthing system.

Earth fault is an electrical connection between a conductor of the main circuit with earth or an earthed part caused by a defect. The electrical connection can also be caused by an arc.

Earth fault current I_F is the current passing to earth or earthed parts when an earth fault exists at only one point at the site of the fault (earth fault location).

This is

a) the capacitive earth-fault current I_C in networks with isolated neutral

b) the earth-fault residual current I_{Rest} in networks with earth-fault compensation

c) the zero-sequence current I''_{k1}in networks with low-resistance neutral earthing.

c) also includes networks with isolated neutral point or earth-fault compensators in which the neutral point is briefly earthed at the start of the fault.

Earthing current I_E is the total current flowing to earth via the earthing impedance.

The earthing current is the component of the earth-ault current I_F *which causes the rise in potential of an earthing system.*

Types of earth electrodes

Classification by location

The following examples are distinguished:

a) *surface earth electrodes* are earth electrodes that are generally positioned at shallow depths to about 1 m. They can be of strip, bar or stranded wire and be laid out as radial, ring or meshed earth electrodes or as a combination of these.

b) *deep earth electrodes* are earth electrodes that are generally positioned vertically at greater depths. They can be of tubular, round or sectional material.

Classification by shape and cross section

The following examples are distinguished:

Strip, stranded wire and tube earth electrodes.

Natural earth electrodes are metal parts in contact with the ground or water, directly or via concrete, whose original purpose is not earthing but they act as an earth electrode. They include pipes, caisson walls, concrete pile reinforcement, steel parts of buildings etc.

Cables with earthing effect are cables whose metal sheathing, shield or armouring provides a leakage to earth similar to that of strip earth electrodes.

Foundation earths are conductors embedded in concrete that is in contact with the ground over a large area . Foundation earths may be treated as if the conductor were laid in the surrounding soil.

Control earth electrodes are earth electrodes that by their shape and arrangement are more for potential control than for retaining a specific dissipation resistance.

Rod earth electrodes of any significant length generally pass through soil horizons of varying conductivity. They are particularly useful where more conductive lower soil horizons are available and the rod earth electrodes can penetrate these horizons sufficiently (approximately 3 m). To determine whether more conductive lower soil horizons are available, the specific resistance of the soil at the site is measured (see Section 5.3.4).

Relevant standards on earthing

DIN VDE 0100-410 (VDE 0100 Part 410)
Installation of power systems with nominal voltages to 1000 V; protective measures; protection against electric shock.

DIN VDE 0100, Part 540.
Installation of power systems with nominal voltages to 1000 V; selection and installation of electrical equipment, earthing; protective conductors; equipotential bonding conductors.

DIN VDE 0151 Materials and minimum dimensions of earth electrodes with reference to corrosion.

DIN VDE 0101: 2000-01
Power installations exceeding AC 1kV

DIN VDE 0800 Part 2.
Telecommunications; earthing and equipotential bonding

IEC 60621-2
Electrical installations for outdoor sites under heavy-duty conditions (including open-cast mines and quarries). Part 2: General protection requirements.

IEC/TR 2 60479-1

Effects of currents passing on human beings and livestock.
Part 1: General aspects.

IEEE Std 80-1986 IEEE Guide for Safety in AC Substation Earthing.

5.3.2 Earthing material

Earth electrodes (under ground) and earthing conductors (above ground) must conform to specific minimum dimensions regarding mechanical stability and possible corrosion resistance as listed in Table 5-6.

Selection of material for earth electrodes with respect to corrosion (no connection to other materials) may be made in accordance wtih the following points (DIN VDE 0151):

Hot-dip galvanized steel is very durable in almost all soil types. Hot-galvanized steel is also suitable for embedding in concrete. Contrary to DIN 1045, foundation earths, earthing conductors embedded in concrete, equipotential bonding conductors and lightning conductor leads of galvanized steel can be connected to reinforcing steel if the joints are not subjected to prolonged temperatures higher than 40 °C.

Copper is suitable as an earth electrode material in power systems with high fault currents because of its significantly greater electrical conductivity compared to steel.

Bare copper is generally very durable in the soil.

Copper coated with tin or zinc is, like bare copper, generally very durable in the soil. Tin-plated copper has no electrochemical advantage over bare copper.

Copper with lead sheath. Lead tends to form a good protective layer underground and is therefore durable in many soil types. However, it may be subject to corrosion in a strongly alkaline environment (pH values ≥ 10). For this reason, lead should not be directly embedded in concrete. The sheath may corrode under ground if it is damaged.

Table 5-6

Minimum dimensions for earth electrodes and earthing conductors

Material	Form	DIN VDE 0101 DIN VDE 0151		IEC 60621-2	
Copper	Strip	50 mm²	1)	25 mm²	
		16 mm²	2)	16 mm²	3)
	Stranded wire, copper bar	25 mm²			
		16 mm²	2)		
Steel 4)	Strip	90 mm²	5)	50 mm²	
		50 mm²	2)	16 mm²	3)
	Steel bar	78 mm²	6) 7)		
		50 mm²	2)		
	Tube	25 mm Ø	8)		
	Steel sections	90 mm²	9)		
Steel coated with copper	Steel bar	50 mm²	10)	no data	
Aluminium 2)		35 mm²		no data	

1) Minimum thickness 2 mm

2) For above-ground earthing conductors only

3) For conductors protected against corrosion

4) When laid in the soil: hot-dip galvanized (minimum coating 70 µm)

5) Minimum thickness 3 mm (3.5 mm as per DIN 48801 and DIN VDE 0185)

6) Equivalent to 10 mm diameter

7) With composite deep ground electrodes: at least 16 mm diameter.

8) Minimum wall thickness 2 mm

9) Minimum thickness 3 mm

10) For steel wire, copper coating: 20 % of the steel cross section (min. 35 mm²), for composite deep ground electrodes: minimum 15 mm diameter

Refer to Table 5-7 for the combination of different materials for earth electrodes underground (DIN VDE 0151).

The area rule means that the ratio of the anode area F_A (e.g. steel) to the cathode area F_K (e.g. copper) is crucial for the formation of corrosion elements. As the area ratio F_A/F_K decreases, the rate of corrosion of the anode area increases. This is why coated steel pipe conductors are in danger when connected to a copper earthing system, because the surface ratio of steel to copper at fault positions in the pipe coating is unfavorable and causes fast corrosion (breakthrough). Connecting such pipe conductors to earth electrodes of copper is not approved as per DIN VDE 0151.

Table 5-7

Connections for different earth electrode materials
Ratio of large area : small area ≥ 100:1

Material with small surface area	Material with large surface area							
	Steel, hot-dip galvanized	Steel	Steel in concrete	Steel, hot-dip galvanized in concrete	Copper	Copper tin-plated	Copper, hot-dip galvanized	Copper with lead sheath
Steel, hot-dip galvanized	+	+ Zinc loss	—	+ Zinc loss	—	—	+	+ Zinc loss
Steel	+	+	—	+	—	—	+	+
Steel in concrete	+	+	+	+	+	+	+	+
Steel with lead sheath	+	+	○ Lead loss	+	—	+	+	+
Steel with Cu sheath	+	+	+	+	+	+	+	+
Copper	+	+	+	+	+	+	+	+
Copper tin-plated	+	+	+	+	+	+	+	+
Copper galvanized	+	+ Zinc loss	+ Zinc loss	+ Zinc loss	+ Zinc loss	+ Zinc loss	+	+ Zinc loss
Copper with lead sheath	+	+	+ Lead loss	+	+ Lead loss	+	+	+

+ Good for joining
○ Can be joined
— must not be joined

5.3.3 Dimensioning of earthing systems

The cross-section of earth electrodes and earthing conductors must be measured so that in the event of a fault current I_F (I''_{K1} in networks with low-resistance neutral earthing), the strength of the material is not reduced. The required cross-section may be determined as follows:

$$A = I_F \cdot \frac{\sqrt{t_F}}{k}$$

Where

I_F : fault current
t_f : duration of fault current
k : material coefficient

The material coefficient for copper is (see Sec. 5.1.3 for other materials)

$$k = 226 \sqrt{\ln \left(1 + \frac{\vartheta_f - \vartheta_i}{234.5\ °C + \vartheta_i}\right)}\ A \cdot \sqrt{s}/mm^2$$

Where

ϑ_i : initial temperature in °C (maximum ambient temperature)
ϑ_f : permitted final temperature

For the permissible final temperature see Table 5-8, (see also Sec. 13.1.1). Where earthing conductors and PVC cables are laid on cable racks together ϑ_f must not exceed 150 °C.

Table 5-8

Permissible final temperatures in ° C for various materials

Material	DIN VDE 0101	IEC 60621-2 DIN VDE 0100 Part 540
Cu bare	300 1)	500 2) 200 3) 150 4)
Al bare	300 1)	300 2) 200 3) 150 4)
Steel bare or galvanized	300 1)	500 2) 200 3) 150 4)
Cu tin-plated or with lead sheath	150	no data

1) If there is no risk of fire
2) For visible conductors in locations that are not generally accessible
3) For non-visible conductors in locations that are generally accessible
4) Where hazards are greater
– for non-visible conductors in locations with increased fire risk
– for earthing conductors laid together with PVC cables

The required standard cross-sections for bare copper depending on the single-line fault current and fault current duration are given in Table 5-9.

Personnel safety in the event of malfunction is ensured when the step and touch voltages do not exceed the limit values set in the standards (e.g. DIN VDE 0101). Step and touch voltages can only be calculated with the aid of computer programs in a very complex process.

As per DIN VDE 0101, the touch voltages in outdoor installations are in compliance when the following three conditions are met simultaneously:

1) Presence of a surface earth electrode surrounding the earthing system in the form of a closed ring. Inside this ring there is an earthing grid (grid size ≤ 50 m × 10 m). Any station components outside the ring and connected to the earthing system are provided with control earth electrodes.
2) Fault current duration ≤ 0.5 s
3) Earthing voltage $U_E \leq 3000$ v.

The earthing voltage U_E is the voltage that the entire earthing system has in the event of malfunction compared to reference earth (∞ removed).

Table 5-9 Standard cross-sections

$I''_{k1} = I''_{k3} \dfrac{3}{2 + x_0/x_1}$			Standard cross-sections for earthing material of copper in mm²					
I''_{k3} in *kA*	x_0/x_1	I''_{k1} in *kA*	$\vartheta_i = 30$ °C, $\vartheta_f = 300$ °C 1.0 s	 0.5 s	 0.2 s	$\vartheta_i = 30$ °C, $\vartheta_f = 150$ °C 1.0 s	 0.5 s	 0.2 s
80	1	80	—	4 × 95	2 × 95	—	4 × 120	4 × 70
	2	60	—	2 × 120	2 × 95	—	4 × 95	2 × 120
	3	48	—	2 × 95	120	—	4 × 70	2 × 95
63	1	63	—	2 × 120	2 × 95	—	4 × 95	2 × 120
	2	47.3	—	2 × 95	120	—	4 × 70	2 × 95
	3	37.8	—	2 × 95	95	—	2 × 120	2 × 70
50	1	50	—	2 × 95	120	—	4 × 70	2 × 95
	2	37.5	—	2 × 70	95	—	2 × 120	2 × 70
	3	30	—	120	95	—	2 × 95	120
40	1	40	2 × 120	2 × 95	95	4 × 95	2 × 120	2 × 70
	2	30	2 × 95	120	95	2 × 120	2 × 95	120
	3	24	2 × 70	95	70	2 × 95	2 × 70	95
31.5	1	31.5	2 × 95	120	95	2 × 120	2 × 95	120
	2	23.6	2 × 70	95	70	2 × 95	2 × 70	95
	3	18.9	120	70	50	2 × 70	120	70
25	1	25	2 × 70	95	70	2 × 95	2 × 70	95
	2	18.8	120	70	50	2 × 70	120	70
	3	15	95	70	35	120	95	50
20	1	20	120	95	50	2 × 95	120	70
	2	15	95	70	35	120	95	50
	3	12	70	50	35	95	70	50
16	1	16	95	70	50	120	95	70
	2	12	70	50	35	95	70	50
	3	9.6	70	50	35	70	50	35

(continued)

Table 5-9 (continued)

Standard cross-sections

$I''_{k1} = I''_{k3} \dfrac{3}{2 + x_0/x_1}$			standard cross-sections for earthing material of copper in mm^2					
I''_{k3}	x_0/x_1	I''_{k1}	$\vartheta_i = 30\,°C$, $\vartheta_f = 300\,°C$			$\vartheta_i = 30°C$, $\vartheta_f = 150\,°C$		
in kA		in kA	1.0 s	0.5 s	0.2 s	1.0 s	0.5 s	0.2 s
12.5	1	12.5	70	50	35	95	70	50
	2	9.4	50	35	35	70	50	35
	3	7.5	50	35	35	70	50	35
≤ 10	1	10	70	50	35	95	70	35
	2	7.5	50	35	35	70	50	35
	3	6	35	35	35	50	35	35

x_0/x_1: Ratio of zero-sequence reactance to positive-sequence reactance of the network from the point of view of the fault location; 1 for faults near the generator, heavily loaded networks and in case of doubt; 2 for all other installations; 3 for faults far from the generator.

The earthing voltage U_E in low-resistance earthed networks given approximately by:

$$U_E = r \cdot I''_{K1} \cdot Z_E$$

Where

r : reduction factor

Z_E : earthing impedance

I''_{K1} : single-line initial symmetrical short-circuit current

Overhead earth wires or cable sheaths connected to the earthing system carry some of the fault current in the event of malfunction as a result of magnetic coupling. This effect is expressed by the reduction factor *r*. If overhead earth wires or cable sheaths are not connected, *r* = 1. In the case of overhead earth wires of overhead lines, the typical values given in Table 5-10 apply.

Table 5-10

Typical values for earth wire reduction factors *r*

Earth wire type	r
1 x St 70	0.97
1 x Al/St 120/20	0.80
1 x Al/St 240/40	0.70
2 x Al/St 240/40	0.60

The earthing impedance Z_E is derived from the parallel switching of the dissipation resistance R_A of the installation and the impedance Z_P of parallel earth electrodes (cable, overhead cables, water pipes, railway tracks etc.). The following is approximate:

$$Z_E = \left(\frac{1}{R_A} + \frac{1}{Z_P} \right)^{-1}$$

The dissipation resistance of the mesh earth electrodes of a switchgear installation can be calculated as follows:

$$R_A = \frac{\rho}{4}\sqrt{\frac{\pi}{A}}$$

Where:
ρ : specific resistance of the soil [Ωm]
A: area of mesh earth electrode [m^2]

The guidance values given in Table 5-11 (DIN VDE 0228) apply for the specific resistance of various soil types.

Table 5-12 shows guidance values for the parallel resistances Z_P of various earth electrodes. The values listed there only apply from a specific minimum length. The values for overhead lines only apply for steel towers.

The dissipation resistances of surface and deep earth electrodes can be seen in Figs. 5-9 and 5-10. The broken curve in Fig. 5-10 shows the results of a measurement for comparison.

Table 5-11

Specific resistivity of different soils

Type of soil	Climate normal, Precipitation ≈ 500 mm/year		Desert climate, Precipitation ≈ 250 mm/year	Under-ground saline water
	Typical value Ωm	Range of measured values Ωm		
Alluvium and light alumina	5	2 to 10[1)]		
Non-alluvial clay	10	5 to 20	10 to 1000	3 to 10
Marl, e.g. Keuper marl	20	10 to 30	50 to 300	3 to 10
Porous limestone, e.g. chalk	50	30 to 100	50 to 300	3 to 10
Sandstone, e.g. Keuper sandstone and shale	100	30 to 300	> 1000	10 to 30
Quartz, chalk, solid and crystalline, e.g. marble, carbonaceous limestone	300	100 to 1000	> 1000	10 to 30
Argillaceous slate and shale	1000	300 to 3000	> 1000	30 to 100
Granite	1000	> 1000		
Slate, petrifaction, gneiss, rock of volcanic origin	2000			

1) depending on the groundwater level

Table 5-12

Parallel resistances of earth electrodes

earth electrode type	Zp [Ω]	Minimum length [km]
overhead line with 1 earth wire St 70	3.2	1.8
overhead line with 1 earth wire Al/St 120/20	1.3	4.2
overhead line with 1 earth wire Al/St 240/40	1.2	5.4
overhead line with 2 earth wires Al/St 240/40	1.1	6.8
10-kV cable NKBA 3 × 120	1.2	0.9
Water pipe NW 150	2.3	1.5
Water pipe NW 700	0.4	3.0
Electric rail 1 track	0.6	8.0
Electric rail 2 tracks	0.4	6.9

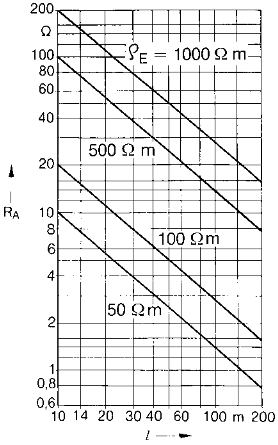


Fig. 5-9

Dissipation resistance R_A of surface earth electrodes (strip, bar or stranded wire) laid straight in homogenous soil in relationship to the length l with different specific resistivities ρ_E

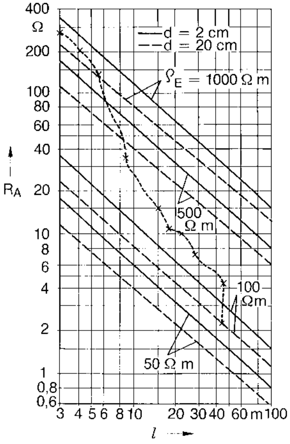


Fig. 5-10

Dissipation resistance R_A of deep earth electrodes placed vertically in homogenous soil in relationship to the electrode length l with various diameters and specific resistivities ρ_E, curve x ... x: Measured values

5.3.4 Earthing measurements

The specific resistivity ρ_E of the soil is important for calculating earthing systems. For this reason, ρ_E should be measured before beginning construction work for a switchgear installation; the measurements are made using the “Wenner Method” (F. Wenner: A Method of Measuring Earth Resistivity, Scientific papers of the Bureau of Standards, No. 248, S. 469-478, Washington 1917).

Measuring the step and touch voltages after setup of a switchgear installation is one way to confirm the safety of the system; the measurements are conducted in accordance with the current and voltage method in DIN VDE 0101.

The current and voltage method also allows the earthing impedance (dissipation resistance) of the installation to be calculated by measuring the potential gradient.

Use of earth testers (e.g. Metraterr II) to measure dissipation resistance should be restricted to single earth electrodes or earthing systems of small extent (e.g. rod earth electrode, strip earth electrode, tower earth electrode, earthing for small switchgear installations).

5.4 Lightning protection

Damage caused by lightning strikes cannot be completely prevented either technically or economically. For this reason, lightning protection facilities cannot be specified as obligatory.

The probability of direct lightning strikes can be greatly reduced on the basis of model experiments, measurements and years of observation with the methods described below.

5.4.1 General

A distinction is made between external and internal lightning protection.

External lightning protection is all devices provided and installed outside and in the protected installation provided to intercept and divert the lightning strike to the earthing system.

Internal lightning protection is total of the measures taken to counteract the effects of lightning strike and its electrical and magnetic fields on metal installations and electrical systems in the area of the structure.

The earthing systems required for lightning protection must comply with DIN VDE 0101, with particular attention paid to the requirements for lightning protection in outdoor switchgear (e.g. back flashover).

Key to symbols used

A		live part
B		overhead earth wire lightning rod
C	(m)	distance between lightning rods
H	(m)	height of earth wire height of lightning rod (height of interception device)
2H	(m)	twice the height of the earth wire
3H	(m)	three times the height of the lightning rod
h	(m)	height of live part over ground level (object height)
h_B	(m)	radius of lightning sphere, flashover distance to earth
h_x	(m)	lowest height of protected zone at midpoint between two lightning rods
L	(m)	distance overhead earth wire to equipment distance lightning rod to equipment
L_x	(m)	distance live part from axis of lightning rod (protected distance)
M		centre of arc for limitation of outer protective zone
M_1		centre of arc for limitation of inner protective zone
R	(m)	radius for M_1-B
r_x	(m)	radius for limitation of protected zone at height h
α		*shielding angle (with universal method)*

5.4.2 Methods of lightning protection

There are currently four methods of designing lightning protection systems:

- Lightning sphere method
- Method as per DIN VDE 0185
- Linck’s universal method
- Method as per DIN VDE 0101

Lightning sphere method

The lightning sphere method ensures complete lightning protection. It is used for residential buildings or high-hazard locations (warehouses with highly flammable materials such as oil, gas, cotton etc.). It is not used for electrical power systems.

The contours of the objects that are to be protected and the planned interception devices are modeled – e.g. at a scale of 1:100 to 1:500. Then a sphere is made with a scale radius of 10, 20 or 40 m depending on the requirements, which corresponds to the flashover distance to earth h_B. The lightning sphere is then rolled around the model on a flat surface. If the lightning sphere only touches the interception devices, the protected objects are completely in the protected area. However, if the lightning sphere does touch parts of the protected objects, the protection is not complete at these sections (see Fig. 5-11).

If the configurations of the air terminals are simple, it will generally be unnecessary to produce a model. The effectiveness of the protection system can be assessed by examinations based on the projection of the lightning sphere.

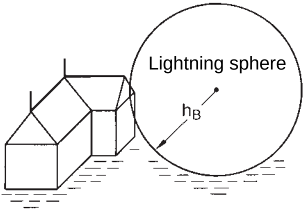


Fig. 5-11

Determining the effectiveness of lightning rods and conductors for protecting the building

Method as per DIN VDE 0185

The lightning protection method as per DIN VDE 0185 ensures that buildings are almost fully protected. The structural features for the protected area are determined by the above method and are generally the same as the method as per DIN VDE 0101.

Linck's universal method

Linck's universal method (see Fig. 5-12) provides the following data for the external lightning protection system (interception devices):

- number and height of lightning rods and overhead earth wires,
- theoretical location layout for interception devices.

Linck's lightning protection method is based on the statistical data of the disconnection frequency in overhead cables.

Disconnecting of overhead lines caused by a direct lightning strike is based on two effects:

- incomplete shielding by the earth wire,
- back flashover.

Depending on the nominal voltage and the shielding angle of the building and overhead line, the back flashover is involved in the following percentages of all disconnections:

min.	0 %
mean	25 %
max.	50 %

When using Linck's method to specify the permissible disconnection frequency for switchgear installations, note that back flashover cannot occur in switchgear installations and the assumed disconnection frequency Y is conservative.

It is calculated as follows:

- defining the required data,
- preparing the input data,
- calculation,
- preparing design data.

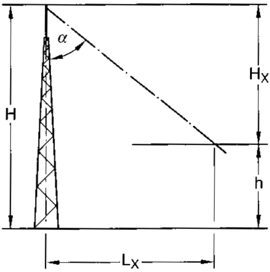


Fig. 5-12

Determining the protected zone by the universal method (Linck)

Method as per DIN VDE 0101

This method ensures almost complete lightning protection and is used exclusively for designing outdoor switchgear installations.

The method described below for determining the protected zone of a high-voltage switchgear installation corresponds to the recommendations of DIN VDE 0101. It has the advantage of being simple for the designer to set the dimensions of the lightning protection facilities. It is suitable for installations of up to approximately 245 kV and protected zone heights of up to approximately 25 metres. Linck's universal method is suited for installations with higher voltage levels and greater protected zone heights or for more precise calculations.

Lightning arresters installed in an installation generally only protect the installation against incoming atmospheric overvoltages (see Sec. 10.6). Overhead earth wires or lightning rods may be installed on the strain portals of the busbars and overhead lines as lightning protection for an outdoor installation. Separate support structures may sometimes be required for this purpose. The overhead earth wires of the incoming overhead lines end at the strain structures of the outdoor installation.

Overhead earth wires and lightning rods must be corrosion-resistant (e.g. Al/St stranded wire, or hot-dip galvanized steel pipes, or bars for rods).

5.4.3 Overhead earth wires

The protected zone, which should enclose all equipment and also the transformers, is determined as shown in Fig. 5-13 or from a diagram (Fig. 5-14).

The sectional plane of the protected zone is bounded by an arc along an overhead earth wire as shown in Fig. 5-13, whose midpoint M is equal to twice the height H of the earth wire both from ground level and from the overhead earth wire B. The arc touches the ground at a distance $\sqrt{3} \cdot H$ from the footing point of the overhead earth wire.

The sectional plane of the protected zone for two overhead earth wires, whose distance from each other is $C \leqq 2 \cdot H$, is shown in Fig. 5-13b. The outer boundary lines are the same as with an overhead earth wire. The sectional plane of the protected zone between the two overhead earth wires B is bounded by an arc whose midpoint M_1 is equal to twice the height 2H of the earth wire from ground level and is in the middle of the two overhead earth wires. The radius R is the distance between the overhead earth wire B and the midpoint M_1.

The angle between the tangents to the two bounding lines is 2 × 30° at their point of intersection. If an angle of around 2 × 20° is required in extreme cases, the distance 1.5H must be selected instead of the distance 2H.

The arrangement of the overhead earth wires for a 245 kV outdoor installation is shown in Fig. 5-13 c. The bounding line of the protected zone must be above the live station components.

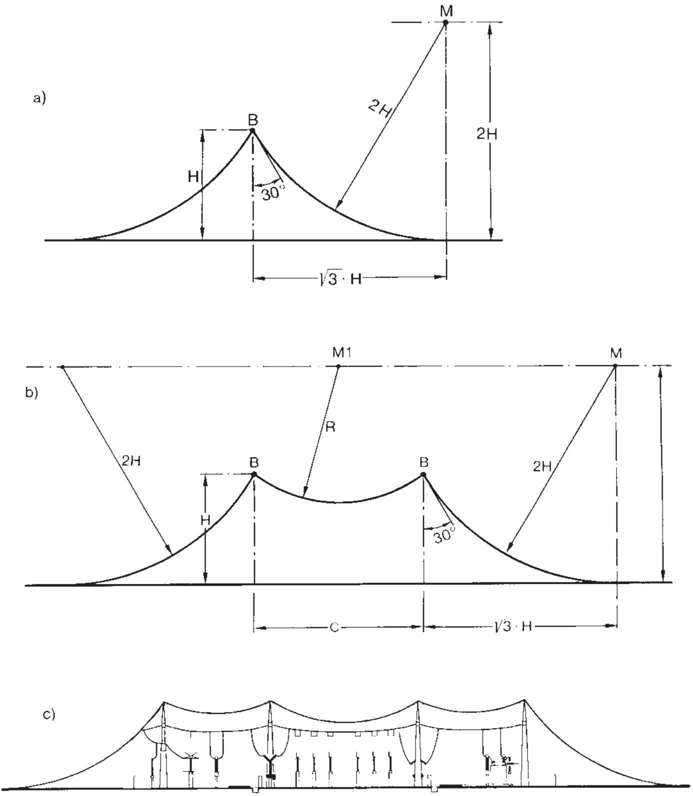


Fig. 5-13

Sectional plane of the protected zone provided by overhead earth wires as per the FGH recommendations:

a) sectional plane of the protected zone with one overhead earth wire,
a) sectional plane of the protected zone with two overhead earth wires,
c) arrangement of the overhead earth wires and protected zone of an outdoor switchgear installation.

The height H of the overhead earth wire can be calculated from Fig. 5-14. The curves show the sectional plane of the protected zone one overhead earth wire.

Example: equipment is installed at a distance of L = 12.5 m from the overhead earth wire, with the live part at height h = 9.0 m above ground level: The overhead earth wire must be placed at height H = 23.0 m (Fig. 5-14).

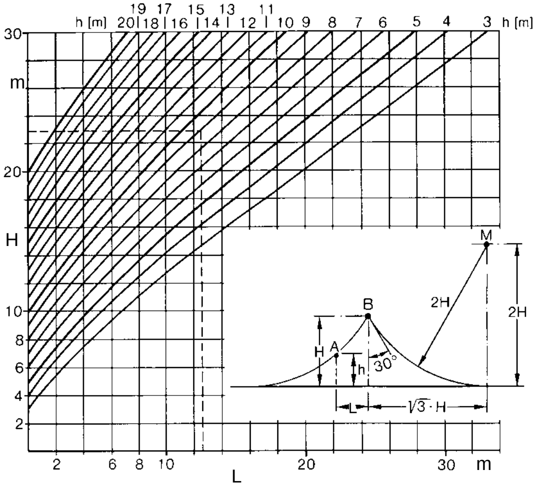


Fig. 5-14

Sectional plane of the protected zone for one overhead earth wire

5.4.4 Lightning rods

Experience and observation have shown that the protected zone formed by rods is larger than that formed by wires at the same height.

A lightning rod forms a roughly conical protected zone, which in the sectional plane shown in Fig. 5-15 a) is bounded by the arc whose midpoint M is three times the height H of the rod both from ground level and the tip of the lightning rod. This arc touches the ground at distance $\sqrt{5} \cdot H$ from the footing point of the lightning rod.

The area between two lightning rods whose distance from each other is $\leqq 3 \cdot H$ forms another protected zone, which in the sectional plane shown in Fig. 5-15 b) is bounded by an arc with radius R and midpoint M_1 at $3 \cdot H$, beginning at the tips of the lightning rods.

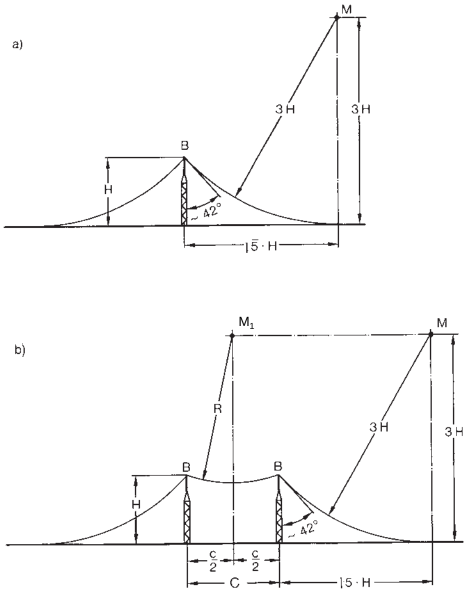


Fig. 5-15

Sectional plane of the zone protected by lightning rods: a) sectional plane of the protected zone with one lightning rod, b) sectional plane of the protected zone with two lightning rods.

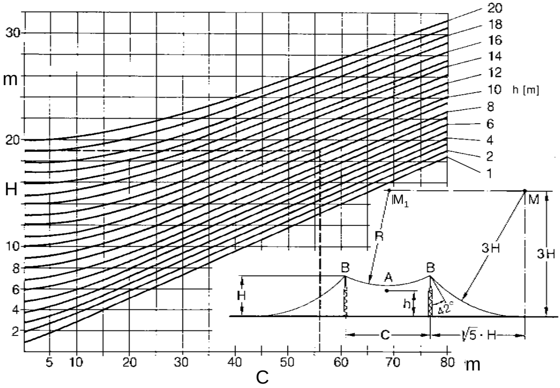


Fig. 5-16

Sectional plane of the protected zone for two lightning rods

The height H of the lightning rod can be calculated from Fig. 5-16. The curves show the protected zone for two lightning rods.

Example: equipment is centrally placed between two lightning rods, which are at distance C = 560 m from each other; the live part is at height h = 10.0 m above ground level: the lightning rods must be at a height of H = 19.0 m (Fig. 5-16).

The width of the protected zone L_x – at a specific height h – in the middle between two lightning rods can be roughly determined from Figs. 5-17 a) and 5-17 b) and from the curves in Fig. 5-17 c).

Example: equipment is centrally placed between two lightning rods at distance L_x = 6.0 m from the axis of the lightning rods; the live part is at height h = 8.0 m above ground level: When the lightning rods are at a distance of C = 40.0 m the height of the lightning rods must be H = 18.5 m (Fig. 5-17).

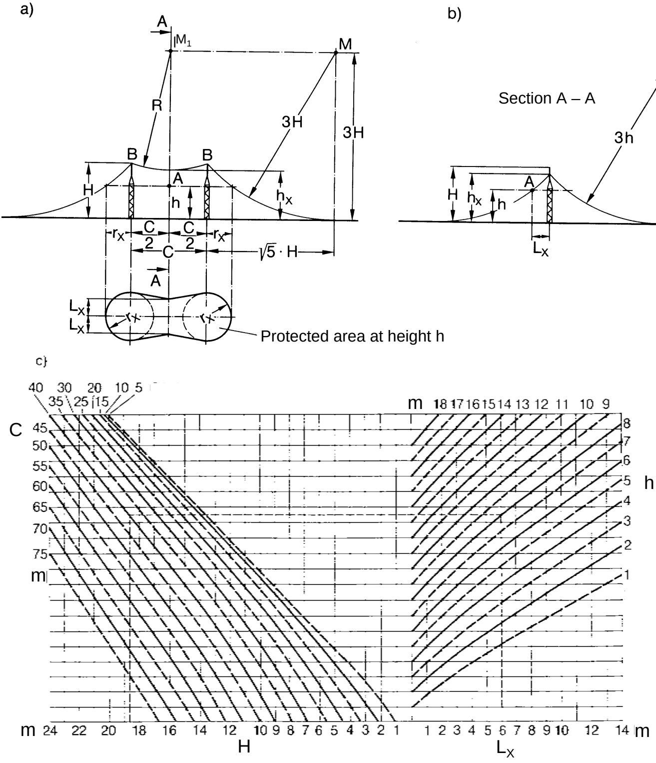


Fig. 5-17

Protected zone outside the axis of 2 lightning rods

5.5 Electromagnetic compatibility

The subject of electromagnetic compatibility (EMC) includes two fundamentally different aspects of the effects of electromagnetic fields, i.e.

– electromagnetic compatibility between electrical equipment and

– the effects of electromagnetic fields on biological systems, particularly on humans.

Effects of electromagnetic fields on humans

Treatment of this part of the subject in the media has resulted in increased worry among the public, although there is no foundation for this, based on events in practice or any relevant research results.

The effects of electromagnetic fields on humans are divided into a low-frequency range (0 Hz to 30 kHz) and a high-frequency range (30 kHz to 300 GHz).

“Approved values” have already been established for both ranges. The low-frequency range is of primary interest for the operation of switchgear installations. The work of standardization in this area is still not complete. Currently there are:

– the 26th federal regulations for the Federal Immission Control Act (26th BImSchV), in force since 1 January 1997 for generally accessible areas without limitation on time of exposure for fixed installations with voltages of 1000 V and above,

– DIN VDE V 0848-4/A3, published in July 1995 as a draft standard and

– ENV 50166-1, a European draft standard from January 1995.

In the low-frequency range, the current density occurring in the human body is the decisive criterion for setting the limit values. According to a study by the World Health Organisation (WHO), interaction between current and muscle and nerve cells occurs above a body current density of 1000 mA/m^2, with proven acute danger to health in the form of interference with the functioning of the nerves, muscles and heart. The lowest limit for detection of biological effects is approximately 10 mA/m^2. Current densities below 1 mA/m^2 have no biological effects.

In 26th BImSchV, a body current density of 1-2 mA/m^2 was selected as the basic value for the derivation of approved field quantities. At 50 Hz this yields permissible values of 5 kV/m for the electrical field and 100 µT for the magnetic flux density.

Short-term higher values to double the permissible value are approved for both values. Higher values in a small space in the same dimensions are approved for the electrical field outside buildings.

DIN VDE V 0848-4 and ENV 50166-1 specify a body current density of 10 mA/m^2 as the initial value for exposure in the workplace with limited exposure time. The associated derived field quantities vary greatly depending on the exposure time. They are significantly higher than those specified by 26th BImSchV.

The approved limit values are set with close attention to the effects detected in the body with due consideration to high safety factors (250-500) with reference to the limit of direct health hazards. The current research results give no indication that lower values should be specified as approved quantities with reference to the occurrences of cancers.

Readings in the field taken under a 380 kV line at the point of greatest sag showed a magnetic flux density of 15 to 20 µT (at half maximum load) and an electrical field intensity of 5-8 kV/m. The corresponding values were lower with 220 kV and 110 kV lines. Electrical field intensities are practically undetectable outside metal-encapsulated switchbays, and the magnetic field intensity generally remains below the limits of 26th BImSchV, even at full load.

Heart pacemakers may, but need not be influenced by electrical and magnetic fields. It is difficult to predict the general sensitivity of pacemakers. When utilizing the approved limit value for workplace exposure, a careful case-by-case analysis is recommended.

Electromagnetic compatibility between electrical equipment

This part of the subject includes terms such as secondary lightning protection, precision protection and nuclear electromagnetic pulses (EMP or NEMP) and radio interference suppression. While these subjects are not treated in detail, this section deals with the physical phenomena and the technical measures described in the following sections.

Electromagnetic compatibility is the capacity of an electrical device to function satisfactorily in its electromagnetic environment without influencing this environment, which includes other equipment, in a non-approved manner (DIN VDE 0870).

The electromagnetic environment of a device is represented by all the sources of interference and the paths to the device (Fig. 5-18). At the same time, the electromagnetic quantities generated in the device also act on the environment through the same paths.

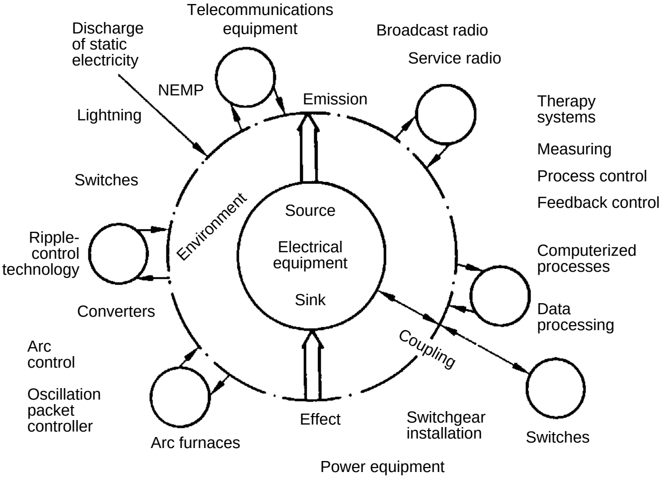


Fig. 5-18

Multilateral interference model

Electromagnetic compatibility (EMC) is essential at every phase of a switchgear installation project and extends from establishing the electromagnetic environment to specifying and checking the measures required to maintaining control over planning and changes to the installation. The EMC activities are shown in Table 5-13.

Table 5-13

Overview of EMC activities during the design of switchgear installations

EMC analysis
- identifying sources of interference
- determining interference quantities
- calculating/estimating/measuring paths
- determining the interference resistance of interference sinks (e.g. from secondary equipment)

Measures for achieving EMC
- measures at interference sources
- measures on coupling paths
- measures at interference sinks

Verification of EMC
- generating interference quantities with switching operations
- simulation of interference quantities in the laboratory

Particularly in the event of a fault, i.e. if there is non-permissible interference, the bilateral influence model as shown in Fig. 5-19 is sufficient to clarify the situation. Action must be taken to decouple the interference source and the interference sink.

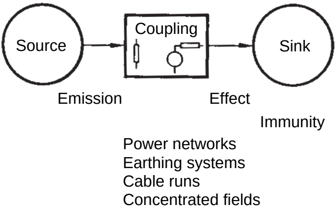


Fig. 5-19

Bilateral interference model

Good electrical conductivity in the system is an essential basis for decoupling measures between the parts of the system and its environment to ensure equipotential bonding and shielding.

Measures for equipotential bonding are combined under the term “bonding”. All electrical conductive parts of a system are connected to an earth. Conducting parts of the system can be conductively connected to this earth to enable operation of the system in accordance with regulations (bonding). If the earth is conductively connected to an earth electrode (earthing), this is considered functional earthing (telecommunications, DIN VDE 0804) or system earthing (low-voltage systems). Functional earthing can also be implemented with protective functions (in connection with low-voltage) and must then be able to meet the corresponding requirements.

Equipment housing that forms a part of the earthing system can be designed so it forms an equipotential envelope, which protects the equipment by shielding it against incoming and outgoing interference fields.

Two important points must be observed when connecting conductive parts of electrical equipment during design of electrical installations:

- protection against unacceptably high touch voltages by protective measures, as specified by DIN VDE 0100 and 0101: a protective conductor system is used for this when required.
- reduction of electromagnetic interference by creating equipotentials: this is the purpose of the bonding system.

5.5.1 Origin and propagation of interference quantities

An electromagnetic interference quantity is an electromagnetic quantity that can indicate undesirable interference in an electrical system.

The interference quantity is a collective term that covers the actual physical terms of interference caused by voltage, current, signals, energy etc. (DIN VDE 0870). Interference quantities are caused by otherwise useful technical quantities or parts of them and by discharge of natural and technically generated static electricity. The term “interference” expresses the intention of considering the quantity in question in terms of its possible interference effects.

Fig. 5-20 shows an overview of the most important interference sources in switchgear installations and their interference quantities and coupling paths.u

The behaviour of an interference quantity over time depends on the type of process that causes it and may be periodic or unique.

Periodic, sinusoidal interference quantities

They are referred to as ripple-control signals or carrier signals in data transmission and in general radio technology. Harmonics caused by the system voltage caused by ignition processes (fluorescent lights, power supplies, power electronics) must also be considered. The actual cause of these harmonics is individual periodic switching operations of electronic devices. Each one of these switching operations can therefore be considered as an interference quantity, which can be classified among the transient, pulse-type sources of interference described below.

Periodic, sinusoidal processes are shown in the frequency range resulting from a Fourier series transformation, in the so-called amplitude spectrum as single lines. The height of these lines represents the proportion of a characteristic frequency, which is contained in the sinusoidal interference signal. These frequency segments can also be directly measured (DIN VDE 0847 Part 1).

Transient, pulse-type interference quantities

These occur with switching operations with a more or less steep transition from one switch status to the other, in arc furnaces, in manually or electrically actuated mechanical switches of the most varied power and in the semiconductors of power-electronic and computer equipment. A discharge process can also act as a general pulse-type interference source. So both the discharge of static electricity, such as natural lightning and the exposed conductive part discharge, and partial discharges in insulation (transformers, transducers, machines) can be described as pulse processes.

Pulse-type, periodic processes, such as are generated by brush motors asynchronously to the network frequency (“brush fire”), must also be classified as transient, pulse-type interference quantities when the individual processes are considered, in spite of a periodicity of the pulse sequences.

A unified and coherent representation of pulse-type interference quantities, including their partial phenomena, is also possible in the amplitude density spectrum, which is derived from the Fourier series transformation and can also be measured (DIN VDE 0847 Part 1).

The interference quantities that originate with the very frequently occurring switching operations in the high-voltage area (primary side) of switchgear installations are listed in Table 5-14. They oscillate with high frequency.

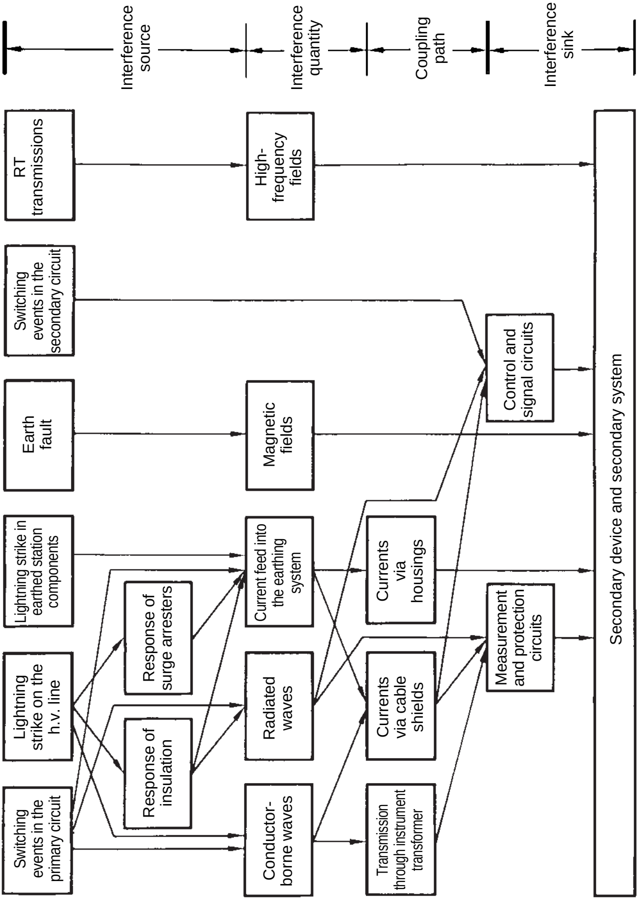
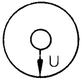
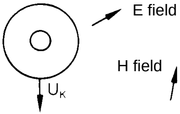
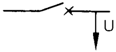
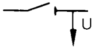
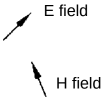


Fig. 5-20

Origin and propagation of interference quantities in switchgear installations.

Table 5-14

Characteristic parameters of interference quantities with switching operations in the primary circuit of high-voltage installations

SF_6 Gas-insulated switchgear (GIS)					Conventional outdoor switchgear installation (AIS)			
					 SF_6 Self-actuating pressure switch	 disconnector		
Quantity	Voltage U	Voltage U_K	E field	H field	Voltage U	Voltage U	E field	H field
Rise time	4 – 7 ns	15 – 50 ns			50 – 100 ns	200 ns	180 – 700 ns	60 – 100 ns
Frequency	kHz – 10 MHz	MHz	– 20 MHz	– 20 MHz	kHz – MHz	kHz – MHz		
Height	system-specific	system-specific	$1^{1)} – 50^{2)}\ \frac{\text{kV}}{\text{m}}$	$2.5^{1)} – 125^{2)}\ \frac{\text{A}}{\text{m}}$	system-specific	system-specific	$5^{3)} – 50^{4)}\ \frac{\text{kV}}{\text{m}}$	$1^{3)} – 2^{4)}\ \frac{\text{A}}{\text{m}}$
Damping	weak	strong	strong	strong	strong	strong	strong	strong
Geometrical distances	small	large			large	large		

1) GIS with building
2) GIS without building

3) 345-kV breakers
4) 500-kV breakers

Interference quantities propagate along the wires and by radiation:

- galvanically, over the apparent resistances of conductors,
- inductively coupled,
- capacitively coupled,
- as a common wave from two conductor systems,
- as a free spatial wave.

Once coupled into the bonding system, earthing system or a signal circuit, the interference quantity moves along the path of the conductor.

An interference quantity varies in time in the course of its propagation according to the coupling between interference source and interference sink:

- partial events may merge,
- an event may be split into partial events.

The spectral energy density of the interference quantity causes the entire system transmitting it to oscillate; see Fig. 5-21, Coupling mechanisms for interference quantities in a high-voltage switchgear installation.

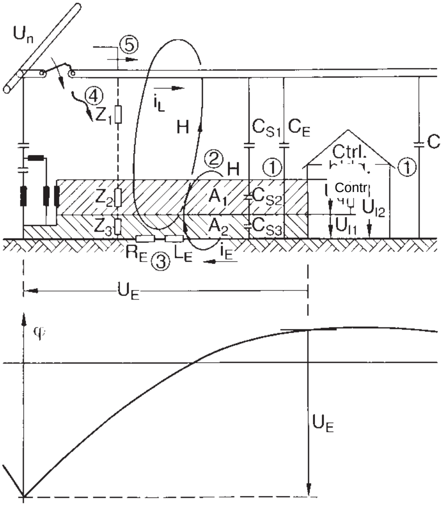


Fig. 5-21

Coupling mechanisms for interference quantities in a high-voltage switchgear installation

U_{l1}, U_{l2} components of longitudinal voltage, U_q transverse voltage

① *Capacitive coupling, C_E capacitance of high-voltage conductor to earth grid, C_{S1}, C_{S2}, C_{S3} capacitances of the secondary system conductor*

② *Inductive couplings, H influencing magnetic fields, A_1, A_2 induction areas*

③ *Galvanic coupling, R_E, L_E resistivity and inductivity of the earth grid, i_E current in earth grid resulting from coupling over C_E*

④ *Radiation coupling*

⑤ *Surge waves from transient processes, Z_1, Z_2, Z_3 wave impedances*

An interference quantity occurs in a current circuit (Fig. 5-22) whose conductors show earth impedances (primarily capacitance). This means that the interference quantity also finds current paths to earth or reference earth. This yields the following interference voltage components:

- symmetrical (differential mode, transverse voltage) between the conductors of the current circuit
- non-symmetrical between a conductor and earth or reference earth
- asymmetrical (common mode, longitudinal voltage) as resultant of non-symmetrical components

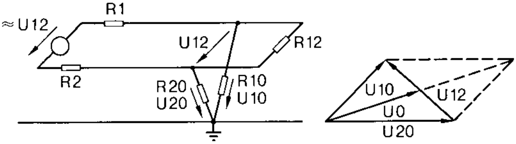


Fig. 5-22

Relationships among potentials of an interference voltage:
U12 symmetrical interference voltage component
U10, U20 non-symmetrical interference voltage components
U0 asymmetrical interference voltage component

If an interference quantity is produced in a current circuit, its asymmetrical component disappears if the current circuit is structured and operated completely symmetrically. The asymmetrical component is the interference quantity, which may cause interference in an isolated sink circuit.

If a conductor of the source current circuit is earthed, i.e. connected with reference earth, its non-symmetrical component becomes very small while the other conductor assumes the symmetrical component as non-symmetrical. In this case, the asymmetrical component is about half the symmetrical.

An asymmetrical interference voltage component coupled to a sink current circuit has a non-symmetrical and a symmetrical component corresponding to the current circuit’s non-symmetry.

5.5.2 Effect of interference quantities on interference sinks

The origin of interference components at the input terminals of a device considered as an interference sink is determined by its design, the operating mode and the design of the connected line and also the device operated via the line.

a) Symmetrical operation:

Symmetrical operating mode for a current circuit occurs when its conductors have equal impedances with respect to reference earth in the frequency range of the useful quantity. Symmetrical operation is achieved by potential separation or the use of differential amplifiers.

- The asymmetrical influence of the line acts equally on both wires of the line and generates non-symmetrical components in accordance with the earth relationships of the line terminals at the equipment. The difference of the non-symmetrical components occurring at higher frequencies is a symmetrical component.

- A symmetrical interference component in the high-frequency range occurs because of non-symmetries of the connected equipment on the asymmetrical coupling path, in the low-frequency range by couplings (inductive for finite area, capacitive for non-symmetrical configuration) in the conductor loop of the line.
- Direct non-symmetrical influence does not occur with symmetrical operation.

b) Non-symmetrical operation:

Non-symmetrical operating mode occurs when the conductors of a current circuit have unequal impedances compared to the reference earth; this is always the case when multiple signal voltages have a common reference conductor.

The interference then affects each wire of the line separately. Particularly in the case of inductive impedances within the equipment, the non-symmetrical interference component on the signal reference conductor is not always zero.

- The symmetrical interference component on the low-frequency range is equal to the non-symmetrical component, and in the high-frequency range approximately equal to the non-symmetrical component.
- The asymmetrical influence has no meaning with non-symmetrical operation.

The ultimate effect of an interference quantity in equipment must be assessed in terms of voltage or current.

An interference effect in or even destruction of a semiconductor only occurs if a voltage (a current) exceeds a specific threshold value and then forms a sufficiently large pulse-time area.

Even if interference does not affect the functioning of an electronic circuit or stop it from functioning, it is essential that the semiconductors used are not overstressed by the interference quantity.

Semiconductors are destroyed by current spikes when exposed to pulsed events or they are affected by cumulative damage until they eventually no longer have the properties required for proper functioning of the device: dielectric strength, current amplification and residual current.

An interference quantity can be superimposed on the useful signal as a symmetrical component and can adversely affect the functioning in the influenced equipment depending on the interference distance (signal level – interference level) or sensitivity.

As a non-symmetrical component, the interference quantity can reach any part of the circuit and result in spurious functions or affect the actual signal processing.

5.5.3 EMC measures

EMC must be planned quantitatively. This means that the interface requirements (emission, strength) must be specified for defined zones (EMC zones). Then the compatibility level is defined, for which various types of decoupling measures are required. In this connection, the bonding system is particularly important.

It is useful to assess the hierarchical elements of a systems, such as the complete plant
equipment room
cubicle assembly
rack assembly
circuit board
circuit section
component
with respect to their multilateral compatibility in their various electromagnetic environments; see Fig. 5-23.

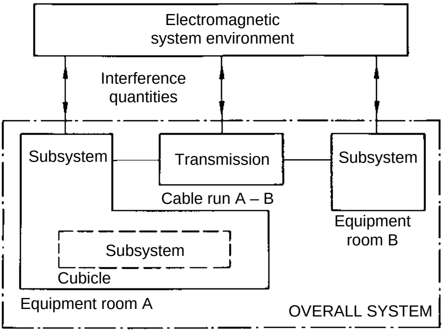


Fig. 5-23

EMC zones in their environment

The purpose of EMC measures is to reduce interference quantities at specific points between the site of origin (interference source) and the site of functional effect (interference sink), see Table 5-15.

Table 5-15

Application of EMC measures in a complete switchgear installation

Zone	Source	Coupling path	Sink
Objective	To reduce Interference emission	To reduce coupling	To enhance interference resistance
Technical measure	Low-inductance earthing	Layout Isolation Equipotential bonding Shielding	Filtering Limitation Optocoupler
	Wiring of relay coils	Balancing Symmetrical operation Non-electrical transmission	
Organizational measures	Separation by coordinating operation processes Fault-tolerant programs and protocols		

The effectiveness of any measures must be assessed depending on the frequency; see Table 5-16. The upper limit frequency for the effectiveness of a measure is limited by the extension of the configuration for which they are used (Lambda/10 rule). This assessment must be applied to the length of earthing conductors, cable shields and their connections, to the side lengths and openings of shielding housings and to the grid size of bonding systems.

Table 5-16

Limit frequencies for the effectiveness of measures

Zone	Upper limit frequency	Max. length
Switchgear installation	100 kHz	300 m
Building	1 MHz	30 m
Equipment room	10 MHz	3 m
Cubicle	15 MHz	2 m
Device (rack – circuit board)	100 – 1000 MHz	30 – 3 cm

EMC measures should prevent or minimize the occurrence of symmetrical and non-symmetrical components. They are generally initially based on minimizing the asymmetrical component and with that, the symmetrical component. Measures against the asymmetrical component are bonding or ground-based. Measures for minimizing the symmetrical component must be compatible with these.

Bonding-based EMC measures are shown in Fig. 5-24 with the example of an outdoor switchgear installation. The following is assumed:

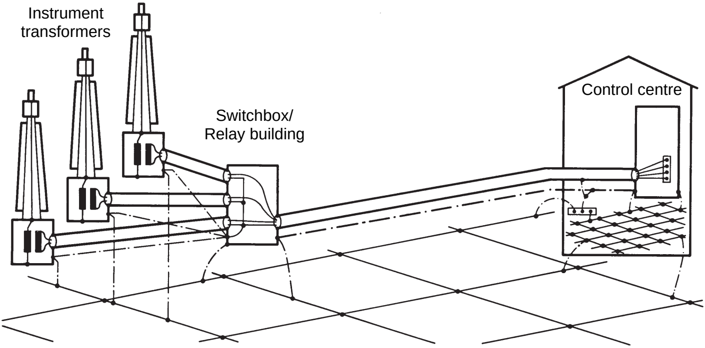


Fig. 5-24

Meshed bonding system and treatment of shielding of secondary wiring in a high-voltage switchgear installation[1]

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[1] ABB publication DSI 1290 88 D, reprint from “Elektrotechnik und Informationstechnik” 105 (1988): p. 357-370: Remde, Meppelink, Brand “Electromagnetic compatibility in high-voltage switchgear installations”.

- secondary lines laid parallel to earth conductors
- screening connected to ground at both ends by coaxial connection wherever possible
- additional equipotential bonding conductor over full length of line
- multiple connection of building earth with the switchgear installation earth
- multiple shield earth connection with increasing density in the direction of the electronics, in accordance with the Lambda/10 rule
- instrument transformer secondary circuit earthed only once per 3-phase group (in local cubicle)

Decoupling measures

The interference level of an interference source acting on an interference sink can be reduced by a number of measures. In most cases, a single type of decoupling measure is not sufficient to achieve the required decoupling damping; several types of measure must be applied in combination. Depending on the design in practice, the following list of options should be considered:

- Routing:
  lines of different interference sensitivity laid separately; minimum clearance, restriction of common lengths.
- Conductors:
  two-wire lines instead of common returns; symmetrical signal transmission with symmetrical source and sink impedances.
- Potential isolation:
  galvanic isolation of the signal circuits at the system boundary; attention to parasitic coupling properties of the isolating components.
- Shielding:
  for extensive compensation of galvanically coupled high-frequency potential differences in the earthing system, generating a negative-sequence field with inductive influence and diversion of displacement currents with capacitive influence.
- Filtering:
  generally low-pass filter with concentrated components.
- Limitation:
  voltage-limiting components (surge arresters) to limit the voltage, but less influence on steepness, source of new interference quantities because of non-linearity; more for protection against destruction than to avoid functional deterioration.
- Equipotential bonding:
  for low-impedance connection of system or circuit sections between which the potential difference should be as low as possible; basic requirement for effectiveness of shielding, filtering and limitation.

Decoupling measures are only effective in restricted frequency ranges (see Fig. 5-25). This makes it all the more important to know what frequency range requires the greatest decoupling damping. The greater the bandwidth of the decoupling is required, the more measures are required in the chain. The basic rule with the application of decoupling measures in the direction of propagation of the interference quantity is to begin with the following:

- from the interference source to the environment with the decoupling of high frequencies,
- from the environment to the interference sink with the decoupling of low frequencies.

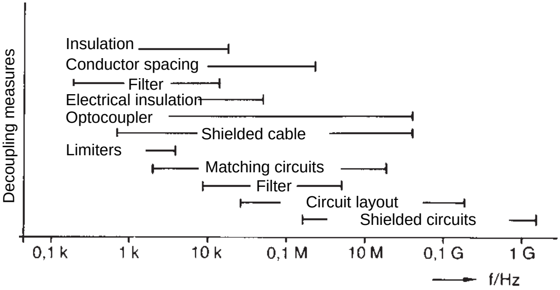

Fig. 5-25

Effectiveness trend of decoupling measures with respect to preferred frequency ranges

Bonding system

The bonding system includes all equipment for electrically connecting the
housing grounds,
shield conductors,
reference conductors where ever they are to be connected to the earth.

DIN VDE 0870 defines the terms for bonding and earthing. Bonding is most important for the requirements of EMC. It is the total of all electrically conductive metallic parts of an electrical system, which equalizes different potentials for the relevant frequency range and forms a reference potential.

Note: The relevant frequency range covers both the functional and the environmental frequencies. This frequency range and the spatial extent of the electrical equipment determine the achievable equipotential bonding and therefore the effectiveness of the bonding system. The bonding does not always cover the safety requirements of the potential equalization.

The bonding can be connected with the earth (protective measures); this is the general rule in switchgear installations.

Telecommunications equipment in particular can be operated with functional earthing. In this case, the earthing has the purpose of enabling the required function of an electrical system. The functional earthing also includes operating currents of those electrical systems that use the earth as a return.

An equipotential bonding between system parts intended for protection against unacceptably high touch voltages and also for electromagnetic compatibility must have sufficiently low resistivity even in the high frequency range in which the line inductance is dominant. This can be done by designing the bonding system as a mesh configuration, which reduces the inductance by up to 5 times more than linear systems. The effectiveness of this measure is limited by the grid size for high frequencies (see Table 5-16).

The leakage currents from limiters, filters and shielding must be considered in the design of a bonding system and coupling in signal circuits must be avoided.

Extended conductors, which of course include conductors for equipotential bonding, are also subject to electromagnetic interference quantities. Coupling an electromagnetic wave carried by a line is reduced as the effective area of the conductor picking up the interference increases. The inductive coupling with meshed conductors is reduced by generating opposing fields around the conductors of the mesh. Therefore, meshed systems, combined with their effective capacitance, particularly with the influence of the housing grounds installed over them, have an excellent stable potential in whose vicinity the influence on the signal lines is low, similar to laying them in natural soil with its natural electrical properties.

The more extensive the design of a system, the more difficult is it to implement a continuous ground plane. For this reason, such grounds are only hierarchical, correspondingly limit the EMC areas and must be consistently linked to the entire bonding system with consideration of their limit frequency. Potential differences between the earths of subsystems distant from one another must be accepted. This means that a non-symmetrical transmission of small signals of high bandwidth between these subsystems may be subject to interference.

The bonding system set up with reference to EMC must be assessed according to the following regulations:

- DIN VDE 0160 for heavy-current installations with electronic equipment
- DIN VDE 0800 for the installation and operation of telecommunications systems including data-processing systems
- DIN VDE 0804 for telecommunications devices including data-processing devices

DIN VDE 0160 deals with the properties of the operational leakage currents (from all practical busbar systems) that can occur in industrial power systems in the data processing and heavy current subsystems.

In this case, a hierarchical, radial earthing design offers advantages for decoupling the subsystems and systems with respect to interference.

DIN VDE 0800 and 0804 deal with the requirements of more extended data-processing systems where the levels handled are generally of the same order of magnitude and interference by common busbars is not anticipated, making it unnecessary to decouple the busbars. This is advantageous for the treatment of the signal interfaces.

Systems and subsystems complying with the above regulations can be integrated into an earthing/bonding concept if a bonding system with a superimposed protective conductor system is designed. The interface between the subsystems and their environment is defined as follows:

- protective conductor connection
- bonding system connection.

For more general reasons, structures intended for installation in systems (radial or mesh) may be specified for the bonding system. It is possible to use radial substructures in a meshed bonding system with no particular measures.

If a radial bonding system is specified (Fig. 5-26), the earths of the subsystems must only be connected together over the common equipotential bonding. This means that the following configurations are not permitted when signals are exchanged between subsystems:

- shielding connected at both ends,
- signal exchange with reference to a common signal reference conductor connected to the earth at both ends
- signal exchange over coaxial cable connected to earth at both ends.

This means that signal connections between subsystems must be configured in a radial bonding system to be always isolated.

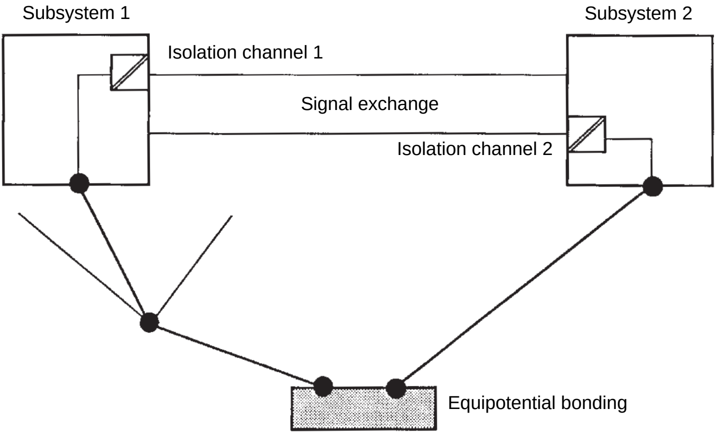

Fig. 5-26

Two subsystems in a radial bonding system

Shielding

Cables are shielded to protect the internal conductors of the cable against interference, which can be coupled capacitively and inductively or galvanically (alternating values). With respect to the effect, the shielding must initially be considered as the influenced conductor. Coupling interference quantities in this conductor yields a current that generates a voltage between the inner conductor and shield as a product of the shielding current and the complex shield resistance. The complex shield resistance is identical to the shield-coupling resistance. The lower the shield resistance, the greater the decoupling effect of the shield. In practice, it is essential to include the resistance of the entire shield circuit, i.e. the shield connection, in the calculation.

A shield that is connected to reference earth at just one end only acts against the capacitive interference. It then forms a distributed low-pass filter whose full capacitance acts at the end of the line to which the shield is connected. The interference coupling tends to increase at the open end of the shield, which becomes particularly evident at high interference frequencies.

If a shield can only be earthed at one end, this should always be the point of lower interference resistance. This is often the receiver, amplifier or signal processor side.

A shield earthed at both ends, closes the current circuit around the area carrying a magnetic flux. A current that acts against the interference field according to the Lentz rule flows and so has a decoupling effect on the conductors of the shielded cable. This effect can also be induced with non-shielded lines by using free wires or closely parallel earth conductors as substitute shields.

The assumption here is that the shielded line is not influenced by low frequency shield currents resulting from equipotential bonding. This requirement is met by a bonding system that has sufficiently low impedances with the relevant frequencies. For frequencies where the external inductive component of the shield resistance is sufficiently large compared to its real component, i.e. at high frequencies, a coupling caused by potential difference is reduced to a value only induced by the transfer impedance.

The higher limit frequency of the shield effect depends on the length of the shield between its connections to earth. Therefore, a shield must be connected to earth at shorter intervals, the higher the limit frequency of its effectiveness should be. Fig. 5-27 shows typical methods of connecting shields for control cables.

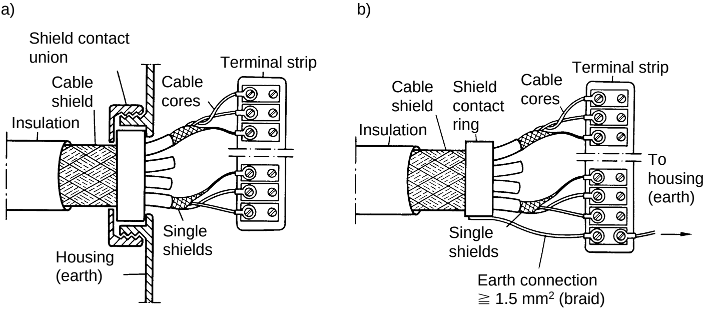

Fig. 5-27

Methods of connecting shielded control cables:
a) coaxial (preferred) b) braided (less effective)

There are (fully insulated) devices with no connection to a protective conductor system. However, they have an inner shield for connection to the shield of the signal lines. This shield may carry interference voltages relative to its environment (“remote earth”).

The manufacturer’s directions for installation of all types of devices must be observed, without affecting the structure of the bonding system (DIN VDE 0160 or DIN VDE 0800/0804).

Cable shields should always be connected at both ends. The ground connection between the subsystems to be connected with the shielded cable should have a lower resistance than the shield circuit. This is sufficient to prevent interference from bonding currents on the shield.

The relevant equipment can have a shield conductor rail (as per DIN VDE 0160) or special shield conductor terminals (as per DIN VDE 0800). Design in accordance with DIN VDE 0800 should be preferred for data-processing systems when considering the possibility of interference. Where several systems interact, both bonding principles can be applied independently with reference to their shield connections, as shown in Fig. 5-28.

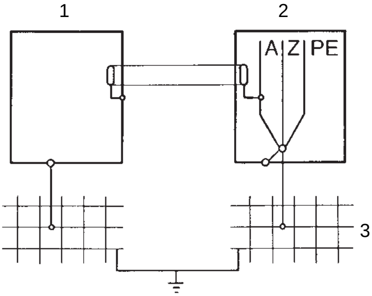

Fig. 5-28

Shielding of systems as per DIN VDE 0160 and 0800:

1 shielding as per DIN VDE 0800, 2 shielding as per DIN VDE 0160 with busbars A to connection of shield conductor, Z to connection of the signal reference conductor, PE to connection of protective conductor, 3 spatial bonding system(s)

Cable routing

Signal cables of control systems must always be laid separately from the general installation network. However, power supply cables leading from a central distribution point to subsystems (e.g. peripheral devices) should be laid with the signal cables. – A clearance of more than 0.3 m between the cables is sufficient for separate cable laying.

In the control rooms, the power supply lines are laid in a radial pattern from the low-voltage distributors to the various devices or subsystems. They are laid along the conductors of a bonding system that is meshed wherever possible.

Switch cabinets

The following information applies for proper design of switchbays with respect to EMC:

- Wide-area, metallic conductive equipotential bonding of all metallic components of the switchbox together is essential.
- Use support plates, rails and racks of galvanized sheet steel only. Note: painted, anodized or yellow-passivized components in some cases have very high resistance values above the 50 Hz frequency.
- Metallic components and parts inside the switchbay must be connected over a wide area and reliably. Ensure that appropriate contact material (screws and accessories) is selected.
- Wide-area, low-resistance earthing of interference sources (equipment) on support plates and racks prevents unwanted radiation.

- The cable layout inside the cabinet should be as close as possible to the reference potential (cabinet ground). Note: freely suspended cables act preferably as active and as passive antennas.
- Unused wires, particularly those of motor and power cables, should be placed on protective conductor potential (PE) at both ends.
- Unshielded cables and wires of a circuit – i.e. feed and return – should be twisted together because of symmetrical interference.
- Relays, contactors and magnetic valves must be switched by spark suppressor combinations or by overvoltage-limiting components. Line filters or interference suppression filters increase the interference resistance of the switchgear installation depending on the interference frequency at the network input.

5.6 Partial-discharge measurement

Partial-discharge measurement is an important tool for assessing the status of high-voltage insulation. It is a proven technique for diagnosing errors in the laboratory, for quality assurance in production and on-site for all high-voltage equipment, such as transformers, instrument transformers, cable systems, insulating bushings and gas-insulated switchgear.

Partial discharges can damage solid insulation materials in the interior and on the surface and may result in breakdown of the insulation. Partial discharges can decompose fluid and solid insulation.

Technical interpretation of the results obtained from the partial-discharge measurements enables detection of weak points at or in insulation systems and provides information on the continuing availability of the equipment.

Partial discharges (PD) are low-energy electrical discharges, which bridge only part of the insulating clearance. They occur when the electrical strength between electrodes of different potential is exceeded at a localized point and result in brief discharges of partial capacities within insulation. These fleeting phenomena result in high-frequency interference fields. In practice, the operator should be aware of possible damage to insulation, emission of electromagnetic interference fields (EMC) and the development of noise (corona).

Partial discharges may occur as follows:

- in cavities inside solid insulation materials,
- at unhomogenous points of the electrical field in solid, fluid and gas insulation materials
- in conductors without fixed potential and stray particles in the area of electrical fields.

Some typical sources of partial discharges are shown in Fig. 5-29.

Partial discharges are verified by

- electrical partial-discharge measurement,
- acoustic partial-discharge measurement,
- optical partial-discharge measurement,
- chemical tests.

Electrical partial-discharge measurement is discussed below.

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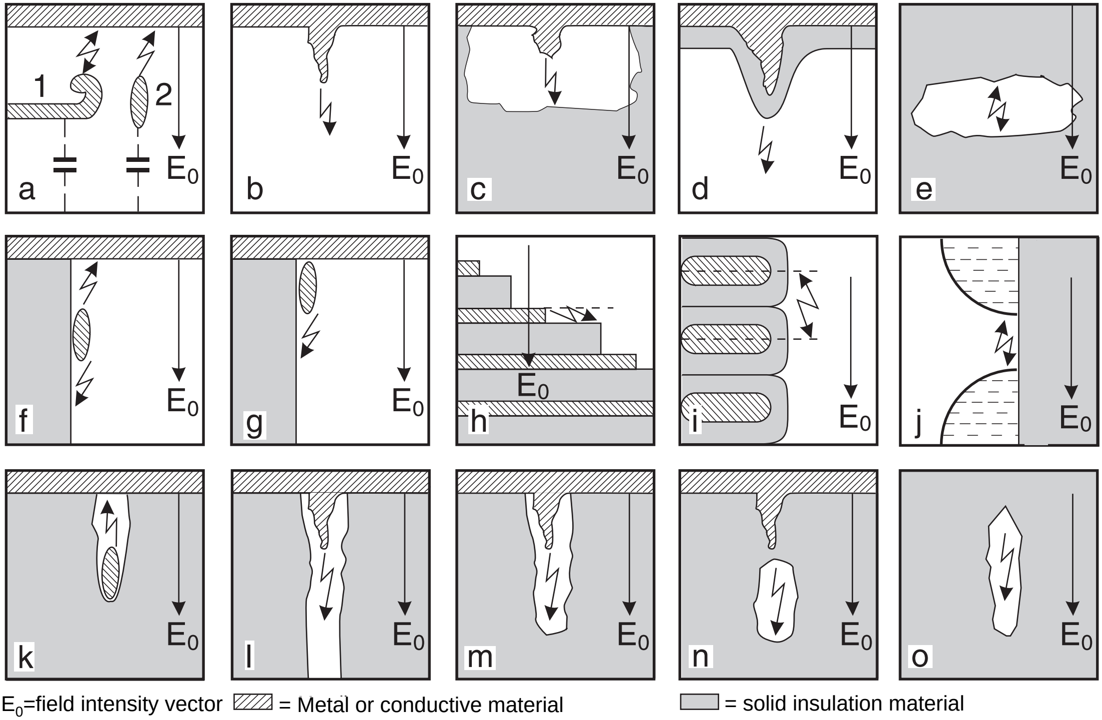

Fig. 5-29 Sources of partial discharge at electrodes, insulation and in gas

5.6.1 Partial discharge processes

There is a basic distinction between internal and external partial discharges.

Internal partial discharges

Internal partial discharges are gas discharges that occur in the cavities of solid insulation material and in gas bubbles in fluid insulation material. This includes discharges in cavities between insulation and electrode (Fig. 5-29 c) and within an insulating body (Fig. 5-29 e).

Fig. 5-30 a shows a faulty insulating body. The non-faulty dielectric is formed by the capacitances C'_3, the gas-filled cavity by C_1 and the element capacitances above and below the fault position by C'_2. The replacement configuration of the insulating body is shown in Fig. 5-30 b. A spark gap F is placed parallel to the cavity capacitance C_1. If the disruptive discharge voltage of the gas-filled fault point is exceeded, it will break down and the capacitance C_1 will be discharged.

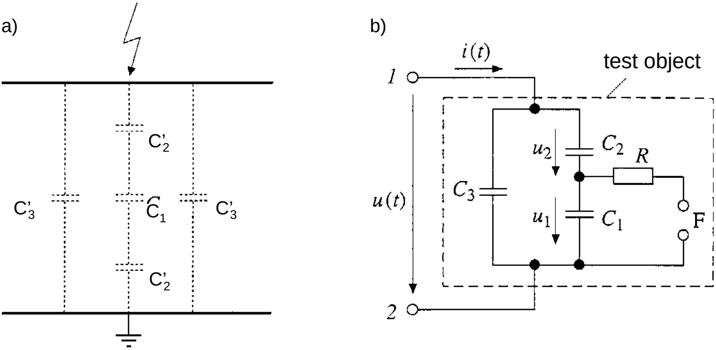

Fig. 5-30

Configuration with internal partial discharges:
a) material background b) equivalent c.t. circuit

If alternating voltage u(t) is applied at the terminals of the equivalent circuit, the voltage at the capacitance of the cavity is found

$$u_{10}\,(t) = \frac{C_2}{C_1 + C_2}\,\hat{U} \cdot \sin(\omega\, t)$$

Fig. 5-31 a shows the two voltage processes. If voltage $u_{10}(t)$ exceeds igniting voltage U_Z of the gas-filled cavity, the spark gap F breaks down and the capacitance C_1 discharges. The persistent voltage value on the test object is referred to as partial discharge (PD) inception voltage. If the voltage on the test object u(t) exceeds this value, the internal discharge will spark several times during a half-wave.

When C_1 is discharged via F, pulse-shaped capactive charging currents i(t) – only partially fed from C_3 but primarily from the external capacitances of the circuit – are superimposed on the network-frequency alternating current (Fig. 5-31 b). The

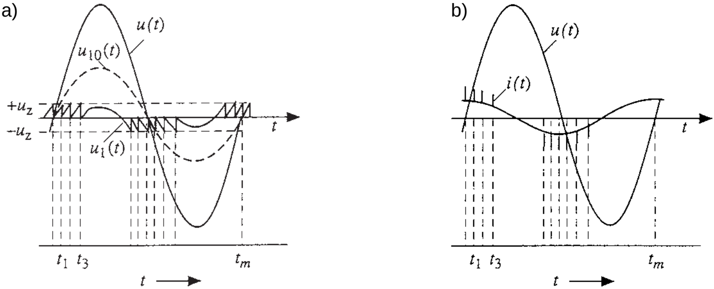

Fig. 5-31

a) voltage characteristics in the equivalent-circuit diagram for pulse-type internal partial discharges
b) current characteristics in the equivalent-circuit diagram for pulse-type internal partial discharges

accumulation of impulses in the area of the zero crossings of voltage u(t) – generally overwhelmingly in the area after the zero crossings – is an indicator for discharges in the cavities of solid insulation materials.

External partial discharges

If the field intensity at air-insulated electrode configurations (e.g. outdoor fittings) – such as in the area before the sharp edges – exceeds the electrical strength of air as a result of impulse ionization in the heavily loaded gas space electron avalanches and photoionization will occur, ultimately resulting in partial breakdown of this area (trichel impulses).

Figs. 5-32 a and b shows a simplified view of the processes with the associated equivalent circuit. In the diagram, C_1 represents the gas space through which the partial discharge breaks down and resistance R_2 represents the charge carriers formed before the peak, which move around in the field cavity and result in a degree of conductivity.

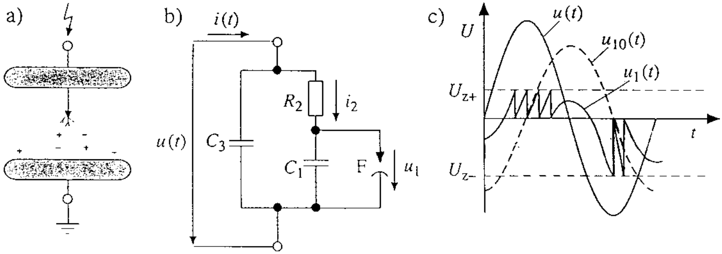

Fig. 5-32

Configuration with external partial discharges: a) peak plate configuration b) equivalent-circuit diagram c) voltage characteristics in the equivalent-circuit diagram for pulse-type external partial discharges.

The associated voltage characteristics of the configuration are shown in Fig. 5-32 c.The voltage characteristic $u_{10}(t)$ at C_1 before the beginning of the first partial discharge follows the equation

$$u_{10}\,(t) = \frac{\hat{U}}{\omega C_1\, R_2}\,\sin(\omega t - \frac{\pi}{2})$$

The response of the spark gap F in the equivalent-circuit diagram shows the pulse-shaped partial breakdown. If the voltage at the test object is sufficiently high over a time range, the result is a number of PD impulses per half-wave. An indication of external partial discharges on sharp-edged electrodes is the accumulation of impulses in the range of the peak values of the external voltage u(t) applied at the fittings.

5.6.2 Electrical partial-discharge measurement procedures

Electrical partial-discharge measurement according to IEC 60270 (DIN VDE 0434)

In the course of almost 40 years of use with simultaneous intensive development of the procedures, this procedure, which is based on the measurement of the apparent charge of the PD impulses at the test object terminals, has become very widespread in the area of high-voltage installations and devices.

Three different test circuits can be used (Fig. 5-33). The coupling capacitor C_K and the four-terminal coupling circuit Z_m (and Z_{m1}) are required for partial-discharge measurement. Impedance Z protects the high-voltage test source and acts as a filter against interference coupled from the network.

The high-frequency high-capacity charging current resulting from the partial discharges in the test object feeds the test object capacitance C_a from the coupling capacitance C_K. Therefore, ratio C_K/C_a determines which charge component at four-terminal coupling circuit Z_m can be measured, i.e., C_K determines the sensitivity of the PD measurement. The quantitative evaluation of the partial-discharge measurement is based on the integration of the high-capacity charging current. This is integrated in the partial discharge instrument within a fixed frequency band.

With respect to the strong influence of the test object and the instrumentation on the result, the test circuit must be calibrated before every test cycle with the test object connected. During this process, a calibration pulse generator feeds defined charge impulses to the terminals of the test object.

The partial discharge instrument gives the apparent charge as a numerical value with the dimension pC (pico-coulomb) as the result of the measurement. The phase angle of the partial charge impulses based on the applied test voltage is also significant. Different displays are shown on monitors for this purpose. Modern devices show the amplitude, rate of occurrence, frequency and phase angle at a specific voltage in a colour image (Fig. 5-34).

The test circuit as shown in Fig. 5-33a is preferred for measurements in practice. In the case of laboratory measurements where the test object is isolated from ground, the test circuit as shown in Fig. 5-33b is suitable.

The partial-discharge measurement technology distinguishes between narrow-band and broad-band partial-discharge measurement. This classification is based on the frequency segment in which the partial discharges are recorded. While measurement with the narrow-band measurement in an adjustable frequency band is done with selected mid-frequency, the broad-band method covers a frequency range of 40 kHz to

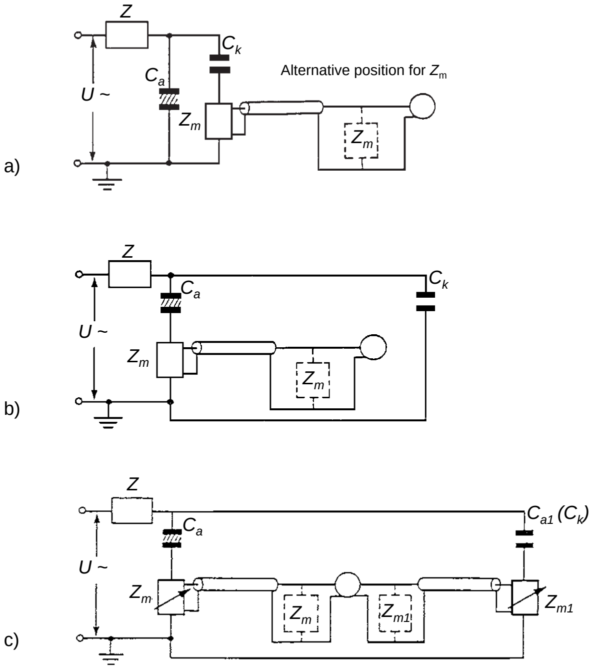

Fig. 5-33

Basic circuit from IEC Publication 60270:
a) + b) direct measurement c) bridge measurement

800 kHz. Interference couplings are a particular problem, as they tend to occur in measurements on site as a result of a lack of shielding. There are now a number of countermeasures for this, such as narrow band measurements and active gate circuits. Another method is to use the bridge test circuit shown in Fig. 5-33 c.

Partial discharges within encapsulated switchgear installations are frequently located by acoustic partial-discharge measurement in addition to electrical partial-discharge measurement. It reacts to the sound energy that is generated by partial-discharge activity. Sensitive sensors, such as parabolic mirrors and structural sound pickups, detect these sounds in the frequency range between 20 kHz and 100 kHz.

UHF measurement

The PD impulse in SF_6-isolated high-voltage installations has a wide frequency

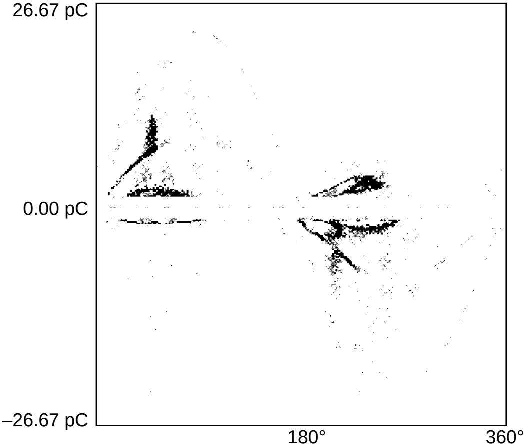

Fig. 5-34

Characteristic partial-discharge image

spectrum up to the GHz range. The electromagnetic waves generated in this process spread inside the encapsulation in the form of travelling waves. They can be detected using capacitive probes integrated into the encapsulation (Fig. 5-35) and used to locate the fault positíon.

However, this requires several probes in one installation, and also the laws of travelling wave propagation, including the effects of joints (such as supports) and branching must be taken into account in the interpretation.

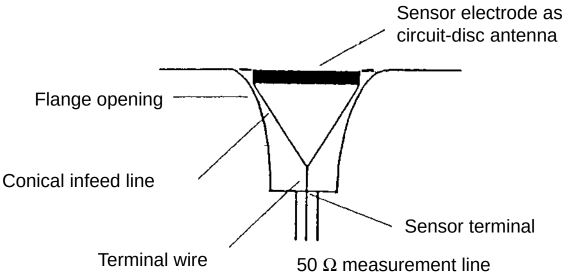

Fig. 5-35

Cone sensor in the flange of a GIS

The characteristic partial-discharge images formed with UHF measurement are similar to those formed by conventional measurement. The measurement sensitivity is not determined with a calibration pulse generator but by applying a voltage to one of the UHF PD probes to determine the transmission function of the installation, including the other PD probes.

One great advantage of the UHF measurement (Ultra High Frequency, 300 MHz to 3 GHz) is the significant decrease of external interference in this frequency range.

UHF measurement by permanently installed probes is particularly suited for monitoring high-voltage installations during operation. Measurements can be made continuously while storing the measured values or at regular intervals (monitoring).

5.7 Effects of climate and corrosion protection

The operational dependability and durability of switchgear installations and their components are strongly influenced by the climatic conditions at their place of installation.

There are two aspects to the demand for precise and binding specifications for these problems:

- The description of the climatic conditions to be expected in service and also during storage, transport and assembly.
- The specification of the test conditions or design requirements that ensure reliable functioning under defined climatic conditions.

5.7.1 Climates

The standard DIN EN 60721-3, “Classes of environmental influence quantities and their limit values”, is a comprehensive catalogue of classes of interconnected environmental factors. Every class is identified with a three-character designation as follows:

1st place: type of product use
(1 = storage, 2 = transport, 3 = indoor application, 4 = outdoor application etc.)

2nd place: type of environmental influence

(K = climatic conditions, B = biological conditions, C = chemically active substances etc.)

3rd place: assessment of the severeness of the environmental influences (higher figures = more difficult conditions)

For example, class 3K5 can be considered for applications of indoor switchgear installations in moderate climate zones. It indicates a total of 16 parameters of different climatic conditions. The most important are summarized in Fig. 5-36 in the form of a climatic diagram.

It must not be assumed that one or even more of the given limit values will occur in service continuously; on the other hand it is also assumed that they will be exceeded for a short period or in rare cases, but with a probability of < 0.01.

The classification of environmental conditions only provides manufacturers and users of electrotechnical products with an orientation and a basis for dialogue. The IEC committees responsible for the product groups are expected to use them as a basis

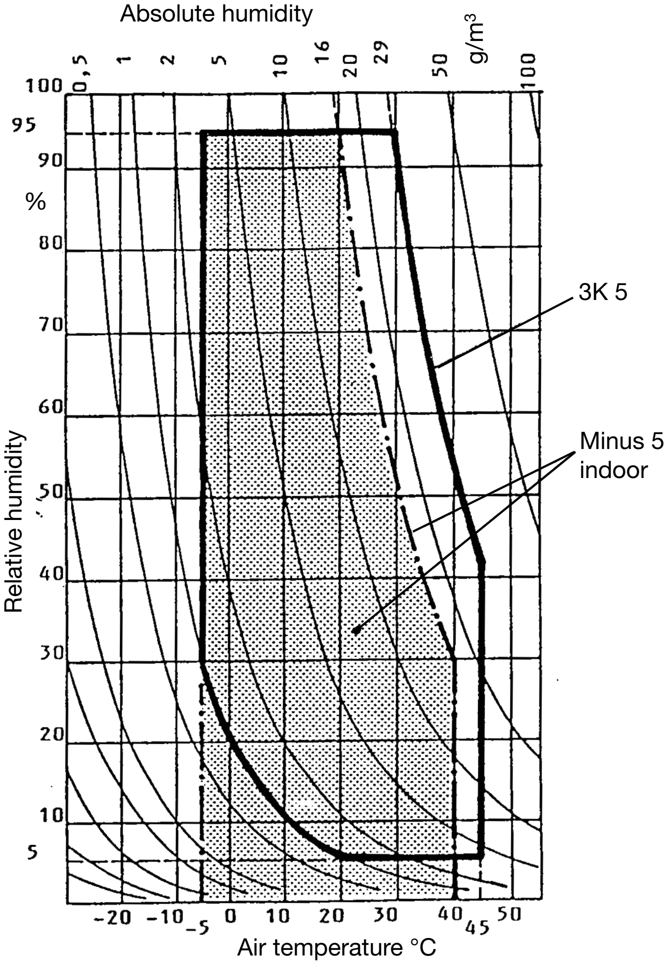

Fig. 5-36

Climatic service conditions for indoor switchgear
Climate diagrams as per DIN EN 60721-3 for class 3K5
and as per DIN EN 60694 for class "Minus 5 indoor"

Table 5-17

Normal and special climatic service conditions for indoor application
N = normal service conditions (with variations N_1, N_2 etc.)
S = special service conditions

Environmental influence	High-voltage switchgear and controlgear DIN EN 60694 (VDE 0670 Part 1000)	Low-voltage switchgear assemblies DIN EN 60439-1 (VDE 0660 Part 500)
Minimum temperature	N_1: – 5°C N_2: – 15°C N_3: – 25°C S: – 50°C/+ 40°C	N: – 5°C
Maximum temperature	N_1: + 40°C N_2: + 35°C (24h average) S: + 50°C/– 5°C	N: + 40°C
Relative humidity	N: 95% (24h average) N: 90% (monthly average) S: 98% (24h average)	N: 50% at 40°C N: 90% at 20°C
Water vapour partial pressure[1]	N: 2.2 kPa (24h average) N: 1.8 kPa (monthly average)	
Condensation	occasional	occasional
Solar radiation	negligible	N: none S: present, caution!
Installation height	N: ≤ 1000 m S: > 1000 m (with dielectric correction)	≤ 2000 m[2]

[1] 2.2 kPa = 22 mbar = 16 g/m3
1.8 kPa = 18 mbar = 12 g/m3

[2] > 1000 m special agreement for electronic equipment

for unified specifications for normal and special service conditions. Tables 5-17 and 5-18 show the corresponding specifications in the product standards DIN EN 60694 (VDE 0670 Part 1000) – High-voltage switchgear and controlgear[3] – and DIN EN 60439-1 (VDE 0660 Part 500) – Low-voltage switchgear assemblies.

These standards also include specifications regarding additional environmental conditions such as contamination, oscillations caused by earthquakes, technically originated external heat, electromagnetic influence etc.

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[3] Compare the climatic diagram (Fig. 5-36).

Table 5-18

Normal and special climatic service conditions for outdoor application
N = normal service conditions (with variations N_1, N_2 etc.)
S = special service conditions

Environmental influence	High-voltage switchgear and controlgear DIN EN 60694 (VDE 0670 Part 1000)	Low-voltage switchgear assemblies DIN EN 60439-1 (VDE 0660 Part 500)
Minimum temperature	N_1: –10 °C N_2: –25 °C N_3: –40 °C S: –50 °C/+ 40 °C	N_1: –25 °C N_2: –50 °C
Maximum temperature	N_1: +40 °C N_2: +35 °C (24h average) S: +50 °C/–5 °C	N: +40 °C +35 °C (24h average)
Condensation and Precipitation	are to be considered	100 % rel. humidity at +25 °C
Solar radiation	1000 W/m^2	N: –– S: If present, caution!
Ice formation	N_1: 1 mm thickness N_2: 10 mm thickness N_3: 20 mm thickness	
Installation height	N: ≤ 1000 m S: > 1000 m (with dielectric correction)	≤ 2000 m[1)]

[1)] above 1000 m special agreement for electronic equipment

Switching devices, including their drives and auxiliary equipment, and switchgear installations must be designed for use in accordance with their ratings and the specified normal service conditions. If there are special service conditions at the installation site, specific agreements are required between manufacturer and user.

5.7.2 Effects of climate and climatic testing

Fig. 5-37 uses examples to indicate the variety of influences possible on switchgear in service resulting from climatic conditions. The development and manufacture of devices and installations that resist these influences require considerable experience. Additional security is provided by conducting appropriate tests based on the relevant product standards. The following are some examples:

– Wet-test procedure of the external insulation of outdoor switchgear as per DIN IEC 60060-1 (VDE 0432 Part 1)

– Limit temperature tests of high voltage circuit-breakers as per DIN VDE 0670-104 (VDE 0670 Part 104)

– Switching of disconnectors and earthing switches under severe icing conditions as per DIN EN 60129 (VDE 0670 Part 2)

– Testing of indoor enclosed switchgear and controlgear (1 kV to 72.5 kV) for use under severe climatic conditions (humidity, pollution) as per IEC Report 60932.

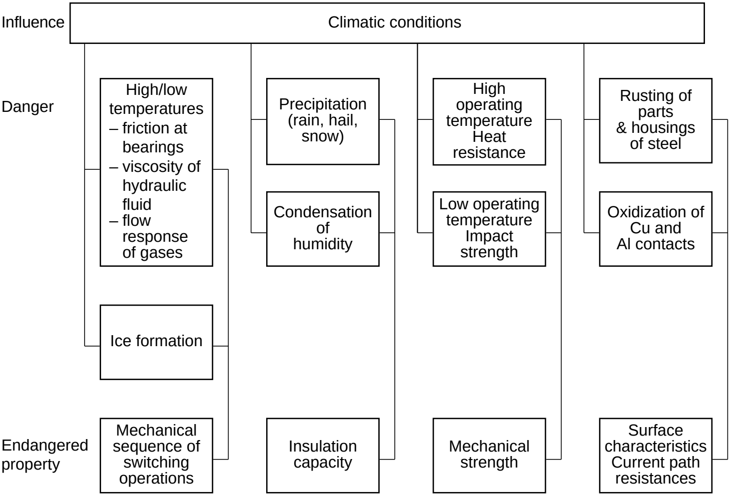


Fig. 5-37

Ways that switchgear and installations are affected by climatic conditions

5.7.3 Reduction of insulation capacity by humidity

The reduction of insulation capacity by humidity is particularly significant on the surface of insulators. With outdoor devices, humidity results primarily from precipitation, such as rain, hail, snow, while in the case of air-insulated indoor switchgear and inside gas-insulated installations (GIS), the problem is condensation from moisture that was previously a component of the ambient gas or the atmosphere.

The moisture content of a gas mixture can be expressed in different ways. From the physicist's point of view, the scale for the fractions of the components of a gas mixture is the partial pressures. The partial pressure of a component is the pressure that is measured at a given temperature if this component is the only constituent of the total volume of the mixture. In the event of unintended admixtures, as observed here, the partial pressure of water vapour varies in the mbar range or when considered as absolute moisture in the range of a few g/m^3. Another possibility of expressing the moisture content quantitatively is to determine the "dew point", i.e. the temperature at which condensation occurs. This information is the most meaningful for the switchgear operator. Fig. 5-38 shows the relations.

The sequence of the reduction of insulation capacity by moisture is the same for all three types of insulator surfaces: Initially only a very slight current flows over the humidity film along the insulator surface because of the very low conductivity of the pure water of the film. Partial discharges along the current path yield decomposition products that continually increase the conductivity until the insulator surface is permanently damaged or a flashover occurs. Any outside contamination that is present already in the beginning significantly accelerates the deterioration process.

Countermeasures for outdoor switchgear are limited to the selection of material (ceramic, glass, cycloaliphatic resins, silicone rubber) and the selection of the creepage distance (cf. DIN EN 60071-2 (VDE 0111 Part 2)). Usage of specific minimum lengths for creepage paths and also material selection are also very important for indoor insulation in atmospheric air. However, condensation can also be prevented if required by the use of air-conditioning or by raising the temperature slightly inside switchbays and cubicles with small anticondensation heaters.

In the case of gas-insulated switchgear (GIS), the problem is different. The moisture content of the insulating gas is not due to climatic conditions but is primarily brought in as the moisture content of solid insulation materials and only gradually transferred to the insulation gas. The installation of drying filter inserts with sufficient moisture-absorbing capacity has been found to be a suitable means of keeping the moisture content of the gas or the dew point low (≤ –5°C).

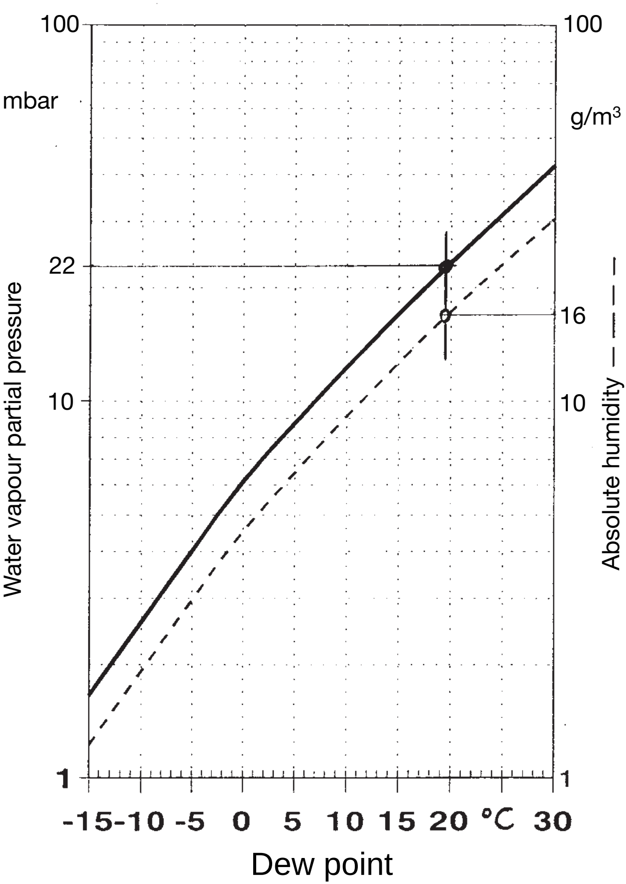


Fig. 5-38

Relation between water-vapour partial pressure, absolute humidity and dew point
10 mbar = 1 kPa

5.7.4 Corrosion protection

Design regulations for preventing corrosion are not included in national and international standards. They are a part of the manufacturer's experience and can be found in internal documents and also occasionally in the supply regulations of experienced users. The following are examples of proven measures:

- Painting and galvanizing sheet metal and sections of steel, aluminium and stainless steel (Fig. 5-39)
  Note: Top-coat varnishing can be done in one pass with the powder-coating process applied to the appropriate thickness instead of several wet-coating passes.
- Structural components of mechanical drives and similar of steel, which are required to meet close tolerances or antifriction properties, such as shafts, latches and guideways, can be effectively protected from corrosion for use indoors by manganese or zinc phosphor treatment (5-8 µm) concluded by an oil bath.
- Structural components of steel which are not subjected to any specific mechanical demands and standard parts are generally galvanized with zinc (12 µm) and then chromatized (passivization).
- Conductor materials such as copper and aluminium must be silver galvanized (20 µm) in contact areas with spring-loaded contacts. Aluminium requires application of a copper coating (10 µm) before the silver is applied. A silver coating of about 20 µm has the optimum resistance to mechanical friction.
  The appearance of dark patches on silver surfaces is generally no reason for concern, because the oxidation products of silver are conductive and this will not greatly affect the conductivity of the contact. The oxidation products of copper are non-conductive, so oxidation on copper surfaces can easily result in an increase in the temperature of the contact and then result in serious problems.
  Oxidation gradually reduces the thickness of the silver coating. Under normal indoor conditions, climatic influences will not generally result in complete loss of the silver coating. However, this must be taken into consideration in industrial premises with particularly chemically aggressive atmospheres. Under these circumstances it may be necessary to use partially gold-plated contacts, even in the area of power engineering.

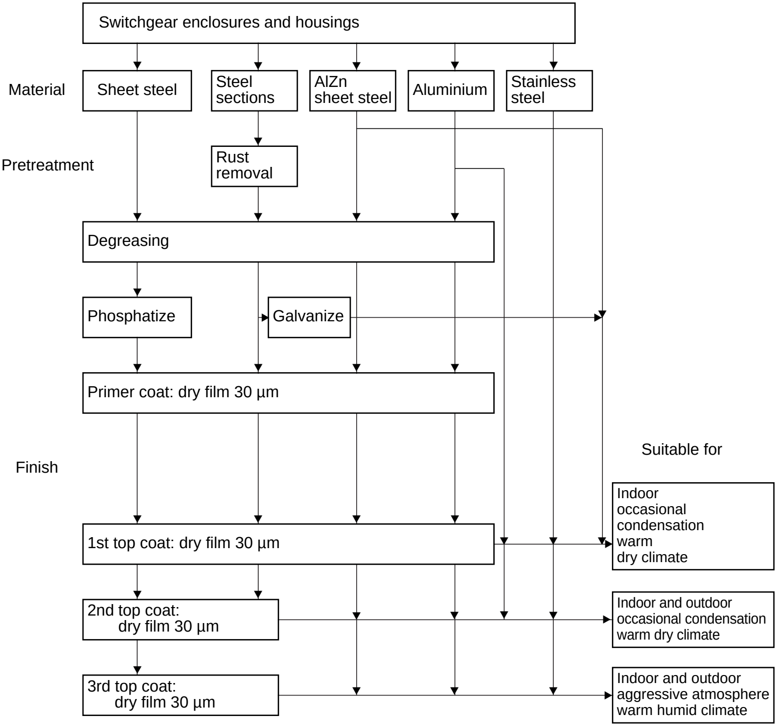


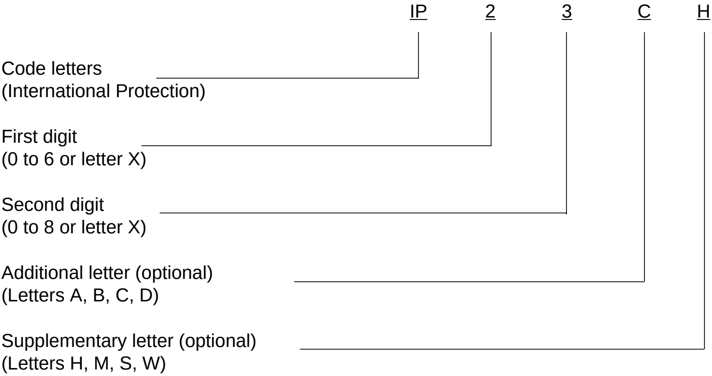
Fig. 5-39

Surface treatment and coating for switchgear installations

5.8 Degrees of protection for electrical equipment of up to 72.5 kV (VDE 0470 Part 1, EN 60529)

The degrees of protection provided by enclosures are identified by a symbol comprising the two letters IP (International Protection), which always remain the same, and two digits indicating the degree of protection. The term ”degree of protection” must be used to indicate the full symbol (code letters, code digits).

Layout of the IP Code



If a code digit is not required, it must be replaced by the letter “X” (“XX”, if both digits are not used).

Table 5-19

IP - degrees of protection

Component	Digits or letters	Significance for protection of the **equipment**	Significance for protection of **persons**
Code letters	IP	–	–-
First digit	0	not protected	
		Protection against ingress of solid bodies	Protection against access to hazardous parts with
	1	≥ 50 mm diameter	back of the hand
	2	≥ 12.5 mm diameter	fingers
	3	≥ 2.5 mm diameter	tools
	4	≥ 1.0 mm diameter	wire ≥ 1.0 mm Ø
	5	dust-protected	wire ≥ 1.0 mm Ø
	6	dustproof	wire ≥ 1.0 mm Ø
Second digit	0	not protected	
		Protection against ingress of water with harmful effects for	
	1	vertical drops	
	2	drops (15 ° angle)	
	3	spray water	
	4	splash water	
	5	jet water	
	6	strong jet water	
	7	temporary immersion	
	8	continuous immersion	
Additional letter (optional)			Protection against access to hazardous parts with
	A		back of hand
	B		finger
	C		tool
	D		wire (1.0 mm Ø, 100 mm long)
Supplementary letter (optional)		Supplementary information especially for	–
	H	High-voltage devices	
	M	Movement during water test	
	S	Stationary during water test	
	W	Weather conditions	

Examples for application of letters in the IP code

The following examples are intended to explain the application and the configuration of letters in the IP code.

IP44 – no letters, no options
IPX5 – first digit omitted
IP2X – second digit omitted
IP20C – use of additional letters
IPXXC – omission of both digits, use of the additional letter
IPX1C – omission of the first digit, use of the additional letter
IP2XD – omission of the second digit, use of the additional letter
IP23C – use of the supplementary letter
IP21CM – use of the additional letter and the supplementary letter
IPX5/ – indication of two different protection classes by one housing against
IPX7 – jet water and against temporary immersion for “versatile” application.

6 Methods and aids for planning installations

6.1 Planning of switchgear installations

6.1.1 Concept, boundary conditions, pc calculation aid

The process of planning switchgear installations for all voltage levels consists of establishing the boundary conditions, defining the plant concept and deciding the planning principles to be applied.

The planning phase is a time of close cooperation between the customer, the consulting engineer and the contractor.

The boundary conditions are governed by environmental circumstances (plant location, local climatic factors, influence of environment), the overall power system (voltage level, short-circuit rating and arrangement of neutral point), the frequency of operation, the required availability, safety requirements and also specific operating conditions.

Table 6-1 gives an indication of the boundary conditions which influence the design concept and the measures to be considered for the different parts of a switchgear installation.

In view of the equipment and plant costs, the necessity of each measure must also be examined from an economic standpoint.

Taking the busbar concept as an example (Table 6-3), the alternatives are evaluated technically and economically. The example is valid for h.v. installations, and to some extent m.v. installations as well.

PC calculation aid

Numerous computer programs are available for use in planning switchgear installations, particularly for design calculation. Sections 6.1.5 to 6.1.7 deal with computer-aided methods for:

– short-circuit current
– cable cross section
– cable routing.

Table 6-2 summarizes the computer programs used in planning switchgear installations, together with their fields of application and contents.

Table 6-1

Choice of plant concept and measures taken in relation to given boundary conditions

Boundary conditions	Concept and measures
Environment, climate, location:	Outdoor/indoor Conventional/GIS/hybrid Equipment utilization Construction Protection class of enclosures Creepage, arcing distances Corrosion protection Earthquake immunity
Network data,network form:	Short-circuit loadings Protection concept Lightning protection Neutral point arrangement Insulation coordination
Availability and redundancy of power supply:	Busbar concept Multiple infeed Branch configuration Standby facilities Uninterruptible supplies Fixed/drawout apparatus Choice of equipment Network layout
Power balance:	Scope for expansion Equipment utilization Instrument transformer design
Ease of operation:	Automatic/conventional control Remote/local control Construction/configuration
Safety requirements:	Network layout Arcing fault immunity Lightning protection Earthing Fire protection Touch protection Explosion protection

Table 6-2

Computer programs for project planning and calculations for switchgear installations (CAD programs, see Section 6.3.3)

Program Name	Application area	Testing, determination, dimensioning
EMTP	Calculation of transient processes in any meshed multiphase electrical systems	– Internal and external overvoltages – Interference voltage affecting telecom cables – Transient voltage elevation in earthing systems on lightning strike – Operational response of battery power systems
PPCP	Calculation of potential-course in earthing systems	– Determination of the propagation resistance – Determination of step and touch voltages
STÖRLI	Calculation of the pressure characteristic in switchgear rooms on arcing	– Checking the pressure resistance of medium-voltage switchgear rooms – Dimensioning pressure relief equipment
KURWIN	Dynamic resistance	– Static resistance and thermal and dynamic short-circuit current capability of switchgear installations with conductor cables and tubular conductors as per DIN EN 60865-1 (VDE 0103)
ROBI	Static resistance	– Deflection line and torque curve of waves and tubular conductors
CALPOS®	Programming system for network calculation with the following modules:	
	Phase fault current calculation; calculation of symmetrical and non-symmetrical fault currents as per – DIN VDE 0102/IEC60909 – Superposting method	– Switchgear installations (busbars, connections) – Equipment (switches, transformers) – Protection devices
	Load flow calculation	– Switchgear installations – Equipment and power – Minimum loss system operation methods – Critical system states – Directed switchovers after equipment failure – Voltage drop on motor startup

(continued)

Table 6-2 (continued)

Computer programs for project planning and calculations for switchgear installations (CAD programs, see Section 6.3.3)

Program Name	Application area	Testing, determination, dimensioning
CALPOS®	Selectivity analysis (overcurrent protection)	– Checking protection coordination in MS and NS networks
	Distance protection	– Protection coordination of cable units – Creation of selective tripping schedules
	Harmonic analysis	– Harmonic currents and voltages in networks with converters – System perturbation by harmonics – Compensation equipment – Propagation of audiofrequency ripple control signals
	Dimensioning of earthing systems (VDE 0141, IEEE 80)	– Cross sections for earthing material – Hazardous voltages
	Dimensioning low-voltage cables	– Specification of cable type – Maximum length – Selection of protective devices
	Motor startup	– Dynamic simulation in the time range
	Dynamic network simulation	– Investigation of system response to dynamic processes
CALPOS® –	Ramses	– Determination of reliability quantities in networks
CALPOS® –	Main	– Determining an optimum maintenance strategy for installation equipment

6.1.2 Planning of high-voltage installations

The following criteria must be considered when planning high-voltage switchgear installations:

Voltage levels

High-voltage installations are primarily for power transmission, but they are also used for distribution and for coupling power supplies in three-phase and HVDC systems. Factors determining their use include network configuration, voltage, power, distance, environmental considerations and type of consumer:

Distribution and urban networks	> 52 – 245 kV
Industrial centres	> 52 – 245 kV
Power plants and transformer stations	> 52 – 800 kV
Transmission and grid networks	245 – 800 kV
HVDC transmission and system interties	> 300 kV
Railway substations	123 – 245 kV

Plant concept, configuration

The circuitry of an installation is specified in the single-phase block diagram as the basis for all further planning stages. Table 6-3 shows the advantages and disadvantages of some major station concepts. For more details and circuit configurations, see Section 11.1.2.

The availability of a switching station is determined mainly by:

- circuit configuration, i. e. the number of possibilities of linking the network nodes via circuit-breakers and isolators, in other words the amount of current path redundancy,
- reliability/failure rate of the principal components such as circuit-breakers, isolators and busbars,
- maintenance intervals and repair times for the principal components.

Table 6-3

Comparison of important busbar concepts for high-voltage installations

Concept configuration	Advantages	Disadvantages
Single busbar	– least cost	– BB fault causes complete station outage – maintenance difficult – no station extensions without disconnecting the installation – for use only where loads can be disconnected or supplied from elsewhere
Single busbar with bypass	– low cost – each breaker accessible for maintenance without disconnecting	– extra breaker for bypass tie – BB fault or any breaker fault causes complete station outage
Double busbar with one circuit-breaker per branch	– high changeover flexibility with two busbars of equal merit – each busbar can be isolated for maintenance – each branch can be connected to each bus with tie breaker and BB isolator without interruption	– extra breaker for coupling – BB protection disconnects all branches connected with the faulty bus – fault at branch breaker disconnects all branches on the affected busbar – fault at tie breaker causes complete station outage
2-breaker system	– each branch has two circuit-breakers – connection possible to either busbar – each breaker can be serviced without disconnecting the branch – high availability	– most expensive method – breaker defect causes half the branches to drop out if they are not connected to both bus bars – branch circuits to be considered in protection system; applies also to other multiple-breaker concepts

(continued)

Table 6-3 (continued)

Comparison of important busbar concepts for high-voltage installations

Concept configuration	Advantages	Disadvantages
Ring bus	– low cost – each breaker can be maintained without disconnecting load – only one breaker needed per branch – no main busbar required – each branch connected to network by two breakers – all changeover switching done with circuit-breakers	– breaker maintenance and any faults interrupt the ring – potential draw-off necessary in all branches – little scope for changeover switching
1½-breaker system	– great operational flexibility – high availability – breaker fault on the busbar side disconnects only one branch – each bus can be isolated at any time – all switching operations executed with circuit-breakers – changeover switching is easy, without using isolators – BB fault does not lead to branch disconnections	– three circuit-breakers required for two branches – greater outlay for protection and auto-reclosure, as the middle breaker must respond independently in the direction of both feeders

Dimensioning

On the basis of the selected voltage level and station concept, the distribution of power and current is checked and the currents occurring in the various parts of the station under normal and short-circuit conditions are determined. The basis for dimensioning the station and its components is defined in respect of

- insulation coordination
- clearances, safety measures
- protection scheme
- thermal and mechanical stresses

For these, see Sections 3, 4, and 5.

Basic designs and constructions

The basic designs available for switching stations and equipment together with different forms of construction offer a wide range of possibilities, see Table 6-4. The choice depends on environmental conditions and also constructional, operational and economic considerations.

For further details, see Sections 10 and 11.

Table 6-4

The principal types of design for high-voltage switchgear installations and their location

Basic design	Insulating medium	Used mainly for voltage level (kV)	Location	
			Outdoor	Indoor
Conventional	Air	>52 – 123	×	×
Conventional	Air	123 – 800	×	
GIS	SF_6	>52 – 800	× [1]	×
Hybrid[2]	Air/SF_6	245 – 500	×	

[1] GIS used outdoors in special cases

[2] Hybrid principle offers economical solutions for station conversion, expansion or upgrading, see Section 11.4.2.2.

There are various layouts for optimizing the operation and space use of conventional outdoor switchgear installations (switchyards), with different arrangement schemes of busbars and disconnectors, see Section 11.3.3

6.1.3 Project planning of medium-voltage installations

Medium-voltage networks carry electrical energy to the vicinity of consumers. In public networks (electrical utility networks), they carry the power to local and private substations. In industrial and power station auxillary systems, larger motorized consumers are directly connected as well as the low-voltage consumers.

Most common voltage levels for medium-voltage networks (in Germany):

Electrical utility networks:	10 kV, 20 kV, (30 kV),
Industrial and power station service networks:	6 kV, 10 kV.

Industrial and power station service installations are primarily supplied by radial systems. Important installations are redundantly designed to meet the requirements regarding availability.

Characteristics of industrial and power station auxillary networks:

- high load density
- high proportion of motorized consumers
- occurrence of high short-circuit power.

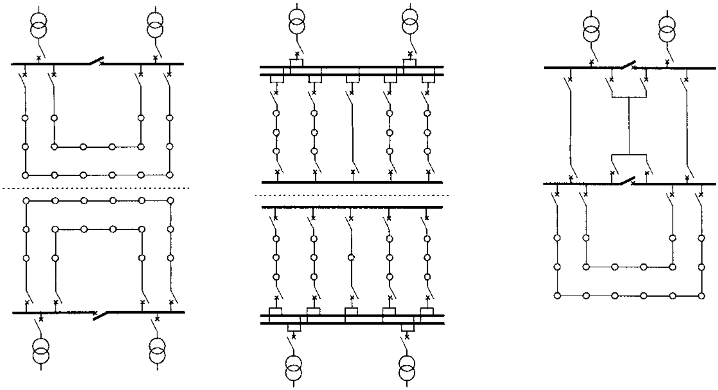
Planning medium voltage distribution networks

Distribution networks have, in general, developed historically and as a result are frequently characterized by a high degree of meshing. The task of system planning is to design these networks to be simple and easy to comprehend.

In planning electrical networks, a distinction is made between operational structural planning and basic strategic planning. Basic planning covers the following points:

- Supply principles,
- Network concepts,
- Standard equipment,
- Standard installations.

The following forms of network are used with the corresponding switchgear installation configurations (DSS, ESS):



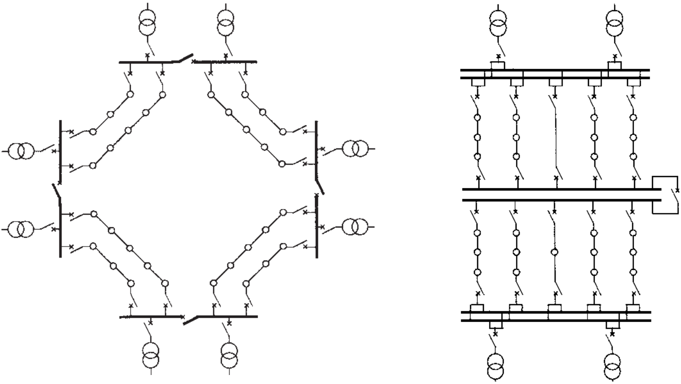
Ring network

Network with opposite station

Network with load-centre substation

Fig. 6-1:

Networks in which the individual transformer substations on the medium-voltage side are not interconnected



Corresponding transformer substations

Corresponding transformer substations with opposite station

Fig. 6-2:

Networks in which the individual transformer substations on the medium-voltage side are interconnected

A simple protection concept can be implemented in radial networks. Troubleshooting in the event of a fault is much easier, particularly with single-phase faults.

An important aspect of system planning is the neutral treatment. Public distribution systems today are still mostly operated with earth fault compensation, with no tripping in the event of an earth fault. The low-resistance neutral earthing is available for selective breaking of single-phase faults. However, a new trend is to operate the networks with compensation and also to install short-time low-resistance neutral earthing (Kurzzeitige NiederOhmige SternPunktErdung, KNOSPE). The advantage of KNOSPE is its selective interception of earth faults without interruptions of power supply. The networks must be operated primarily as radial systems. Short-circuit indicators must be installed in the substations to allow selective fault location.

Planning medium-voltage switchgear

The standard structure of medium-voltage switchgear today is the factory-assembled type-tested switchgear installation conforming to DIN EN 60298 (VDE 0670 Part 6). The most common structural types are described in Section 8.2.

The most important distinguishing characteristics of the currently available structural types and the associated decision-making criteria are:

Distinguishing characteristics		Technical decision-making criteria
Low costs	Higher costs	—
Single busbars	Double busbars	Network concept
Air-insulated	Gas-insulated	Dimensions of the installation environmental conditions (contamination, moisture, service requirements, cleaning)
Cubile	Metal-clad	Personnel safety during wiring work Restriction of damage in the event of internal arcing (if compartmentalization is designed for this)
Switch disconnector installation type	Circuit-breaker installation type	Rating data – Short-circuit currents – Operating currents – Switching frequency Protection concept

6.1.4 Planning of low-voltage installations

Low-voltage installations are usually near the consumer and generally accessible, so they can be particularly dangerous if not installed properly.

The choice of network configuration and related safety measures is of crucial importance. The availability of electricity is equally dependent on these considerations.

Table 6-5 compares the advantages and disadvantages of commonly used network configurations, see also Section 5.1.

Another important step in the planning of low-voltage switchgear installations consists of drawing up a power balance for each distribution point. Here, one needs to consider the following:

- nominal power requirement of consumers,
- short-time power requirement (e.g. motor startup),
- load variations.

The IEC recommendations and DIN VDE standards give no guidance on these factors and point out the individual aspects of each installation.

For power plants and industrial installations, the circumstances must be investigated separately in each case.

The following Tables 6-5 and 6-6 are intended as a planner’s guide. The planners can use the information in Table 6-6 for reference.The total power is derived from the sum of the installed individual power consumers multiplied by the requirement factor with the formula:

$$P_{max} = \Sigma Pi \cdot g$$

P_{max} = power requirement
Pi = installed individual power producer
g = requirement factor

Table 6-5

Summary of network configurations and protection measures for low-voltage installations

System[1]	Advantages	Disadvantages	Main application
TN system	Fast disconnection of fault or short circuit. Least danger for people and property.	High cost of wiring and cable due to protective conductors. Any fault interrupts operations.	Power plants, public power supply and networks.
TT system	Less wiring and cable required. Zones with different touch voltages permitted. Can be combined with TN networks.	Complex operational earthing ($\leq 2\ \Omega$). Equipotential bonding necessary for each building.	Livestock farming.
IT system	Less expensive in respect of wiring and cables. Higher availability: 1st fault is only signalled, 2nd fault is disconnected.	Equipment must be insulated throughout for the voltage between the outside conductors. Equipotential bonding necessary.	Hospitals Industry.
Total insulation	Maximum safety. Can be combined with other networks.	Equipment doubly insulated, economical only for small consumers. With heat-generating loads, insulation constitutes fire hazard.	Residential, small-scale switchboards and equipment
Safety extra-low voltage Functional extra-low voltage	No dangerous touch voltages.	Limited power with cost-effective equipment use. Special requirements for circuitry.	Small apparatus.

[1] For definitions and block diagram of the systems, see Section 5.1.2

Table 6-6

Demand factor g for main infeed of different electrical installations

Type of installation or building	Demand factor *g* for main infeed	Remarks
Residential buildings		
Houses	0.4	Apply *g* to average use per dwelling.
Blocks of flats		Total demand = heating + a.c. + general.
– general demand (excl. elec. heating)	0.6 typical	
– electric heating and air-conditioning	0.8 to 1.0	
Public buildings		
Hotels, etc	0.6 to 0.8	Power demand strongly influenced by climate, e.g. – in tropics high demand for air-conditioning – in arctic high heating demand
Small offices	0.5 to 0.7	
Large offices (banks, insurance companies, public administration)	0.7 to 0.8	
Shops	0.5 to 0.7	
Department stores	0.7 to 0.9	
Schools, etc.	0.6 to 0.7	
Hospitals	0.5 to 0.75	
Places of assembly (stadiums, theatres, restaurants, churches)	0.6 to 0.8	
Railway stations, airports, etc.	no general figure	Power demand strongly influenced by facilities
Mechanical engineering		
Metalworking	0.25	Elec. drives often generously sized.
Car manufacture	0.25	
Pulp and paper mills	0.5 to 0.7	*g* depends very much on standby drives.
Textile industry		
Spinning mills	0.75	
Weaving mills, finishing	0.6 to 0.7	
Miscellaneous Industries		
Timber industry	0.6 to 0.7	
Rubber industry	0.6 to 0.7	
Leather industry	0.6 to 0.7	
Chemical Industry **Petroleum Industry** }	0.5 to 0.7	Infeed must be generously sized owing to sensitivity of chemical production processes to power failures.
Cement works	0.8 to 0.9	Output about 3500 t/day with 500 motors. (Large mills with h.v. motor drives.)
Food Industry	0.7 to 0.9	
Silos	0.8 to 0.9	
Mining		
Hard coal		
Underground working	1	
Processing	0.8 to 1	
Brown coal		
General	0.7	
Underground working	0.8	

(continued)

Table 6-6 (continued)

Demand factor g for main infeed of different electrical installations

Type of installation or building	Demand factor *g* for main infeed	Remarks
Iron and steel industry		
(blast furnaces, convertors)		
Blowers	0.8 to 0.9	
Auxiliary drives	0.5	
Rolling mills		
General	0.5 to 0.8[1]	[1] *g* depends on number of standby drives.
Water supply Ventilation	0.8 to 0.9[1]	
Aux. drives for		
– mill train with cooling table	0.5 to 0.7[1]	
– mill train with looper	0.6 to 0.8[1]	
– mill train with cooling table and looper	0.3 to 0.5[1]	
Finishing mills	0.2 to 0.6[1]	
Floating docks		
Pumps during lifting	0.9	Pumping and repair work do not occur simultaneously.
Repair work without pumps	0.5	
Lighting for road tunnels	1	
Traffic systems	1	Escalators, tunnel ventilation, traffic lights
Power generation		
Power plants in general		
– low-voltage station services	no general figure	
– emergency supplies	1	
Nuclear power plants		
– special needs, e.g. pipe heating, sodium circuit	1	
Cranes	0.7 per crane	Cranes operate on short-time: power requirements depend on operation mode (ports, rolling mills, ship-yards) .
Lifts	0.5 varying widely with time of day	Design voltage drop for simultaneous startup of several lifts

The *type of construction* depends on the station's importance and use (required availability), local environmental conditions and electromechanical stresses.

Construction	Main application
Type-tested draw-out switchgear	Main switching stations Emergency power distribution Motor control centres
Type-tested fixed-mounted switchgear	Substations a.c./d.c. services for h.v. stations Load centres
Cubicles or racks	Light/power switchboards Load centres
Box design	Local distribution, Miniature switchboards

The short-circuit currents must be calculated in terms of project planning activity, the equipment selected in accordance with thermal stresses and the power cable ratings defined. See also Sections 3.2, 7.1 and 13.2. Particularly *important is the selectivity* of the overload and short-circuit protection.

Selective protection means that a fault due to overloading or a short circuit is interrupted by the nearest located switchgear apparatus. Only then can the intact part of the system continue to operate. This is done by suitably grading the current/time characteristics of the protection devices, see also Sections 7.1.4,14.3 and 15.4. The choice of relays can be difficult if account has to be taken of operating conditions with powerful mains infeeds and comparatively weak standby power sources. In some cases changeover secondary protective devices have to be provided.

6.1.5 Calculation of short-circuit currents, computer-aided

A knowledge of the expected short-circuit currents in an installation is essential to the correct selection of the switching stations and the line-side connected networks. The methods of calculation are described in chapter 3.

The upper limit value of these fault currents determines:
- power ratings of the circuit-breaker,
- mechanical design of the installation,
- thermal design of the equipment,
- electrical design and configuration of earthing systems,
- maximum permissible interference in telecommunications systems.

The lower limit value of these fault currents determines:
- protective relays and their settings.

The calculation of short-circuit currents therefore helps to solve the following problems:
- dimensioning of equipment on the basis of (dynamic) stresses on closing and opening and also the thermal stress,
- designing the network protection system,
- questions of compensation and earthing,
- interference problems (e.g. in relation to telecommunications lines).

The CALPOS computer program enables simple but comprehensive calculation of short-circuit currents. It takes account of:

- different switching conditions of the installation,
- emergency operation,
- cold and hot states of the cable network,
- contribution of motors to short-circuit currents.

The program output provides the short-circuit currents at the fault location and in the branches

a) for the transient phase after occurrence of the fault:

- initial symmetrical short-circuit current I''_k,
- peak short-circuit current i_p,
- symmetrical short-circuit breaking current I_a.

b) for the steady-state phase after occurrence of the fault:

- sustained short-circuit current I_k,
- short-circuit powers S''_k,
- voltages at the nodes.

The results can be printed out both as phase values (L1, L2, L3) and as component values (1, 0, 2).

The comprehensive graphic functions offered by Calpos enable phase fault results to be displayed and plotted on the monitor as well as the network topology, see Fig. 6-3. The user creates and edits the graphic network display interactively with the mouse or the digitizing tablet. The calculation as done by the program closely follows the method described in Section 3.3 according to DIN VDE 0102/IEC 60909.

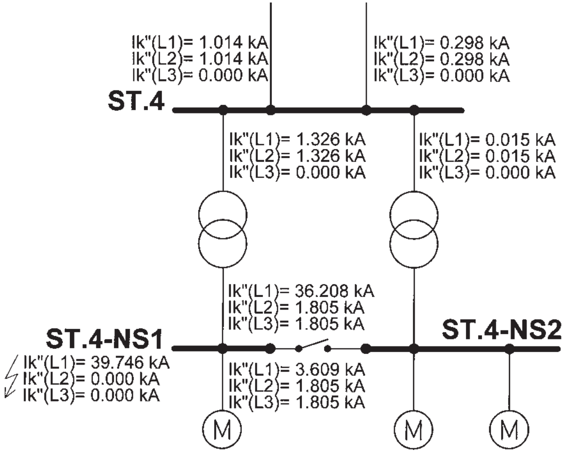


Fig. 6-3

Example of graphic output (plot) of a computer-supported short-circuit current calculation (partial section) done with the CALPOS program.

6.1.6 Calculation of cable cross-sections, computer-aided

Before the cross-sections of cables between the switchgear and their connected loads are finalized, they must be calculated in relation to the operating conditions and cable length.

Factors influencing the cross-section in this calculation are:

- permitted loadings under normal conditions, taking into account ambient temperatures and methods of laying,
- thermal short-circuit strength,
- permitted voltage drop along the cable run under normal conditions, and also during the starting phase when feeding motors,
- response of protective devices in the event of overloads and the smallest possible short-circuit current to interrupt dangerous touch voltages.

The ABB-developed LEIOP computer program and the matching Calpos module makes it possible to carry out this comprehensive calculation for every current circuit. By entering the circuit data, such as operating current, max. and min. short-circuit current, tripping currents/times of the protective devices and maximum permitted voltage drops, the program selects the appropriate minimum cross-section for the considered cable length. With the aid of program parameters, the range of cable types to be used can be limited, and a choice provided of the number of parallel cables for a given cable cross section. The method of calculation is in accordance with DIN VDE 0100, VDE 0276 and the respective cable manufacturer’s data.

6.1.7 Planning of cable routing, computer-aided

The routing of cables in complex industrial installations, power plants and switching stations requires a great deal of work on the part of the planner. It involves arranging the cables to give the shortest path between their starting point and destination, while at the same time ensuring that certain combinations do not adversely influence each other.

The ABB program LEIOP offers very effective support here. It can provide data on the following:

- Cable lists
- Cable quantities incl. fittings (number of terminal ends, individual cable lengths)
- Cable markings
- Information on cable installation
- Information on tailoring cables for racks, trenches and conduit

6.2 Reference designations and preparation of documents

Two important series of standards in the last few years have guided the rules for the reference designation of equipment and the preparation of circuit documents. The symbols for individual equipments are specified in the series DIN 40900, and the series DIN 40719 regulates reference designation and representation.

The two series of standards have been or are being superseded due to international standardization in the IEC. DIN 40900 has been replaced by the series DIN EN 60617. The changes are minor, because DIN 40900 was already based on an earlier version of the international standard IEC 60617. The new revision corrects errors and includes essential supplementary symbols. The most important parts of DIN 40719 were superseded by DIN EN 61082 in 1996/97. Part 2 of DIN 40719, which covers the identification of electrical equipment, and Part 6, covering the area of function charts, are still applicable for Germany. The structure of reference designation systematics has been fundamentally revised on an international level. With the publication of DIN EN 61346-1, the first part – the basic rules – has already appeared. Part 2 with the important tables of code letters is currently in preparation. DIN 40719 Part 2 will remain in force until the German version is published. In the following section, the current designation systematics practice is reproduced virtually unchanged from the 9th edition, because this system is still used for extensions and for running projects. Section 6.2.4 gives an overview of future developments in reference designation systematics, in accordance with the new international standard IEC 61346.

6.2.1 Item designation of electrical equipment as per DIN 40719 Part 2

Four designation blocks are available to identify every single device (equipment) in the plant and in the circuit diagrams. They are distinguished by prefix signs.

Prefix signs	Designation block
=	Higher level designation
+	Location of item
–	Type, number, function of the item
:	Terminal designation

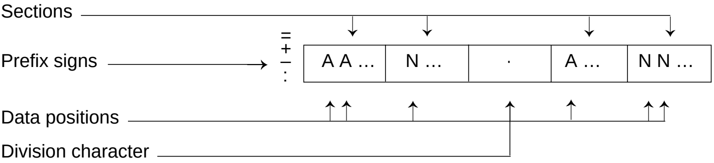
Each designation block consists of a sequence of alphanumeric characters. It is divided into sections and each section into data positions. These signify:

A – an alphabetic data position (letter),
N – a numerical data position (digit).

Defined for each designation block are:

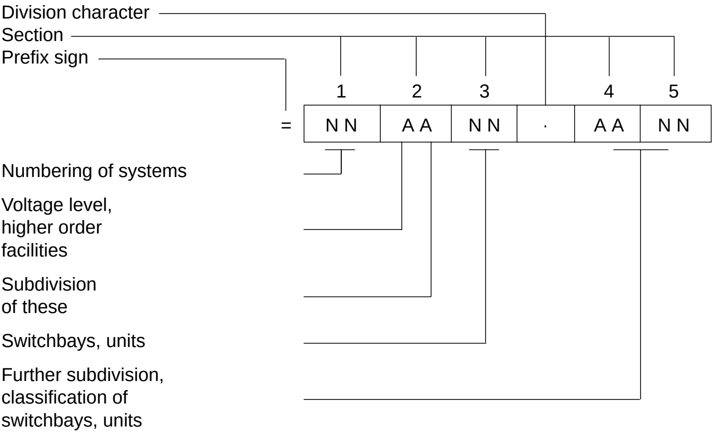
- the prefix signs,
- the maximum number of sections,
- the maximum number of data positions per section,
- the meaning of specific data positions in individual sections,
- whether and where an designation block is to be subdivided by the division character of a full stop (.) in order to split up its contents and make it easier to read.

The general structure of the four designation blocks is therefore as follows:



Designation block ‘higher level’

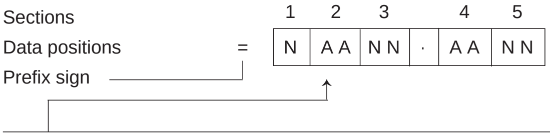
The designation block for ‘higher level’ consists of five sections and is split between sections 3 and 4 by the division character (.). It begins on the left with the largest system component, and ends on the right with the smallest.



The meanings of the alphabetical data positions in section 2 are defined in the standard and can be seen in Tables 6-7 and 6-8.

Table 6-7

Letters for identifying voltage level in the designation block ‘higher level assignment’, 2nd section, 1st alphabetical data position (as Table C7 of DIN 40 719 Part 2).

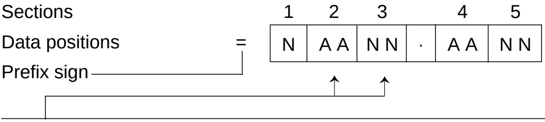


Identifying letter	System	
A	–	
B	> 420 kV	
C	380 kV to 420 kV	
D	220 kV to < 380 kV	
E	110 kV to < 220 kV	
F	60 kV to < 110 kV	
G	45 kV to < 60 kV	
H	30 kV to < 45 kV	
J	20 kV to < 30 kV	
K	10 kV to < 20 kV	
L	6 kV to < 10 kV	
M	1 kV to < 6 kV	
N	< 1 kV	
P	–	
Q	Facilities for measuring and metering	Facilities and systems not specifically referring to a branch or voltage
R	Facilities for protection	
S	–	
T	Facilities for transformers	
U	Facilities for control, signalling and auxiliary equipment	
V	–	
W	Facilities for control rooms	
X	Central facilities, e g process computers, alarm systems	
Y	Facilities for telecommunications	
Z	–	

Note: The letters A to N for voltage level are the same as in Table 6-9, but there they are used for a different identification purpose.

Table 6-8

Letters for identifying voltage levels < 1 kV in designation block ‘higher level assignments’, 2nd section, 2nd alphabetical data position when the letter N is defined for the first alphabetical data position in *Table 6-7* (as Table C9 of DIN 40719 Part 2)



Identifying letter	Meaning
N	Systems < 1 kV
NA	AC 500 to 1000 V
NB	AC 500 to 1000 V
NC	AC 500 to 1000 V
ND	–
NE	AC 400/230 V
NF	AC 400/230 V
NG	AC 400/230 V
NH	AC 400/230 V
NJ	–
NK	DC 220/110 V
NL	DC 220/110 V
NM	DC 220/110 V
NN	DC 220/110 V
NP	–
NQ	DC 60/48 V
NR	DC 60/48 V
NS	DC 60/48 V
NT	–
NU	DC 24/12 V
NV	DC 24/12 V
NW	DC 24/12 V
NX	–
NY	–
NZ	–

Designation block ‘location’

The ‘location’ designation block is qualified by a plus sign (+) and indicates where an item of equipment is situated, e.g. topographical site: building, room, cubicle, rack and position.
The designation block is divided into six sections:

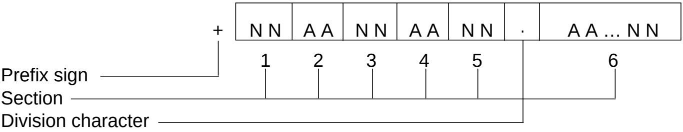
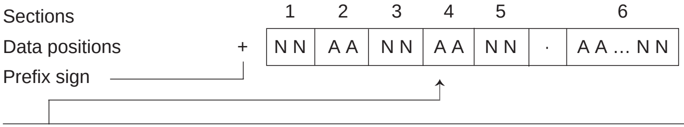


Table 6-9

Letters for identifying locations in designation block ‘location’, 4th section, 1st alphabetical data position (as Table C10 of DIN 40719 Part 2)



Identifying letter	Meaning
A	–
B	> 420 kV
C	380 to 420 kV
D	220 to < 380 kV
E	110 to < 220 kV
F	60 to < 110 kV
G	45 to < 60 kV
H	30 to < 45 kV
J	20 to < 30 kV
K	10 to < 20 kV
L	6 to < 10 kV
M	1 to < 6 kV
N	< 1 kV bays
P	Desks
Q	Boards and cubicles for measuring and metering
R	Boards and cubicles for protective devices
S	Boards and cubicles decentralized
T	Boards and cubicles for transformers
U	Boards and cubicles for control, signalling and auxiliary systems
V	Marshalling cubicles
W	Control room board
X	Boards and cubicles for central facilities, e. g. alarm systems and process computers
Y	Boards and cubicles for telecommunications
Z	–

Application: The letters A to N for voltage level are the same as in Table 6-7, but there they are used for a different identificatiaon purpose.

The designation block begins on the left with the unit of largest volume or construction, and ends on the right with the smallest.

The designation block can be subdivided by the division charakter (·) between sections 5 and 6.

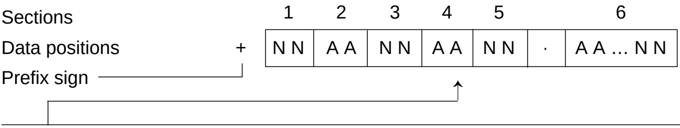
To the left of the division character is information on the location (building, room, row, etc.) and the nature of the structural unit (bay, cubicle, rack).

To the right of the division character in section 6 is information on the position (row, column, etc.) of an item of equipment within the structural unit. Section 6 may have up to eight data positions (letters and numbers in any sequence).

The meanings of the alphabetical data positions in section 4 are shown in Tables 6-9

Table 6-10

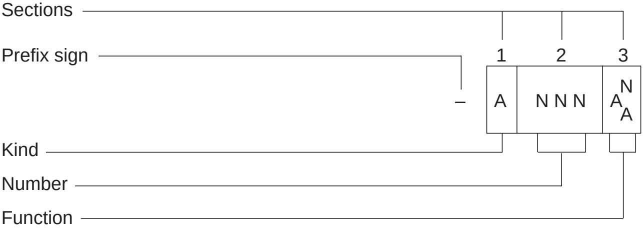
Letters for identifying application in designation block ‘location’, 4th section, 2nd alphabetical data position (as *Table C11* of DIN 40719, Part 2)



Identifying letter	Meaning
A	Circuit-breaker accessories
B	Multiply, re-position, decouple
C	Instrument transformer accessories
D	Compressed air, hydraulics
E	–
F	–
G	–
H	–
J	Automatic, closed-loop control
K	–
L	Simulating network, voltage selection
M	Measurement
N	System services
P	Recorder
Q	Metering
R	Protection
S	Synchronizing
T	Transformers
U	Auxiliaries
V	Main, secondary busbars etc.
W	Display, operation, supervision
X	Alarm system
Y	–
Z	–

Designation block 'identification of item'

The designation block for 'identification of item' is qualified by a hyphen (–) and consists of three sections.
Specified for the data positions in this designation block are the following symbols (letters and numbers) in the order given.



Section 1 identifies the kind of item as in Table 6-11.

Section 2 states the number of the equipment. Each item of equipment must be identified by a number of one to three digits.

Items of different kinds that belong together should be given the same number.

DIN 40719 Part 2 gives rules for the numbering of items in high-voltage switchgear installations, a distinction being made between numbers for

- switchgear in the main circuits (Table 6-12a)
- auxiliary devices which can be assigned to the switchgear in the main circuits (Table 6-12b)
- current and voltage transformers in the main circuits (Table 6-13)
- equipment which is specific to a branch but cannot be assigned to the main switchgear (Table 6-14).

If necessary, the function of an item of equipment can be identified in section 3. The following letters are specified for the alphabetical data position:
A – OFF function
E – ON function
L – conductor identification

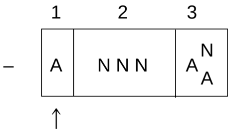
The other letters can be chosen arbitrarily.

The second data position for further subdivision/numbering can be occupied by an additional, arbitrarily chosen letter or number.

In the case of conductor identification, a distinction is made between a neutral identity LA, LB, LC and an identity assignable to the conductors L1, L2, L3. If neutral conductor identification is used, its assignment to L1, L2 and L3 must be stated in the circuit documentation.

Table 6- 11

Letters for identifying the kind of item *(as Table 1* of DIN 40719 Part 2)

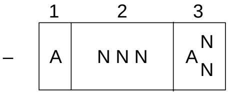


Letter code	Kind of item
A	Assemblies, subassemblies
B	Conversion from non-electrical to electrical quantities and vice versa
C	Capacitors
D	Binary elements, delay devices, storage devices
E	Miscellaneous
F	Protection devices
G	Generators, power supply systems
H	Signalling systems
J	–
K	Relays, contactors
L	Inductors, reactors
M	Motors
N	Analogue elements as amplifiers, controllers
P	Measuring instruments, testing devices
Q	Switching devices for power circuits
R	Resistors
S	Switching devices for control circuits, selectors
T	Transformers
U	Modulators, converters from one electrical quantity to another
V	Tubes, semiconductors
W	Transmission paths, cables, busbars, hollow conductors, antennas
X	Terminals, plugs, sockets
Y	Electrically operated mechanical devices
Z	Terminations, bifurcations, filters, equalizers, limiters, balancing devices, bifurcation terminations

Table 6-12

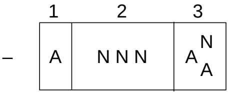
Designation block ‘identification of item’

Table 6-12a (taken from *Table* C3 of DIN 40719 Part 2). Number for the designation of switchgear in the main current circuit in the title block “Type, number, function”, 2nd section, 1st and 2nd numeric data position.



If in the 1st section, the letter “Q” as in *Table 6-11* is used for switchgear in the main circuit.

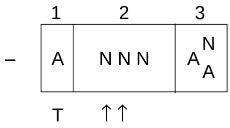
Table 6-12b (taken from *Table C4* of DIN 40 719 Part 2). Number for the designation of auxiliary devices that can be associated with the switchgear as in Table 6-12a in the title block “Type, number, function”, 2nd section, 1st and 2nd numeric data position.



Kind of item	Designation	Control-discrepancy switch	Control button	
			open	closed
Circuit-breakers				
General	Q 0	S 0	S 0A	S 0E
1st circuit-breaker	Q01	S01	S01A	S01E
2nd circuit-breaker	Q02	S02	S02A	S02E
Bus system I				
Bus disconnector	Q 1	S 1	S 1A	S 1E
Bus-coupler disconnector, 2nd disconnector	Q10	S10	S10A	S10E
Bus sectionalizer	Q11…14	S11…14	S11…14	S11E…14E
Bus-earthing switch	Q15…19	S15…19	S15A…19A	S15E…19E
Maintenance earthing sw.				
General	Q 5	S 5	S 5A	S 5E
1st maint. earthing sw.	Q51	S51	S51A	S51E
2nd maint. earthing sw.	Q52	S52	S52A	S52E
Freely available neutral earthing switch, test disconnector	Q 6	S 6	S 6A	S 6E
Bypass bus				
Disconnector	Q 7	S 7	S 7A	S 7E
2nd disconnector	Q70	S70	S70A	S70E
Sectionalizer	Q71…74	S71…74	S71A…74A	S71E…74E
Earthing switch	Q75…79	S75…79	S75A…79A	S75E…79E
Earthing switches				
General	Q 8	S 8	S 8A	S 8E
1st earthing switch	Q81	S81	S81A	S81E
2nd earthing switch	Q82	S82	S82A	S82E
Feeder disconnector				
General	Q 9	S 9	S 9A	S 9E
1st feeder disconnector	Q91	S91	S91A	S91E
2nd feeder disconnector	Q92	S92	S92A	S92E

Table 6-13

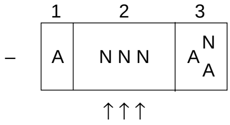
Number for identifying the application in designation block ‘identification’, 2nd section, 1st and 2nd numerical data position (as Table C5 of DIN 40 719 Part 2) if the letter “T” as in Table 5 is used in the section for instrument transformers in the main circuits.



Instrument transformers Kind of item	Designation	Kind of item	Designation
Current transformers		Voltage transformers	
Feeder transformers	T 1 to 4	Feeder transformers	T 5 to 9
Transformer bus I	T11 to 14	Transformer bus I	T15 to 19
Transformer bus II	T21 to 24	Transformer bus II	T25 to 29
Transformer bus III	T31 to 34	Transformer bus III	T35 to 39
Transformer bus IV	T41 to 44	Transformer bus IV	T45 to 49
Cable-type transformers			
General	T90		
1st transformer	T91		
2nd transformer	T92		

Table 6-14

Number for identifying purpose of non-assignable feeder-related auxiliaries in designation block ‘identification’, 2nd section, 1st, 2nd and 3rd numerical data position (as Table C6 of DIN 40719 Part 2)



Identifying letter as *Table 6-11,* three-digit number

Recommended categories for the three-digit number:

100 to 199 Station services
200 to 299 Control
300 to 399 Protection
400 to 499 Measurement
from 500 arbitrary use

The number of auxiliaries in higher-order facilities and within branch-related combinations can be chosen at will.

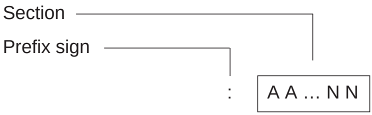
Composite items

To identify an item of equipment forming part of higher level equipment (composite item), the identifying designation blocks are arranged in sequence with the higher level equipment at the left. In the case of composite items, each item is given its own identity and the prefix sign of a hyphen (–) is repeated for each item, e.g. –QO-Y1 for a circuit-breaker –QO containing a tripping coil –Y1.

The numbers for equipment forming part of higher level equipment can be chosen arbitrarily, e.g. equipment in disconnector operating mechanisms, circuit-breakers, combinations, truck-mounted assemblies.

Designation block 'terminal'

The 'terminal' designation block has the prefix sign of a colon (:) and consists of one section.



The designation block contains the terminal identifications as stated on the equipment.

6.2.2 Preparation of documents

As per DIN EN 61082, “document” is defined as “information on a data medium”; “documentation” as:

- collection of documents related to a given subject, and
- processing of documents.

The “standard” classification for documents in electrical engineering as per DIN 40719 distinguishes between a) purpose and b) type of representation. The most important parts of DIN 40719 were superseded by DIN EN 61082 in 1996. This standard is a direct translation of the international standard IEC 61082 “Preparation of documents used in electrotechnology”. Document classification is also covered here – including new terms in some cases. The following definitions of the new standard can be assigned to the term “purpose” in the old standard without problems:

- Function oriented documents
- Location documents
- Connection documents
- Item lists
- Installation-specific documents
- Other documents
- Commissioning-specific documents
- Operation-specific documents
- Maintenance-specific documents
- Reliability and maintainability-specific documents

Regarding the “type of representation”, the new standard distinguishes the following types:

- Attached representation
- Semi-attached representation
- Detached representation
- Repeated representation
- Grouped representation
- Dispersed representation
- Multi-line representation
- Single-line representation

A distinction is also made between a “functional oriented layout” and a “topographical oriented layout” in the types of representations for circuit diagrams.

An important change from the former practice as per DIN 40719 is the strict separation of title block data and information on the reference designation (formerly equipment identification). Common designation blocks for represented equipment may no longer be given in the title block. Only data relevant to the document itself is given here now. Higher-order parts of the reference designation must be given at the specified positions in the drawing field (e.g. top left of the circuit diagram).

The following definitions from DIN 61082 / IEC 61082 and descriptions are given for some documents – important for substation engineering.

Overview diagram
An overview diagram is a relatively simple diagram often using single-line representation, showing the main interrelations or connections among the items within a system, subsystem, installation, part, equipment or software (Fig. 6-4).
The overview diagram of a switchgear should include, as the minimum information, the reference designation of the station components and of the equipment represented and also the most important technical data. The designation and cross-references to documents of a lower level should also be included.

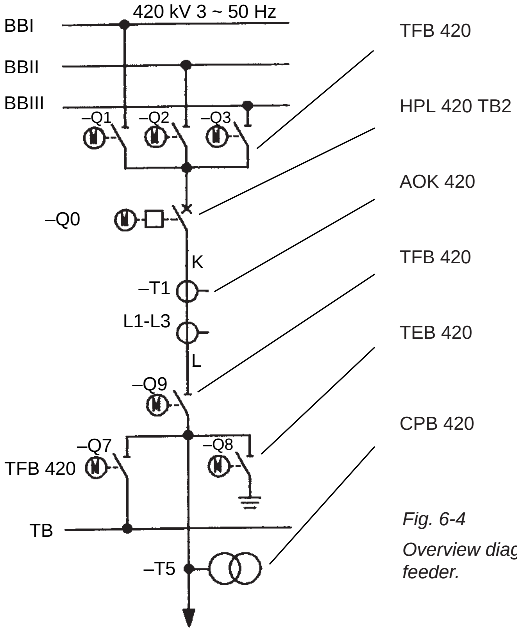


Fig. 6-4

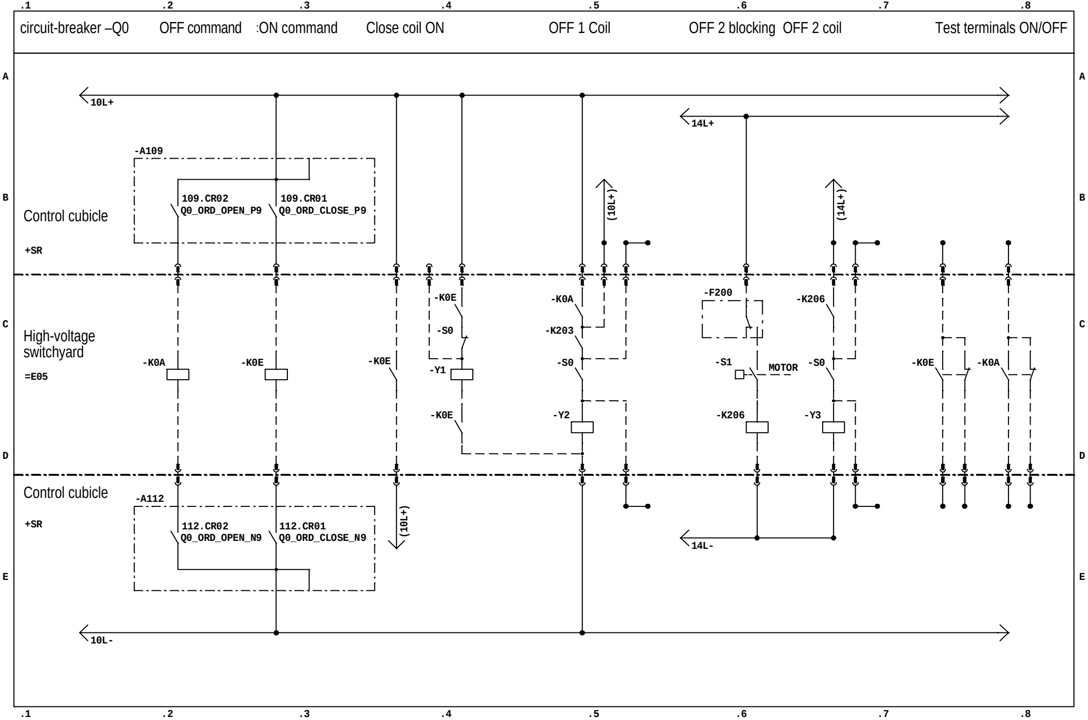
Overview diagram of a 420 kV feeder.

Function chart
A function chart is a diagram that describes the functions and behaviour of a control or regulation system using steps and transitions.

Circuit diagram
The circuit diagram is the diagram that shows the circuits of a functional or structural unit or an installation as they are implemented. The parts and connections are represented by graphical symbols. Their configuration must show the function. The size, shape and location of the equipment does not need to be considered (Fig. 6-5).

Fig. 6-5

Circuit diagram



The circuit diagram for a feeder or a functional unit is generally subdivided into function groups, such as control, position indication, interlocking, alarm, synchronization, protection, measuring etc. Above the current path, a short description of the represented subfunction using keywords is useful. The most important part of the circuit diagram is the information on following circuits or signals and notes on further representations.

Terminal function diagram
A circuit diagram for a functional unit, which shows the terminals for the interface connection and describes the internal functions. The internal functions may be shown or described in simplified form.

Arrangement drawing
A drawing showing the location and/or the physical implementation of a group of associated or assembled parts.

Terminal connection diagram
A diagram that shows the terminals of a construtional unit and the internal and/or external connections.

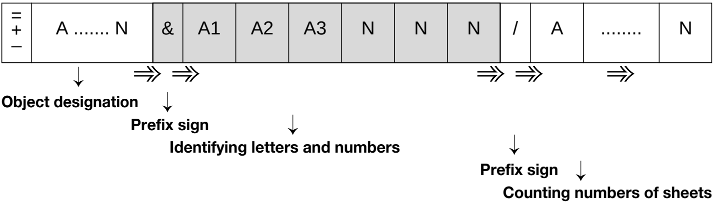
6.2.3 Classification and designation of documents

The international standard IEC 61355 has the title “Classification and designation of documents for plants, systems and equipment”. The goal of this standard is described as follows in its introduction:

> *One aim of this standard is to establish a method for better communication and understanding between parties involved in document interchange. In order to get a basis for a system, it is necessary to disregard, more or less, what a document is called today. Different names are in use for the same document kind or the names may have different meanings for different parties. The purpose and object of interest are sometimes also part of document titles, which hampers general understanding. Therefore the basis for a common understanding should be a classification scheme which is based only on the content of information.*
>
> *Another aim of this standard is to set up rules for relating documents to the objects they describe. For this purpose a document designation system is provided, linking the document kind designation to the object designation used within the plant, system or equipment. Following the rules and recommendations given, the documentation reflects the structure of the “real installation”. By that also guidance is given for order and filing as well as for structured searching for information, for example in document retrieval systems.*

The principle of classification also covers the needs of computer-based documentation in general. An increasing amount of information will be stored and interchanged in a standardized data base format. The information to be delivered may be specified in such a way that each document kind required and agreed tby parties can be derived from that data base by the receiver's computer system.

This standard specifies a generally valid "Document kind Classification Code (DCC)" for the first time and explains it in a detailed table with examples – see the fields with grey background in the following table.
Documents are identified in accordance with the following scheme:



The letter symbol "A1" stands for the Technical Area, e.g. "E" for electrotechnology; the letter symbol "A2" stands for the "Main Document Kind Class", e.g. "F" for function-describing documents; the letter symbol "A3" stands for the "Document Type Subclass", e.g. "S" for circuit diagram.
Object designation follows the rules of IEC 61346, and currently still DIN 40719-2. The page number after the prefix sign "/" has a maximum of six data spaces and can be formed by the customary procedure (e.g. "D" for power supply AC, or "N" for protection).
Table 6-15 shows examples of document kind classes from switchgear installation technology.

Table 6-15
Examples for documents in switchgear installations

Letter symbol 2nd & 3rd A position as per IEC 61355	**Document kind; examples from switchgear installation technology**
	Documentation describing documents
AA	Administrative documents: cover sheets, documentation structure, designation system
AB	Tables: lists of documents, lists of contents
	Management documents
B.	Document list, schedule, delivery list, training documentation, letters, memos
	General technical documents
DA	Dimension drawings, circuit diagrams for equipment
DC	Operating and maintenance instructions
	Technical requirements and dimensioning documents
E.	Environmental conditions, studies, calculations
	Function-describing documents
FA	Overview diagrams, network maps
FB	Flowcharts, block diagrams
FE	Function descriptions
FF	Function diagrams
FP	Signal descriptions, signal lists
FS	Circuit diagrams
FT	Software-specific documents
	Location documents
LD	Site plan, cable routing drawings, earthing plans, layouts, dispositions, sections
LH	Building plans
LU	Assembly drawings, arrangement drawings, equipment layout diagrams
	Connection-describing documents
MA	Terminal diagrams, connection diagrams, interconnection diagram
MB	Cable tables, cable lists
	Documents listing material
PA	Material lists (conduits, stranded wires, terminals, bolts ...)
PB	Parts lists, spare parts lists, lable lists
	Quality managment documents
QA	Test reports, test certifications, audit reports

6.2.4 Structural principles and reference designation as per IEC 61346

As noted in the introduction to Section 6.2, this section gives an outlook on the expected structural principles and reference designations in installations for energy distribution. The significance of this change from the former practice justifies this early explanation.

Formerly designation in installations was done with designation blocks and tables with a fixed arrangement for particular, specified data positions within the designation blocks. However, in future, the hierarchical structure will be in the foreground and at the centre. Hierarchical structures are characterized in that they build on “component relationships". The elements in a lower-order level in such a structure are always a complete component of the next higher level. The structure formed in this way can be depicted as a tree structure with nodes and branches (Fig. 6-6).

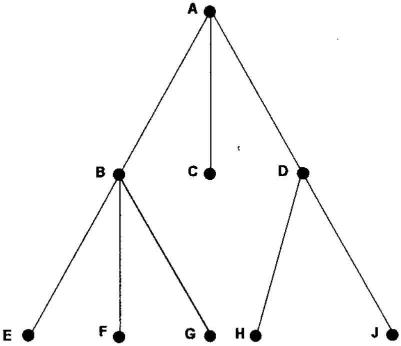


Fig. 6-6
Example of tree structure
B, C and D are components of A
E, F and G are components of B

The letters are for explanation only; they have nothing to do with any coding.

In its practical application for a switchgear installation, a structure will be implemented in accordance with the purpose under the following familiar classes: “association with voltage level” and “function”. Every object considered in a hierarchical structure, in fact the entire structure, the entire system itself can be considered from various points of view, referred to as “aspects”, e. g.:

- what it does;
- how it is constructed;
- where it is located.

With reference to these three types of aspect, the new designation system distinguishes system structures under the following three views:

- function-oriented structure;
- product-oriented structure;
- location-oriented structure.

Reference designations derived from this are identified with the allocated prefix signs "=", "–" and "+". Note the following: the functional identification "=" is used only for identifying pure functions, such as "= F" for "protection"; implementation with any product is not considered at this stage! An example of an application would be a neutral description independant of manufacturer as a request in a specification. In actual use this function might be implemented with, for example, the protection device "- F 312". Consultations have shown that it makes sense for equipment in installations of energy distribution to be designated under a product-based structure. Designation in the location-oriented structure "+" remains open for straight topographical information, such as waypoints, floors, room numbers, etc. The difference from the previous equipment designation is primarily that there is no combination of the designation blocks "=", "–" and "+".

An actuating element in a 380 kV control cubicle would for example be uniquely described with the reference identification **"– C3 – S1 – K1"** in the product-oriented structure.

6.3 CAD/CAE methods applied to switchgear engineering

The first CAD systems came on the market early in 1970. They were suitable for 2-dimensional design work, e.g. drafting circuit diagrams, circuit board layouts and simple design drawings. Now there is a wide variety of CAD workstations available, from low- to high-performance and all kinds of applications. Since 1970, CAD stations and methods have evolved into a powerful tool. This development process can be expected even to accelerate in coming years. The following section aims to explain the most important terms that have grown out of this new technology, and to give a general picture of the hardware and software systems employed. Attention is focused on the CAD methods used by ABB for switchgear engineering, together with examples.

6.3.1 Terminology, standards

Table 6-16 gives an outline of the principal CAD terms and their related fields of application.

Table 6-16

CAD terms, summary and applications

CIM	Computer-Integrated Manufacturing		
	CAE	Computer-Aided Engineering	
			Typical applications
		CAD Computer-Aided Design Computer-Aided Drafting	Design development; Preparation of drawings and calculation
		CAP Computer-Aided Planning	Production planning e.g. pricing and deployment
		CAM Computer-Aided Manufacturing	Production control e.g. parts lists, documentation for NC machines
	CAT	Computer-Aided Testing	Control of automatic testing; test reports

Depending on the degree of standardization, the solutions stored in the computer and the ability to help the designer find the right solution, CAD = Computer-Aided Drafting becomes a complete design system. By further processing of CAD data for manufacturing documents, production planning and testing, you can create a CAM or CIM system. Fig. 6-7 gives a general overview of the CAD areas in relation of the engineering and manufacturing, showing the possibilities for standardization in the preparation of circuit diagrams.

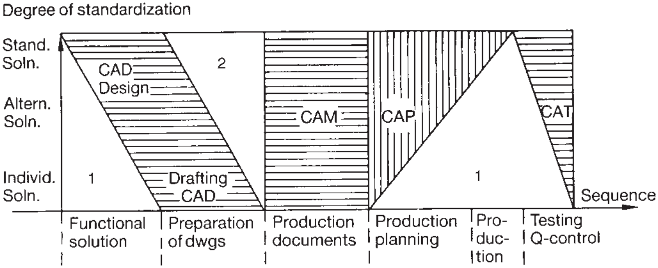


Fig. 6-7

Possibilities of standardization using CAD for producing circuit diagrams
hatching = CAD / CAE solutions
1 Preparatlon by hand, 2 Manual preparation is replaced by advancing use of CAE

Table 6-17

Overview of the most important CAD standards

Standard	Status	Working title
DIN V 40719 -1000	04/93	Rules for computer-supported creation of circuit diagrams
DIN EN 61355	11/97	Classification and identification of documents for installations, systems and equipment
DIN EN 61082-1 bis-4	*)	Documents of electrical engineering
DIN EN 61360-1, -2 und -4	*)	Standard data element types with associated classification scheme for electrical components
DIN EN 81714 -2	09/99	Generating graphic symbols for application in the documentation of products
DIN EN 60617-2 bis -13	*)	Graphic symbols for circuit diagrams

*) See Table 6-24

(continued)

Table 6-17 (continued)

Overview of the most important CAD standards

Standard	Status	Working title
DKE standard symbol file	04/96	Standard symbol file for graphic symbols according to DIN EN 60617 standards series based on DIN V 40900-100 and DIN V 40950
CAD-Lib		Standard library with standard mechanical parts
VDA-PS		FORTRAN interface for graphic design
IGES		Initial graphics exchange standard, interface for exchange of CAD data, emphasis in geometry
EDIF		Electronic data interface format for electrical engineering, emphasis on digital and analogue elements
DIN V 40950	08/92	Process-neutral interface for circuit-diagram data (VNS) Format for exchange of documentation of electrotechnical installations 2nd edition
ISO/IEC 10303		STEP Standard for the exchange of product-model data

In the last few years, the necessity of standards in the CAD area has been recognized at both national and international level. Table 6-17 contains an overview of the most important standards and drafts in the CAD area.

All interfaces are worked out at international level by the ISO (International Organization for Standardization) in TC 184 “STEP”, with application models for the various applications being processed in special working groups.

6.3.2 Outline of hardware and software for CAD systems

A CAD station consists of a computer with its immediate peripherals such as disk and cassettes, the dialogue peripherals and the CAD output devices. Tables 6-18 to 6-21 show selection criteria and the capabilities of components for CAD systems. The CAD workstation today is a single working place with central data storage at a server in the network.

Table 6-18

CAD computer system with directly connected peripherals (without plotter);

Main processor of the CAD computer	Application	Peripheral
Personal computer with graphics processors	2D/3D	Magnetic disk Floppy disk CD drive
Workstation with graphics processors	2D/ 3D	Magnetic disk Cassette drive

Table 6-19 Input/output devices of CAD systems

	Input device	Output device	Graphics	Alpha-numeric
Digitizer	×		×	
Plotter		×	×	
Laser printer		×	×	×
Passive graphics terminal		×	×	
Interactive alphanumer. terminal	×	×		×
Interactive graphics workstation	×	×	×	×

Table 6- 20
Alternative hardware components of an interactive graphics CAD terminal

Graphics display unit	Coordinate positioning and input	Command input, alphanumeric
– refresh rate > 75 Hz mono/colour 15” to 19” diagonal 1024 x 768 pixels	– electronic stylus with menu tablet – mouse	– A/N keyboard – predefined fields on menu – allocation of function keys – command menu display on screen, selection mouse (windows method)

Table 6-21

The important graphics output devices

Plotter principle	Format size	Output, quality	Plot production time
Electrostatic plotter, drawing resolved into dots	Height A4 to A0 Length up to 10 m	Multicolour, quality very good	1 to 2 minutes
Ink-jet plotter, Ink spray nozzle	A4 to A0	Multicolour, filled-in areas, quality average	Up to 1 hr, depending on information volume
Microfilm plotter	Up to A0	Film, quality very good	Measured in seconds, up to 1 minute to A1/A0
Laser printer/plotter	A4 to A0	Multicolour, quality very good	Seconds to minutes

The performance of CAD systems depends not solely on the hardware, but to a very large degree on the software. While the hardware generally determines the response time and processing speed, the software influences the methodology and how the applications function.

The bottom rung in the software hierarchy is the operating system level, which is usually provided by the hardware supplier. The CAD software constitutes the user software and is the second level in the software hierarchy. This user software is usually divided into a general CAD-oriented part and a problem-oriented part which takes into account the particular criteria and boundary conditions of the engineering task in hand. A CAD system for switchgear engineering thus includes problem-oriented user software for tasks such as

- station layout and planning,
- planning of buildings,
- preparation of circuit diagrams,
- cable systems,
- mechanical design

The computer is able to generate either 2D or 3D models.

Here,
2D means representation in one plane.

3D means true working in three dimensions, showing views from different angles and perspectives. A distinction is made between edge or wire models, surface and volume models.

The objectives of introducing CAD methods are as follows:

- Improved quality of engineering solutions and drawing documentation,
- Time savings on individual steps and entire project,
- Flexible handling of modifications,
- Technically safe, common standard variants and repeating solutions,
- Comprehensive use of EDP by linking CAD, CAM, CAP and CAT.

In any overall assessment of new CAD methods or systems, these advantages must be set against the preparatory work and requirements in each individual case:

- Analysis of present situation and structuring of tasks,
- Investment for hardware and software,
- Establishment of symbol and drawing library and databases,
- Training of engineering staff,
- Initial acceptance.

6.3.3 Overview of CAD applications in ABB switchgear engineering

ABB switchgear engineering has been using CAD methods for many years and on an ever increasing scale for planning tender and order processing. The CAD systems are subject to a continuous process of development to meet the continuing progress in the area of switchgears and the increasing use of digital station control systems.

Integration of the various CAD systems into an object-oriented environment is an essential requirement for optimizing the entire planning process. This extends from processing tenders to processing orders for commissioning and further to service. So also the documentation of the installation and archiving is included.

The CAD systems in use are based on CAD operating software, which can now generally run on different hardware platforms with different operating systems. In addition, problem-oriented application programs, mostly ABB-internal, have been developed to run with them. They are designed to meet the requirements of users and customers. The quality assurance of the process is shown in Fig. 6-8.

A number of CAD systems with varying internal system logic are available on the German market in the area of electrical engineering. A decisive point in selecting a CAD system, in addition to the straight hardware and software costs, is the expense of the training required and of establishing internal company databases for symbols and components. Other important criteria are the functionality of the CAD system, the options for connecting to the internal company processes and the supported interfaces.

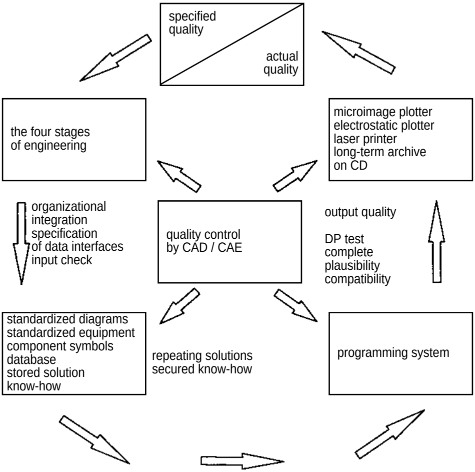
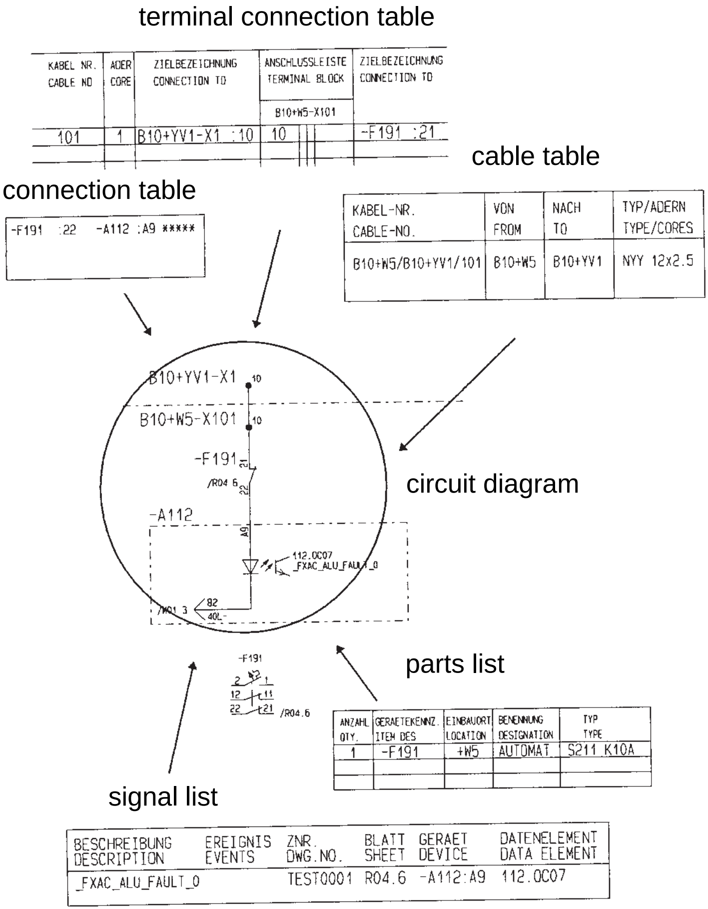


Fig. 6-8

Quality features of the CAD/CAE process. Quality loop with the engineering organization control functions, repeating solution, data processing testing and output technology.

The time sequence in switchgear engineering and the requirement for high-quality documentation (Fig. 6-9) demands the application of highly developed CAE techniques.



terminal connection table

KABEL NR. CABLE NO	ADER CORE	ZIELBEZEICHNUNG CONNECTION TO	ANSCHLUSSLEISTE TERMINAL BLOCK				ZIELBEZEICHNUNG CONNECTION TO
			B10+W5-X101				
101	1	B10+YV1-X1 :10	10				-F191 :21

cable table

KABEL-NR. CABLE-NO.	VON FROM	NACH TO	TYP/ADERN TYPE/CORES
B10+W5/B10+YV1/101	B10+W5	B10+YV1	NYY 12x2.5

connection table

-F191 :22 -A112 :A9 *****

circuit diagram

parts list

ANZAHL QTY.	GERAETEKENNZ. ITEM DES	EINBAUORT LOCATION	BENENNUNG DESIGNATION	TYP TYPE
1	-F191	+W5	AUTOMAT	S211 K10A

signal list

BESCHREIBUNG DESCRIPTION	EREIGNIS EVENTS	ZNR. DWG.NO.	BLATT SHEET	GERAET DEVICE	DATENELEMENT DATA ELEMENT
_FXAC_ALU_FAULT_0		TEST0001	R04.6	-A112:A9	112.0C07

Fig. 6-9

Documentation automatically generated by CAD/CAE with cross references between circuit diagram, terminal connection table, cable table, connection table, parts list and signal list.

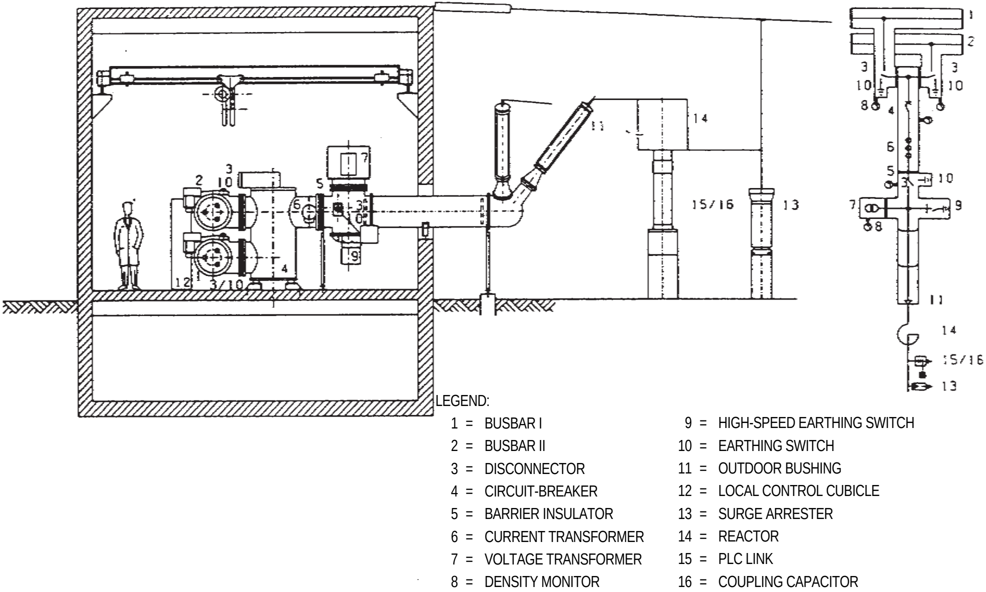
Interfaces for high-end data exchange are becoming increasingly important for CAD/CAE technologies. More and more customers today are demanding their documentation on electronic media. Particularly in Germany, the CAD system with which the documentation must be generated is frequently specified. For switchgear engineering, this is a significant restriction and above all, extremely cost-intensive. Today in particular, no company can afford to run several CAD systems internally in parallel for one application. The cost of hardware, software, administration and employment of trained staff for several systems is simply too high.

However, even within ABB, data must be forwarded to subcontractors and processed. This leaves only the subject of interfaces (and those high-end) as the only alternative for an efficient data exchange.

The standard IGES and DXF interfaces are suitable only for simple graphic data exchange. Higher-end interfaces such as VNS (process-neutral interface for circuit diagram data as per DIN V 40950 2nd edition) offer options for exchanging graphic and logical information between electrical CAD systems at a significantly higher level. A data exchange process that covers nearly everything has been developed with STEP (**ST**andard for the **E**xchange of **P**roduct model data as per ISO/IEC 10303). However, this also requires a general rethink among the software suppliers, because data exchange using STEP also requires STEP-conforming tools with object-oriented databases as a starting point. The first CAD suppliers have already started on this path. The interface properties defined as the application model for the various applications have already been published for mechanical engineering (AP 214) as a standard, and are in the process of being internationally approved for electrical engineering (AP 212).

Suitable CAD/CAE tools are also available for CAD and computer-supported processing of the primary engineering. Here the entire spectrum is being processed with the encapsulated medium-voltage substations of the voltage level from 6 kV to the 3-phase encapsulated GIS switchgears of the ELK-0 range to 170 kV up to outdoor switchgears to the 500 kV and even 800 kV maximum voltage levels. Various tools are also used here for the correspondingly varied requirements and developed structures at the various engineering locations. However, even these tools are embedded in the entire engineering process. It begins at tender preparation with automatic printout of tender documents; it includes the generation of the CAD drawings and contains check mechanisms; automatic generation of derived documents, drawings as well as material and order lists are also included. Finally, the process is complete after submission of the final documentation to the customer with long-term archiving.

Figs. 6-10 and 6-11 show disposition drawings prepared with CAD/CAE .



LEGEND:

1 = BUSBAR I
2 = BUSBAR II
3 = DISCONNECTOR
4 = CIRCUIT-BREAKER
5 = BARRIER INSULATOR
6 = CURRENT TRANSFORMER
7 = VOLTAGE TRANSFORMER
8 = DENSITY MONITOR
9 = HIGH-SPEED EARTHING SWITCH
10 = EARTHING SWITCH
11 = OUTDOOR BUSHING
12 = LOCAL CONTROL CUBICLE
13 = SURGE ARRESTER
14 = REACTOR
15 = PLC LINK
16 = COUPLING CAPACITOR

Fig. 6-10

Sectional elevation and gas diagram of a 145 kV GIS branch with cable basement and outdoor connection

Fig. 6-11 shows the plan view of a 123 kV switchyard created by using the CAD system, with double busbars and in-line layout.

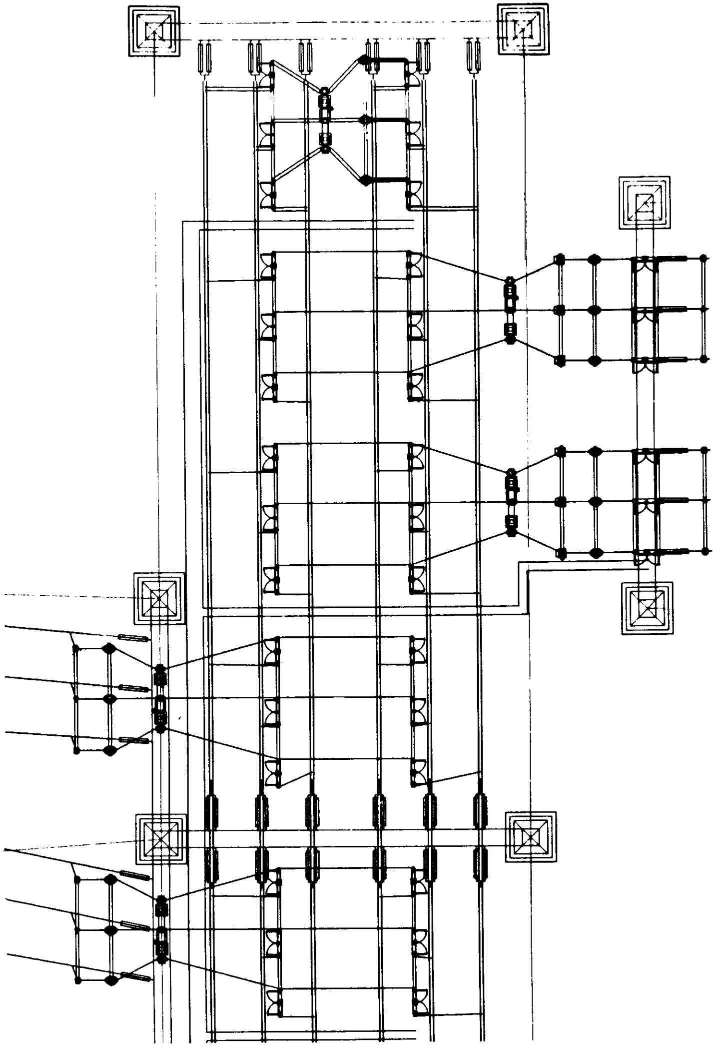


Fig. 6-11

123 kV outdoor switching station with double busbars, in-line layout

6.4 Drawings

In technical drawings the information required for constructing and operating an installation or a station component is given in a font that is “readable” for engineers and technicians. The drawings, or these days preferably referred to as documents, are therefore subject to specific, generally accepted rules and implementation guidelines, which are based on national and international standards. The specifications cover such items as:

- Paper formats, paper types
- Representation, symbols, characters
- Lettering, font sizes
- General design, header, metadata
- Document types, -identification and -order
- Creation of documents, processing
- Minimum content of documents

6.4.1 Drawing formats

Table 6-22

A-series formats as per DIN 6771-6, and ISO 5457

Format symbol	Size		Number of fields	
	cut	uncut	short side	long side
A0	841 x 1189	880 x 1230	16	24
A1	594 x 841	625 x 880	12	16
A2	420 x 594	450 x 625	8	12
A3	297 x 420	330 x 450	6	8
A4	210 x 297	240 x 330	4	6

Table 6 -23

Continuous formats as per DIN 6771-6

Format symbol	Size		Number of fields	
	cut	uncut	short side	long side
A2.0	420 x 1189	450 x 1230	8	24
A2.1	420 x 841	420 x 880	8	16
A3.0	297 x 1189	330 x 1230	6	24
A3.1	297 x 841	330 x 880	6	16
A3.2	297 x 594	330 x 625	6	12

Continuous formats should be avoided as far as possible.
For formats >A0, see DIN 476.

6.4.2 Standards for representation

The rules for representation in electrical engineering documents are specified in DIN standards. There have been some modifications in connection with the incorporation of international standards since the last edition of the ABB manual; see also Section 6.2. Table 6-24 gives an overview of the most important DIN standards covering the preparation of electrical engineering documents.

Table 6-24
Overview of important DIN standards for the preparation of drawings

Standard or Part	Edition	Title
DIN 6-1, 6-2	12.86	Representation, views, sections
DIN 15-2, 15-3	12.86	Basics, lines
DIN 6771-1	12.70	Title blocks for drawings, plans and lists
DIN 6771-5	10.77	Standard forms for technical documentation; circuit diagram in A3 format
DIN 6776-1	04.76	Lettering, graphic characters
DIN 40719-2	06.78	Circuit documentation; reference designation of electrical equipment
DIN 40719-2 Sup. 1	06.87	Circuit documentation; reference designation of electrical equipment, alphabetically arranged examples
DIN 40719-6	02.92	Circuit documentation; rules for functional diagrams; IEC 848 modified
DIN EN 61082-1	05.95	Documents in electrical engineering – Part 1: General requirements
DIN EN 61082-1/A1	05.96	Documents in electrical engineering – Part 1: General rules, amendment 1
DIN EN 61082-1/A2	07.97	Documents in electrical engineering – Part 1: General rules, amendment 2
DIN EN 61082-2	05.95	Documents in electrical engineering – Part 2: Function-oriented diagrams
DIN EN 61082-3	05.95	Documents in electrical engineering – Part 3: Connection diagrams, tables and lists
DIN EN 61082-4	10.96	Documents in electrical engineering – Part 4: Location and installation documents
DIN EN 61346-1	01.97	Structuring principles and reference designations – Part 1: General requirements
DIN EN 61175	05.95	Designations for signals and connections
DIN EN 61355	11.97	Classification and designation of documents for plants, systems and equipment

(continued)

Table 6-24 (continued)
Overview of important DIN standards for the preparation of drawings

Standard or Part	Edition	Title
DIN EN 60617-2	8/97	Graphical symbols for diagrams; Part 2: Symbol elements and other symbols having general application
DIN EN 60617-3	08/97	Graphical symbols for diagrams; Part 3: Conductors and connecting devices
DIN EN 60617-4	08/97	Graphical symbols for diagrams; Part 4: Basic passive components
DIN EN 60617-5	08/97	Graphical symbols for diagrams; Part 5: Semiconductors and electron tubes
DIN EN 60617-6	08/97	Graphical symbols for diagrams; Part 6: Production and conversion electrical energy
DIN EN 60617-7	08/97	Graphical symbols for diagrams; Part 7: Switchgear, controlgear and protection devices
DIN EN 60617-8	08/97	Graphical symbols for diagrams; Part 8: Measuring instruments, lamps and signalling devices
DIN EN 60617-9	08/97	Graphical symbols for diagrams; Part 9: Telecommunications: switching and peripheral equipment
DIN EN 60617-10	08/97	Graphical symbols for diagrams; Part 10: Telecommunications: transmission
DIN EN 60617-11	08/97	Graphical symbols for diagrams; Part 11: Architectural and topographical installation plans and diagrams
DIN EN 60617-12	04/99	Graphical symbols for documentation; Part 12: Binary logic elements
DIN EN 60617-13	01/94	Graphical symbols for documentation; Part 13: Analogue elements
DIN EN 61360-1	01/96	Standard data element types with associated classification scheme for electric components – Part 1: Definitions - principles and methods
DIN EN 61360-2	11/98	Standard data element types with associated classification scheme for electric components – Part 2: EXPRESS data model
DIN EN 61360-4	06/98	Standard data element types with associated classification scheme for electric components – Part 4: IEC Reference collection of standardized data elements type, component classes and terms.

On a national german level the recommendations of the IG EVU, i.e. the “Energy Distribution Group”, have been developed into generally accepted rules with normative character for documentation of plants, process sequences and equipment.

6.4.3 Lettering in drawings, line thicknesses

Letter type B as per DIN 6776. Preferred font sizes: 2.5, 3.5, 5 and 7 mm (2 mm for CAD processing).

The font sizes, letter and line thicknesses must be selected so that the alphanumeric characters and lines are still easily readable at reduced reproduction sizes; this meets the requirements for microfilming drawings.

Table 6-25

Recommended line thickness (stroke widths in mm)

Line types			Recommended application of line thicknesses (mm)			
			A 4 / A 3	A 2 / A 1	A 0	
Thick	A G	——— ━ ▪ ━	0.5	0.7	1	1.4
Medium	D	---------	0.25	0.35	0.5	0.7
Thin	B C E	——— 〰 —·—·—		0.25	0.35	0.5
Thick/Thin	F	—·━·—	0.25 / 0.5	0.25 / 0.7	0.35 / 1	0.5 / 1.4

Table 6-26

Recommended font sizes for drawings (mm)

Sheet size	Drawing title	Drawing number	Text, remarks	Item no.
A4 A3 A2	3.5-5	5 – 7	2.5 – 3.5	5 – 7
A1 A0	5 – 7	7	3.5 – 5	7

The above table values must be considered generally applicable typical values. The font sizes depend on the format. Once selected, the font size shall be retained for dimensions, positions, remarks, etc. within one drawing. A 2 mm font size is preferred for CAD-generated circuit documents.

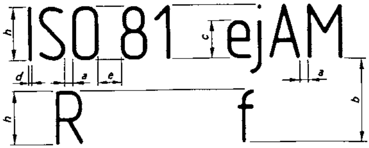


Table 6-27

Font style B (d = h / 10) to DIN 6776

Type		Ratio	Dimension in mm						
Letter height									
Upper case (capital)	*h*	(10/10) *h*	2.5	3.5	5	7	10	14	20
Lower case (small) (without ascenders/decenders)	*c*	(7/10) *h*	–	2.5	3.5	5	7	10	14
Minimum foot spacing	*a*	(2/10) *h*	0.5	0.7	1	1.4	2	2.8	4
Minimum line spacing	*b*	(14/10) *h*	3.5	5	7	10	14	20	28
Minimum word spacing	*e*	(6/10) *h*	1.5	2.1	3	4.2	6	8.4	12
Stroke width	*d*	(1/10) *h*	0.25	0.35	0.5	0.7	1	1.4	2

6.4.4 Text panel, identification of drawing

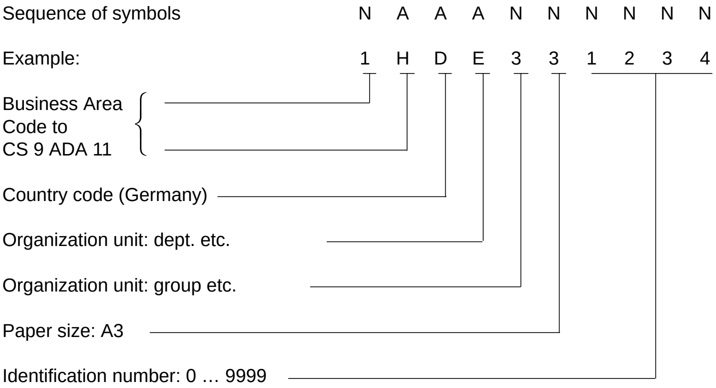
A drawing is a document which aids in setting up or operating an installation or a station component. It must therefore include identifications and data showing its content, status and origins.

- Origin, originator, release
- Date of production, if necessary with indication of source in view of patent claims
- Drawing number
- Subject of drawing (title block)
- Modification status
- Filing instructions, if appropriate
- Scale (for layouts, designs)
- Classification

From these indications and by filling out the text panel, it is confirmed that the relevant standards and quality specifications have been observed.

The identifier drawing number at ABB consists of a minimum of three alpha and seven numeric characters, whose position provides varying information.

Key to drawing number:



If a drawing consists of several pages, e.g. circuit documentation manual, additional information is required, see Section 6.2.

6.4.5 Drawings for switchgear installations

The drawings are classified in the following groups, according to their function:

- Civil engineering drawings, architectural diagrams
- Layout drawings
- Design drawings, arrangement drawings, parts lists
- Circuit documentation
- Tables of contents, lists of drawings

Standard paper sizes are available for the different kinds of drawings, depending on their purpose. DIN format A3 with title block conforming to DIN 6771 Part 5 is preferred for circuit documentation and also for related switchboard arrangement drawings, tables etc.

Layout and design drawings have to be drawn to scale. Format and title block are selected in accordance with DIN 6771-1. Preferred scales are specified for the different kinds of installation and voltage levels (Table 6-28).

Table 6-28

Preferred scales

Design Layout	Scale
Outdoor installations	
Up to 525 kV	1 : 500; 1 : 200
Up to 245 kV	1 : 200; 1 : 100
Up to 145 kV	1 : 100; 1 : 50
GIS installations	1 : 50; 1 : 25 (not standardized)
Generator busducts	1 : 50; 1 : 20
Medium-voltage installations	1 : 20
Cubicles, inside arrangement	1 : 10
Other, details	1 : 5; 1 : 2.5; 1 :1
Enlargements	2 : 1; 5 : 1; 10 :1

6.4.6 Drawing production, drafting aids

The following methods are used for economical preparation of documents:

- CAD (Computer-Aided Design and Drafting) with drawings output by plotter, see Section 6.3
- CAE (Computer-Aided Engineering) with documents generated by computer programs and output by plotters, see Section 6.3.3, e.g. terminal diagrams, wiring lists, cable tables, etc.
- Drawing reproduction with photomachines
- Computer-aided microfilming (COM system)

7 Low-voltage Switchgear

7.1 Switchgear apparatus

Low-voltage switchgear is designed for switching and protection of electrical equipment. The selection of switchgear apparatus is based on the specific switching task, e.g. isolation, load switching, short-circuit current breaking, motor switching, protection against overcurrent and personnel hazard. Depending on the type, switchgear apparatus can be used for single or multiple switching tasks. Switching tasks can also be conducted by a combination of several switchgear units. Fig. 7-1 shows some applications for LV switchgear.

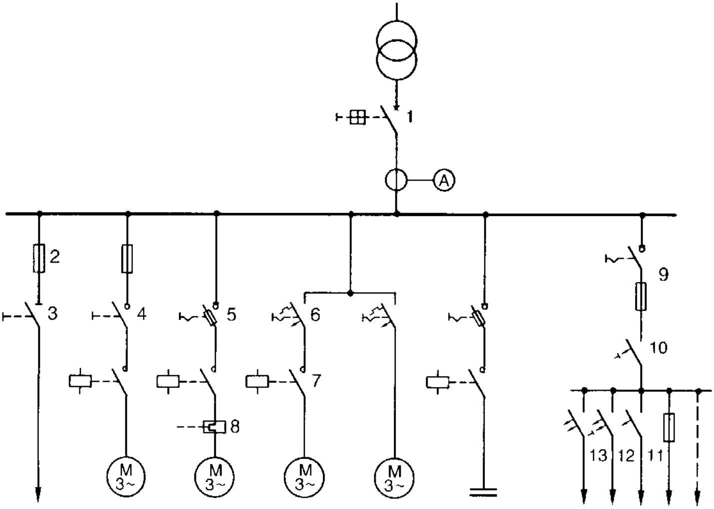


Fig. 7-1

Examples for use of low-voltage switchgear:

1 Circuit-breaker, general 2 Fuse, 3 Disconnector, 4 Loadbreak switch, 5 Fused switch-disconnector, 6 Motor starter (motor protection switch), 7 Contactor, 8 Overload relay, 9 Switch disconnector with fuses, 10 Residual current-operated circuit-breaker (RCCB), 11 Miniature circuit-breaker, 12 Residual current-operated circuit-breaker with overcurrent tripping (RCBO), 13* Residual current-operated miniature circuit-breaker (RCD)*

** Graphic symbols not standardized*

7.1.1 Low-voltage switchgear as per VDE 0660 Part 100 and following parts, EN 60947 – ... and IEC 60947 – ...

Table 7-1 shows a partial overview of the applicable standards for switchgear apparatus.

Table 7-4 of the utilization categories for contactors already corresponds to IEC 60947-4-1, because it has been supplemented with reference DIN VDE. Utilization categories for switchgear as per IEC 60947-3 are shown in Tables 7-6 and 7-7.

In accordance with the regulations, for all devices the rated voltages (formerly referred to as nominal voltages) are specified whose insulation voltages are assigned as test values. For example, devices up to 690 V have a test value of 2 500 V. The rated impulse voltage resistance U_{imp} must be shown on the switch or be included in the manufacturer's documentation. The design of a low-voltage system must ensure that no voltages can occur which are higher than the rated insulation voltages of the devices.

Table 7-1

Partial overview of the most important standards for low-voltage switchgear

	German standard [1]	Classification VDE 0660 [2]	European standard	International standard
General specification	DIN EN 60947-1	Part 100	EN 60947-1	IEC 60947-1
Circuit-breaker	DIN EN 60947-2	Part 101	EN 60947-2	IEC 60947-2
Electromechanical contactors and motor starters	DIN VDE 660-102	Part 102	EN 60947-4-1	IEC 60947-4-1
Switches, disconnectors, switch-disconnectors and fuse combination units	DIN VDE 660-107	Part 107	EN 60947-3	IEC 60947-3
Semiconductor contactors	DIN VDE 660-109	Part 109	–	IEC 60158-2 mod.
Multifunction equipment, automatic transfer switch	DIN VDE 0660-114	Part 114	EN 60947-6-1	IEC 60947-6-1
Multifunction equipment, control and protection switching devices	DIN EN 60947-6-2	Part 115	EN 60947-6-2	IEC 60947-6-2
Contactors and motor starters, semiconductor motor controllers and starters for AC	DIN EN 60947-4-2	Part 117	EN 60947-4-2	IEC 60947-4-2 mod.
Control devices and switching elements, electromechanical control circuit devices	DIN EN 60947-5-1	Part 200	EN 60947-5-1	IEC 60947-5-1

[1] Current valid designation

[2] Classification in VDE specifications system

Circuit-breakers

Circuit-breakers must be capable of making, conducting and switching off currents under operational conditions and under specified extraordinary conditions up to the point of short circuit, making the current, conducting it for a specified period and interrupting it. Circuit-breakers with overload and short-circuit instantaneous tripping are used for operational switching and overcurrent protection of operational equipment and system parts with low switching frequency. Circuit-breakers without overcurrent releases, but with open-circuit shunt release (0,1 to 1,1 Un), are used in meshed systems as „network protectors“ to prevent reverse voltages.

Circuit-breakers are supplied with dependent or independent manual or power actuation or with a stored-energy mechanism. The circuit-breaker is opened by manual actuation, electrical actuation by motor or electromagnet, load current, overcurrent, undervoltage, reverse power or reverse current tripping.

Preferred values of the rated control voltage are listed in Table 7-2.

Table 7-2

Preferred values of the rated supply voltage of control devices and auxiliary circuits as per DIN EN 60947-2 (VDE 0660 Part 101)

U_s DC voltage						AC single-phase voltage					
24	48	110	125	220	250	24	48	110	127	220	230

The major classification criteria of circuit-breakers are

– *by utilization categories*

A: without short-time grading of delay tripping for selectivity under short-circuit conditions

B: with intended short-time delay of short-circuit tripping (adjustable or non-adjustable)

– *by type of arc extinction medium*

Air, vacuum, gas

– *by design*

compact design or „moulded case“ type,
open design or „air-break“ type

– *by installation type*

fixed,
draw-out

– *by type of arc extinction*

current-limiting circuit-breaker,
non-current-limiting circuit-breaker

„Moulded case“ circuit-breakers consist of an insulation case that contains the components of the breaker. This type of breaker is designed for rated currents up to about 3 200 A.

“Open type circuit-breakers” or also “air-break circuit-breakers” do not have a compact insulation case. They are designed for rated currents up to 6 300 A.

Non-current-limiting circuit-breakers extinguish the arc at the natural alternating current zero crossing. The conducting paths are so dimensioned that they can conduct the full short-circuit current thermally. All downstream system components are also thermally and dynamically loaded with the unlimited peak short-circuit current.

Current limiting circuit-breakers interrupt the short-circuit current before it reaches the peak value of the first half-cycle. The peak short-circuit current is limited to a value (cut-off current I_D) that significantly reduces the thermal and dynamic stress on the downstream components. Fig. 7-2 shows the energy-limiting and current-limiting characteristics of a current-limiting circuit-breaker.

Current-limiting circuit-breakers, like fuses, are particularly suitable for short-circuit protection of switchgear with lower switching capacity (back-up protection).

Rated short-circuit currents: Rated-operating short-circuit current I_{CS}

Test duty: O – t – CO – t – CO

Rated-limiting short-circuit current I_{CU}

Test duty: O – t – CO

O = open; CO = close-open; t = dead time between operations (3 min)

Table 7-3

a) Recommended percentage values for I_{cs} based on I_{cu}
as per DIN EN 60947-2 (VDE 0660 Part 101)

Utilization category A % of I_{CU}
25
50
75
100

Utilization category B % of I_{CU}
–
50
75
100

b) Ratio *n* between short-circuit-making and -breaking capacity and associated power factor (with alternating current circuit-breakers)
as per DIN EN 60947-2 (VDE 0660 Part 101)

Short-circuit-breaking capacity I (rms value in kA)	Power factor	Minimum value for n $n = \frac{\text{Short-circuit-making capacity}}{\text{Short-circuit-breaking capacity}}$
4.5 < I ≤ 6	0.7	1.5
6 < I ≤ 10	0.5	1.7
10 < I ≤ 20	0.3	2.0
20 < I ≤ 50	0.25	2.1
50 < I	0.2	2.2

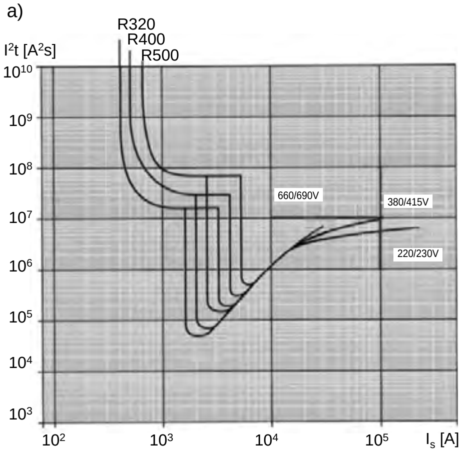


Fig. 7-2a

Limitation of let-through power I^2•t by a current-limiting circuit-breaker for I_n = 630 A with various tripping settings (R 320 to R 500)

I_s = short-circuit current, prospective r.m.s. values

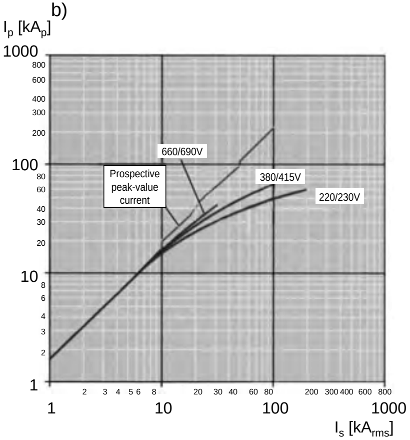


Fig. 7-2b

Limitation of the short-circuit current by a current-limiting circuit-breaker for I_n = 630 A with various service voltages

I_p = let-through current, peak current values
I_s = short-circuit current, prospective r.m.s. values

Contactors

Contactors are remote-control switching devices with restoring force, which are actuated and held by their actuator. They are primarily intended for high-switching frequency for switching currents with equipment in a healthy state, including operational overload. Contactors are suitable for isolation to a limited extent only, and they must be protected against short circuit by upstream protection equipment.

Apart from the electromagnetic actuation most often used, there are also contactors with pneumatic or electropneumatic actuation.

Contactors are selected by utilization categories, Table 7-4.

Table 7-4

Utilization categories for contactors as per VDE 0660 Part 102, EN 60947-4-1

Current type	Utilization category	Typical application
Alternating current	AC-1	Non-inductive or weak inductive load, resistance furnaces
	AC-2	Slip-ring motors: starting, disconnecting
	AC-3	Squirrel-cage motors: starting, disconnecting while running[1)]
	AC-4	Squirrel-cage motors: starting, plug braking, reversing, jogging
	AC-5a	Switching gas-discharge lights
	AC-5b	Switching incandescent lights
	AC-6a	Switching transformers
	AC-6b	Switching capacitor banks
	AC-7a	Weakly inductive load in household appliances and similar applications
	AC-7b	Motor load for household devices
	AC-8a	Switching hermetically sealed refrigerant compressor motors with manual reset of the overload release[2)]
	AC-8b	Switching hermetically sealed refrigerant compressor motors with automatic reset of the overload release[2)]
Direct current	DC-1	Non-inductive or weakly inductive load, resistance furnaces
	DC-3	Shunt motors: starting, plug braking, reversing, jogging, resistance braking
	DC-5	Series motors: starting, plug braking, reversing, jogging, resistance braking
	DC-6	Switching incandescent lights

[1)] Devices for utilization category AC-3 may be used for occasional jogging or plug-braking for a limited period, such as setting up a machine; the number of actuations in these circumstances shall not exceed five per minute and ten per ten minutes.

[2)] In the case of hermetically sealed refrigerant compressor motors, compressor and motor are sealed in the same housing without an external shaft or with the shaft sealed, and the motor operates in the refrigerant.

Table 7-5

Making and breaking capacity of contactors

Making and breaking conditions in accordance with the utilization categories2)
as per DIN EN 60947-4-1 (VDE 0660 Part 102)

Utilization category	Making and breaking conditions			
	I_c/I_e	U_r/U_e	cos φ	Number of switching cycles
AC-1	1.5	1.05	0.8	50
AC-2	4.0	1.05	0.65	50
AC-3	8.0	1.05	1)	50
AC-4	10.0	1.05	1)	50
AC-5a	3.0	1.05	0.45	50
AC-5b	1.5	1.05		50
AC-6a				
AC-6b				
AC-7a	1.5	1.05	0.8	50
AC-7b	8.0	1.05	1)	50
AC-8a	6.0	1.05	1)	50
AC-8b	6.0	1.05	1)	50
			L/R (ms)	
DC-1	1.5	1.05	1.0	50
DC-3	4.0	1.05	2.5	50
DC-5	4.0	1.05	15.0	50
DC-6	1.5	1.05		50

Utilization category	Making conditions for additional operations			
	I_c/I_e	U_r/U_e	cos φ	Number of switching cycles
AC-3	10	1.05	1)	50
AC-4	12	1.05	1)	50

I	Making current. The making current is stated as direct current or symmetrical alternating current r.m.s. value, where with alternating current, the asymmetrical current may be higher.
I_c	Making and breaking current, stated as direct current or symmetrical alternating current r.m.s. value.
I_e	Rated normal current
U	Applied voltage
U_r	Power frequency recovery voltage or DC recovery voltage
U_e	Rated voltage
cos φ	Test-circuit power factor
L/R	Test-circuit time constant

1) cos φ = 0.45 for $I_e \leq 100$ a, cos φ = 0.35 for $I_e \geq 100$ A

2) More information can be found in the standards listed in Table 7-1

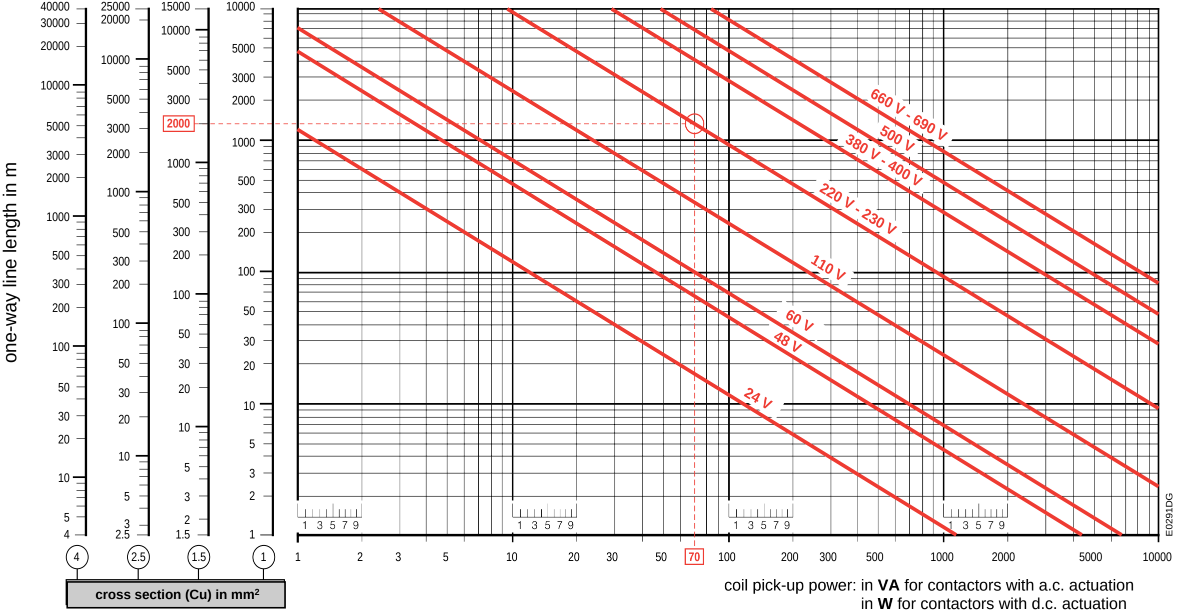


Fig. 7-3

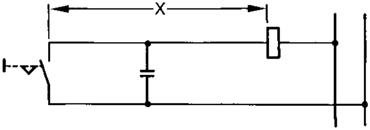
Permissible one-way control line length when closing contactors

Contactors are fitted with current-dependent protection devices to prevent thermal overload of motors. For protection against motor overload or in the event of external conductor failure, e.g. line break or blowing of only one fuse, the overload relays are set to the rated current of the motor. Modern overload relays have a temperature compensation facility to prevent interference from varying ambient temperatures affecting the trip times of the bimetallic contacts. They also have a phase failure protection; manual or automatic reset can be selected.

For preferred values for the rated supply voltage see Table 7-2. Protection must be actuated without problem within the voltage limits of 85 % and 110 % – with control current flowing.

When sending commands over long control lines, the contactor may not react to the command on closing because of excessive voltage drop (AC and DC actuation) or on breaking because of the excessive capacitance on the line (Fig. 7-4). A voltage drop of max. 5 % is permissible for calculating the length of the control line. The permissible line lengths for making and breaking can be determined using Figs. 7-3 to 7-5.

Circuit A:
Sending continuous commands over a two-core cable
(e.g. capacity 0.2 µF/km)
× = one-way line length



Circuit B:
Sending commands by push-button with locking contact,
three-core cable
(e.g. capacity 2 × 0.2 = 0.4 µF/km)
× = one-way line length

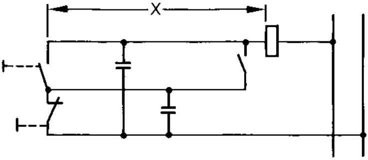


Fig. 7-4

Circuits for actuating contactor coils with line capacities

Example for Fig. 7-3:

Contactor A9, coil 230 V, 50 Hz, power input of coil of the contactor: 70 VA,
cross section of the control wiring: Cu 1.5 mm^2,
Permissible line length: 2000 m

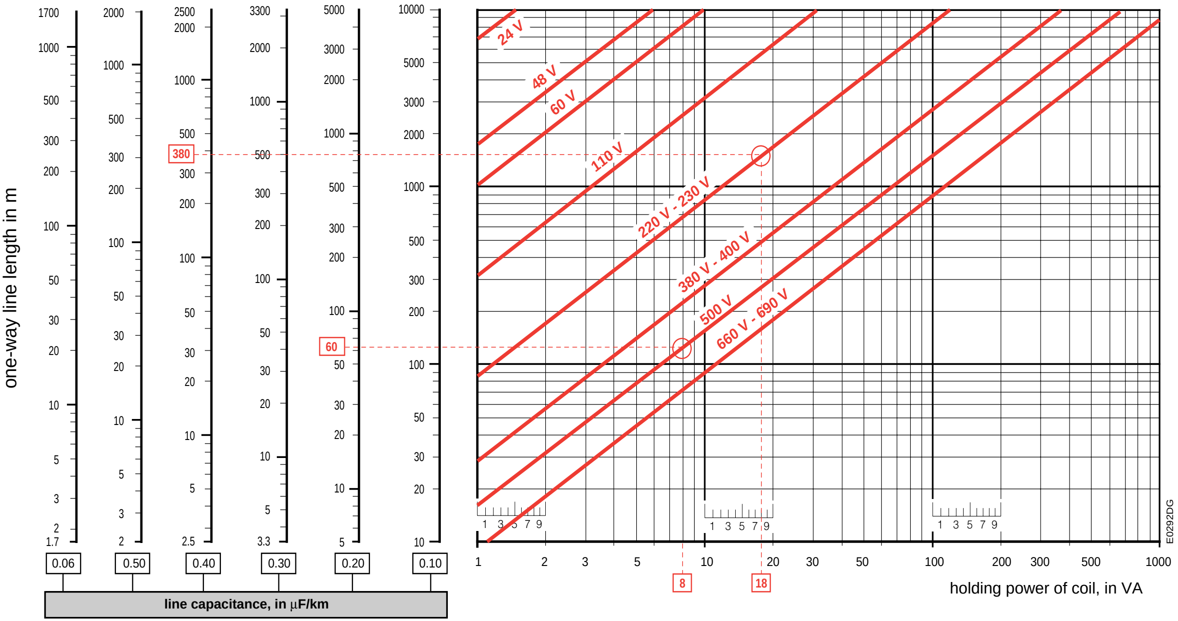


Fig. 7-5

Permissible one-way length for control lines when opening contactors

Example A for Fig. 7-5:

Contactor A 16, coil U_c = 500 V, 50 Hz,
Holding power of coil: 8 VA.

Continuous command via
two-core cable
with a capacity of 0.2 µ F/km
Max. permissible line length: 60 m

Example B for Fig. 7-5:

Contactor A 50, coil U_c = 230 V, 50 Hz
Holding power of coil: 18 VA.
Circuit with push-button
commands and locking contact
three-core cable with a capacity
of 2 x 0.2 µ F/km = 0.4 µ F/km
Max. permissibleble line length: 380 m

Motor starter

The motor starter is the term for the combination of all devices required for starting and stopping a motor in connection with appropriate overload protection.

Compact, manually operated motor starters, also referred to as motor protection switches, are suitable for switching short-circuit currents if they meet the conditions for circuit-breakers.

Motor starters can be actuated manually, electromagnetically, by motor, pneumatically and electropneumatically. They are suited for operation with open-circuit shunt releases, undervoltage relays or undervoltage tripping releases, delayed overload relays, instantaneous overcurrent relays and other relays or releases.

The rated normal current of a motor starter is dependent on the rated operating voltage, the rated frequency, the rated operating duty, the utilization category (Table 7-4) and the type of housing.

Other switchgear apparatus (DIN VDE 0660 Part 107)

Disconnector 

Switching devices that for safety purposes has isolating distances in the open position in conformity with specific requirements. A disconnector can only open and close a circuit if either a current of negligible quantity is switched off or on, or if there is no significant voltage difference between the two contacts of each pole. It can conduct normal currents under normal conditions and larger currents under abnormal conditions, e. g. short-circuit currents, for a specific period.

Note 1:

Currents of negligible quantity are capacitive currents, which occur at bushings, busbars, very short cables and the currents from voltage transformers and voltage dividers used for measurement purposes.

There is no significant voltage difference in circumstances such as shunting voltage-regulating transformers or circuit-breakers.

Note 2:

Disconnectors can also have a specific making and/or breaking capacity.

Load-break switch

Switching device that under normal conditions in the current circuit, if applicable with specified overload conditions, can make, conduct and break currents and that under specified abnormal conditions such as short circuit can conduct these currents for a specified period.

Note:

> A load-break switch may have a short-circuit-making capacity, but no short-circuit-breaking capacity.

Switch-disconnector

Load-break switch that meets the isolating requirements specified for a disconnector in the open position.

Disconnection (isolating function)

Function for isolating the voltage supply of the entire switchboard or system part, in which the switchboard or system part is disconnected from all energy sources for safety reasons.

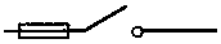
Fuse combination unit

Load-break switch, disconnector or switch-disconnector and one or more fuses in a unit assembled by the manufacturer or in accordance with the manufacturer’s directions.

Disconnector with fuses

Unit comprising disconnector and fuses, in which one fuse is switched in series with the disconnector in one or more phases.

Load-break switch with fuses



Unit comprising load-break switch and fuses, in which one fuse is switched in series with the load-break switch in one or more phases.

Fuse-disconnector

Disconnector in which a fuse link or a fuse holder with fuse link forms the movable contact piece.

Fuse-switch disconnector

Switch-disconnector in which a fuse link or a fuse holder with fuse link forms the movable contact piece.

Note 1:

The fuse may be located on both sides of the contacts or permanently fixed between the contacts.

Note 2:

All switches must have single break or multiple break operation

Note 3:

The graphic symbols correspond to IEC 60617-7

Various switching mechanisms

Dependent manual actuation

Actuation exclusively by human effort, so speed and power for the switching movement depend on the operator.

Independent manual actuation

Actuation by a stored-energy mechanism, in which the energy applied manually is stored as tension and released during the operating motion, so speed and power for the switching movement are independent of the operator.

Stored-energy operation

Actuation by energy stored in the actuating mechanism, which is sufficient to complete the switching operation under specific conditions. The energy is stored before the actuation begins.

Note:

Stored-energy mechanisms are differentiated by:
1. the type of energy storage (spring, weight etc.);
2. the type of energy source (manual, electrical etc.);
3. the type of energy release (manual, electrical etc.).

Table 7-6

Utilization categories for switchgear as per VDE 0660 Part 107, EN 60947-3 for alternating current

Utilization category		
frequent operation	occasional operation	typical application cases
AC-20A*)	AC-20B*)	close and open without load
AC-21A	AC-21B	switching resistive load including minor overload
AC-22A	AC-22B	switching mixed resistive and inductive load including minor overload
AC-23A	AC-23B	switching motors or other highly inductive load

*) See Table 7-7!

Table 7-7

Utilization categories for switchgear as per VDE 0660 Part 107, EN 60947-3 for direct current

Utilization category		
frequent operation	occasional operation	typical application cases
DC-20A*)	DC-20B*)	close and open without load
DC-21A	DC-21B	switching resistive load including minor overload
DC-22A	DC-22B	switching mixed resistive and inductive load including minor overload (e. g. shunt motors)
DC-23A	DC-23B	switching highly inductive load (e. g. series motors)

*) Application of these utilization categories are not permitted in the USA.
Utilization categories with B apply for devices that are only switched occasionally in accordance with their design or application. Examples are disconnectors that are only operated for disconnection during maintenance work or switching devices in which the contact blades of the fuse links form the movable contact.

Table 7-8

Verification of rated making capacity and rated breaking capacity. Conditions for making and breaking in accordance with utilization categories as per VDE 0660 Part 107, EN 60947-3

Current type	Utilization category	I_e A	Making 1)			Breaking		
			I/I_e	U/U_e	cos φ	Ic/I_e	U_r/U_e	cos φ
Alternating current	AC-20	all values	2)	1.1	2)	2)	1.1	2)
	AC-21	all values	1.5	1.1	0.95	1.5	1.1	0.95
	AC-22	all values	3	1.1	0.65	3	1.1	0.65
	AC-23	≤ 17	10	1.1	0.65	8	1.1	0.65
		$17 < I_e \leq 100$	10	1.1	0.35	8	1.1	0.35
		> 100	8 3)	1.1	0.35	6	1.1	0.35
Current type	Utilization category	I_e A	I/I_e	U/U_e	L/R (ms)	I_c/I_e	U_r/U_e	L/R (ms)
Direct current	DC-20	all values	2)	1.1	2)	2)	1.1	2)
	DC-21	all values	1.5	1.1	1	1.5	1.1	1
	DC-22	all values	4	1.1	2.5	4	1.1	2.5
	DC-23	all values	4	1.1	15	4	1.1	15

I	making current
I_c	breaking current
I_e	rated normal current
U	voltage before making
U_e	rated operating voltage
U_r	recovery voltage (between the terminals of the switching device)

1) With alternating current, the making conditions are expressed as rms values, where the peak value of the asymmetrical current can take a higher value depending on the power factor of the current circuit.

2) If the switching device has a making and/or breaking capacity, the values of the current and of the power factor (time constant) must be stated by the manufacturer.

3) However it must be at least 1000 A.

7.2 Low-voltage switchgear installations and distribution boards

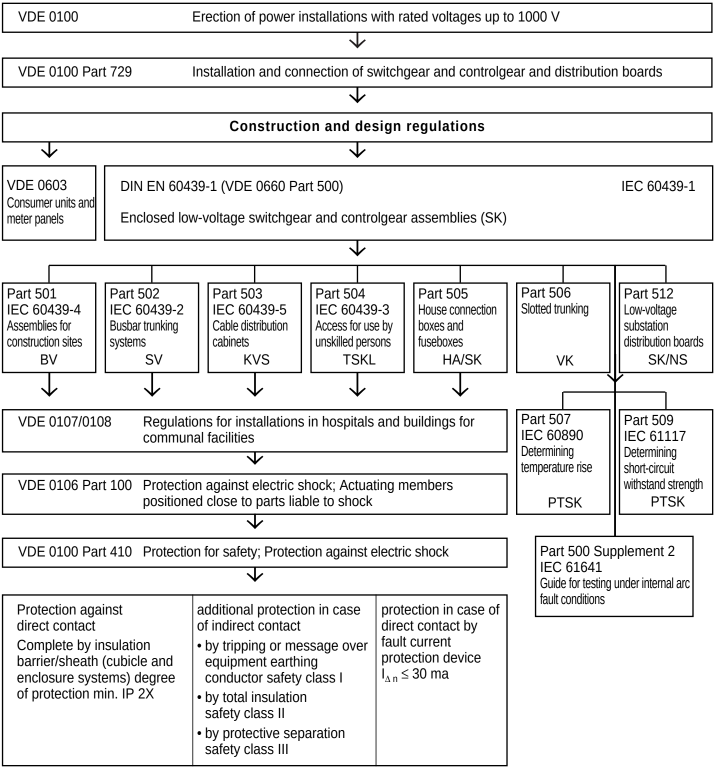
7.2.1 Basics

Low-voltage switchgear installations and distribution boards are used for power distribution, motor power supply and to supply building services.

Depending on the application, they include equipment for switching, protecting, conversion, control, regulation, monitoring and measurement. Because of the extremely varied applications and requirements – from operation of the distribution boards by untrained personnel to operation by trained electrical specialists in electrically seperated control rooms – different enclosure designs and equipment combinations tailored for the specific requirements are required. These applications are described in numerous standards and design regulations (Table 7-17).

Table 7-17

Construction and design regulations for low-voltage switchgear installations and distribution boards



VDE 0100 Erection of power installations with rated voltages up to 1000 V

VDE 0100 Part 729 Installation and connection of switchgear and controlgear and distribution boards

Construction and design regulations

VDE 0603
Consumer units and meter panels

DIN EN 60439-1 (VDE 0660 Part 500) IEC 60439-1
Enclosed low-voltage switchgear and controlgear assemblies (SK)

Part 501
IEC 60439-4
Assemblies for construction sites
BV

Part 502
IEC 60439-2
Busbar trunking systems
SV

Part 503
IEC 60439-5
Cable distribution cabinets
KVS

Part 504
IEC 60439-3
Access for use by unskilled persons
TSKL

Part 505
House connection boxes and fuseboxes
HA/SK

Part 506
Slotted trunking
VK

Part 512
Low-voltage substation distribution boards
SK/NS

VDE 0107/0108 Regulations for installations in hospitals and buildings for communal facilities

VDE 0106 Part 100 Protection against electric shock; Actuating members positioned close to parts liable to shock

VDE 0100 Part 410 Protection for safety; Protection against electric shock

Part 507
IEC 60890
Determining temperature rise
PTSK

Part 509
IEC 61117
Determining short-circuit withstand strength
PTSK

Part 500 Supplement 2
IEC 61641
Guide for testing under internal arc fault conditions

Protection against direct contact Complete by insulation barrier/sheath (cubicle and enclosure systems) degree of protection min. IP 2X	additional protection in case of indirect contact • by tripping or message over equipment earthing conductor safety class I • by total insulation safety class II • by protective separation safety class III	protection in case of direct contact by fault current protection device $I_{\Delta n} \leq 30$ ma

Apart from the small distribution boards, all other low-voltage switchgear installations and distribution boards are considered under the heading low-voltage switchgear assemblies in the standard DIN EN 60439-1 (VDE 0660 Part 500) and the provisions in its subheadings. The base standard specifies the terms, the subdivision and the manufacturer's instructions for the designation of switchgear assemblies and also the operating and environmental conditions, the specified requirements and the testing (type and routine tests).

In recent years, the dimensions of switchgear assemblies have a basic grid of 25 mm (as per DIN 43 660) for flexible internal structure and for modular design. This technology provides the prerequisite for economical planning and manufacture of systems and simplifies later conversion in the event of changes and extensions. The preferred external dimensions are specified in the DIN 41485 standard.

7.2.2 Standardized terms

Only the most basic terms of the many specified in the DIN EN 60 439-1 (VDE 0660 Part 500) standard are listed below.

- *Switchgear assembly (SK)* Combination of one or more low-voltage switching devices with associated equipment for control, measurement, monitoring and the protection and process control units etc., fully assembled under the manufacturer's supervision, with all internal electrical and mechanical connections and design parts.

Note The manufacturer of the complete switchgear assembly has full responsibility also in case of the installation of purchased type-tested units/functional modules.

- *Type-tested low-voltage switchgear assembly (TSK//TTA = type tested assembly):* low-voltage switchgear assembly not substantially different from the original type or system of the switchgear assembly that was type-tested according to the standard.

Note This allows specified assembly work to be done outside the production premises of the manufacturer of the assembly for shipping and manufacturing reasons.

- Partially type-tested low-voltage switchgear assembly (PTSK//PTTA = partially type-tested assembly): low-voltage switchgear assembly (SK) consisting of type-tested and not type-tested modules derived from type-tested modules that have passed the relevant test.

Note Instead of the derivation from type-tested modules, the retention of the temperature rise limit as per VDE 0660 Part 507 and the short-circuit current capability as per VDE 0660 Part 509 may both be confirmed by calculation. A module can comprise one single switching device with the associated electrical and mechanical connections or one single enclosure.

The distinction between TSK and PTSK by the standard does not mean a subdivision into two classes of different quality. Both designs are equal.

The following configurations are among those standardized as units of switchgear assemblies:

- *Section:* unit of a switchgear assembly between two sequential vertical limit levels.
- *Sub-section:* unit of a switchgear assembly between two horizontal limit levels positioned one above the other in a section.
- *Compartment:* section or sub-section that is fully enclosed, except for the openings required for connections, control or ventilation.
- *Functional unit:* part of a switchgear assembly with all electrical and mechanical components required to meet the same function.
- *Fixed part:* a rack of equipment assembled and wired on a common support for fixed installation.

Note: cannot be removed under voltage, even if the rack is designed to be inserted on the supply side.

- *Removable part:* unit that can be removed from the switchgear assembly and replaced as a whole, even when the current circuit to which it is connected is live.
- *Withdrawable part:* removable part that can be placed in a position where an isolating distance is open while it is still mechanically connected to the switchgear assembly.
- *Type tests:* type tests are used to confirm compliance with requirements specified in the standards. Type tests are conducted on an example of a switchgear assembly or on those parts of switchgear assemblies that are repeatedly manufactured in the same or similar type. The tests must be conducted or commissioned by the manufacturer. The testing laboratory prepares a test certificate.
- *Routine testing:* routine testing is used to detect any material and manufacturing defects. Routine testing is conducted on every new switchgear assembly after assembly or on every transport unit. A second round of routine testing at the set-up area is not required. Conducting routine testing at the manufacturing plant does not release the installer of the switchgear assembly from the obligation of a visual inspection of the switchgear assembly after transportation and after erection.

7.2.3 Classification of switchgear assemblies

The variety of applications results in many different designs of low-voltage switchgear assemblies. They can be classified under different criteria. These criteria must be used to select a switchgear assembly suitable for the basic requirements of the specific application (Table 7-18).

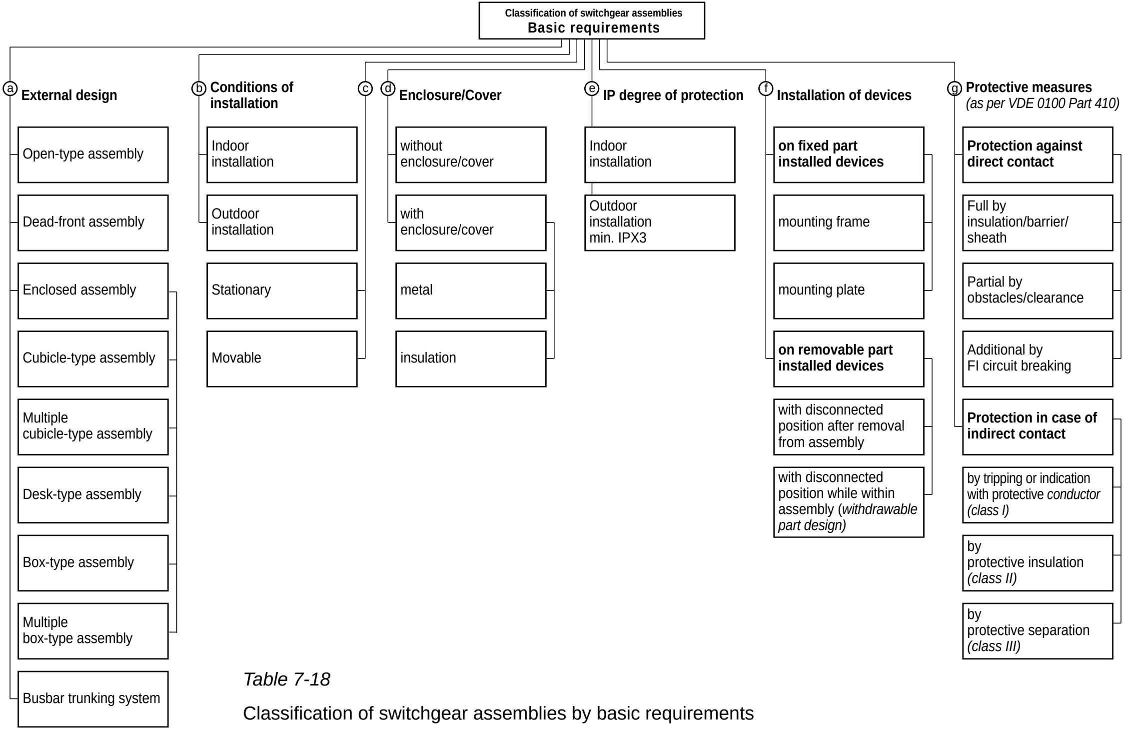


Table 7-18

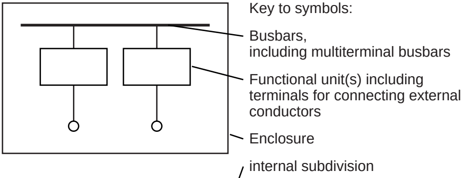
Classification of switchgear assemblies by basic requirements

7.2.4 Internal subdivision by barriers and partitions

A systematic nomenclature for the various options of internal subdivision as adapted to the changing market requirements, particularly as influenced by other European countries, was introduced with the recent edition of DIN EN 60439-1 (VDE 0660 Part 500) (Table 7-19).

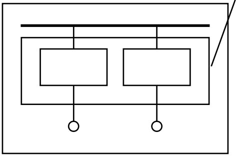
Form 1

No internal subdivision

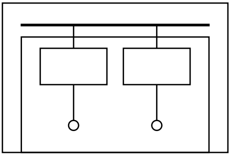


Form 2

Subdivision between busbars and functional units



Form 2a
No subdivision between terminals and busbars



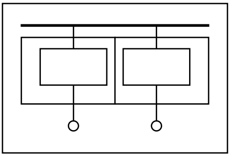
Form 2b
Subdivision between terminals and busbars

Form 3

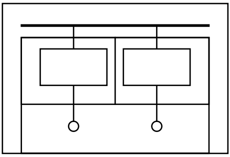
Subdivision between busbars and functional units

Subdivision between functional units

Subdivision between terminals and functional units



Form 3a
No subdivision between terminals and busbars



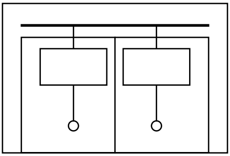
Form 3b
Subdivision between terminals and busbars

Form 4

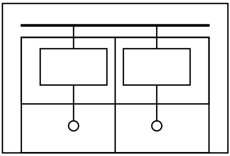
Subdivision between busbars and functional units

Subdivision between functional units

Subdivision between terminals and functional units



Form 4a
Terminals in the same subdivision as the connected functional unit



Form 4b
Terminals not in the same subdivision as the connected functional unit

Table 7-19

Forms of internal subdivision
according to DIN EN 60439-1 (VDE 0660 Part 500)

7.2.5 Electrical connections in switchgear assemblies

A classification with three letters for identifying the connection technology on fixed parts, removable parts and withdrawable parts is in preparation as Ammendment 12 (draft May 1993) to DIN EN 60439-1 (VDE 0660 Part 500). It works as follows

- the first letter refers to the connection point of the supply side of the main circuits,
- the second letter refers to the connection point of the feeder side of the main circuit,
- the third letter refers to the type of connection of the auxiliary circuits.

The following letters are used:

- the letter F for fixed connections (can only be connected or disconnected with tools)
- the letter D means connections that can be released by manual action (without tool), e.g. plug connectors
- the letter W means withdrawable part connections that are automatically connected or disconnected during insertion or withdrawal.

This means that three items are required to determine terminal connections precisely:

- example 1: FFF = fixed-part design
- example 2: WWW = withdrawable-part design
- example 3: WFD = removable-part design
- example 4: DFF = fixed-part design

7.2.6 Verification of identification data of switchgear assemblies

The high degree of safety of a switchgear assembly must be assured by verification of type tests and routine testing by the manufacturer. Table 7-20 shows the verifications and tests required for a type-tested switchgear assembly or partially type-tested switchgear assembly. In general, the user includes the requirements in the request for proposals. The manufacturer may select the type of verification depending on manufacturing technology or economical criteria.

Table 7-20

Verifications that the technical requirements for type-tested low-voltage switchgear assemblies (TTA) and partially type-tested l.v. switchgear assemblies (PTTA) are met

Seq. no.	Requirements to be tested	Section1)	TSK		PTSK	
1	Temperature rise limit	8.2.1	**Type tests**	Verification of non-exceeding of temperature rise limits by testing	**Tests**	Verification that temperature rise limits are not exceeded by testing, extrapolation of TSK or as per VDE 0660 Part 507
2	Dielectric withstand	8.2.2		Verification of dielectric withstand by testing		Verification of dielectric withstand as in section 8.2.2 or verification by dielectric test as in section 8.3.2 or verification of insulation resistance as in section 8.3.4 (see seq. no. 11)
3	Short-circuit current withstand strength	8.2.3		Verification of short-circuit current withstand strength by testing		Verification of short-circuit current withstand strength by testing, extrapolation of similar type-tested configurations or as per VDE 0660 Part 509
4	Effectiveness of the protective conductor	8.2.4		Verification of intact connection between exposed conductive parts of switchgear assembly and protective conductor by checking or resistance test		Verification of intact connection between exposed conductive parts of switchgear assembly and protective conductor by checking or resistance test
	Proper connection between exposed conductive parts of the switchgear assembly and protective conductor	8.2.4.1				
	Short-circuit current withstand strength of the protective conductor	8.2.4.2		Verification of short-circuit current withstand strength of the protective conductor by testing		Verification of short-circuit current withstand strength of protective conductor by testing or corresponding design and configuration of the protective conductor (see section 7.4.3.1.1. last paragraph1)
5	Creepage distance and clearances	8.2.5		Verification of creepage distance and clearances		Verification of creepage distance and clearances
6	Mechanical function	8.2.6		Verification of mechanical function		Verification of mechanical function
7	IP degree of protection	8.2.7		Verification of IP degree of protection		Verification of IP degree of protection
8	Wiring, electrical function	8.3.1	**Routine testing**	Visual inspection of switchgear assembly incl. wiring and if applicable electrical function test		Visual inspection of switchgear assembly incl. wiring and if applicable electrical function test
9	Dielectric withstand	8.3.2		Dielectric withstand test		Dielectric withstand test or verification of insulating resistance as in section 8.3.4 (see seq. no. 11)1)
10	Protective measures	8.3.3		Checking protective measures and visual inspection of electrical continuity of the electrical protective conductor connection		Checking protective measures
11	Insulation resistance	8.3.4		–		Verification of insulation resistance if not tested as in section 8.2.2 or 8.3.2 (see seq. no. 2 & 9)1)

1) DIN EN 60439-1 (VDE 0660 Part 500)

7.2.7 Switchgear assemblies for operation by untrained personnel

The special requirements for switchgear assemblies to which untrained personnel have access for control purposes, also referred to as “distribution boards”, are covered by DIN VDE 0660-504 (VDE 0660 Part 504) in connection with Ammendment DIN EN 60 439-3/A1 (VDE 0660 Part 504/A1).

Rated voltages of up to 300 V (AC against earth) and rated currents of up to 250 A are approved for these applications. There are some additional requirements in the context of type testing and verifications, such as:

- shock resistance of enclosure
- rust resistance
- resistance of insulation materials against heat and
- resistance of insulation materials against excessive heat and fire.

7.2.8 Retrofitting, changing and maintaining low-voltage switchgear assemblies

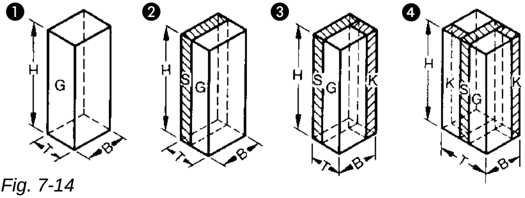
As per DIN EN 60439-1 (VDE 0660 Part 500), older switchgear assemblies manufactured before the beginning of the validity of the standard in its current version do not require retrofitting.

If a switchgear assembly is changed or retrofitted, the requirement for a test depends on the nature and scope of the intervention and must be decided on a case by case basis. Fundamentally, anyone who makes a change or retrofit takes over the manufacturer’s responsibility.

The manufacturer must always set maintenance and service schedules. If the switchgear assembly is not continuously monitored by a qualified electrician, VBG 4 (accident prevention regulations of the German professional association of precision mechanical and electrical technology, April 1996) in Table 1 “Testing electrical systems and stationary equipment” requires a test at least every 4 years. The test must be conducted by an electrical technician.

7.2.9 Modular low-voltage switchgear system (MNS system)

Cost-effective, compact switchgear systems require design and production documentation for functional units in the form of modules that can be combined as necessary (combination modules). The basis for the design is a basic grid dimension E of 25 mm (DIN 43660) in all three dimensions (height, width, depth). Fig. 7-14 gives an overview of the modular arrangement options and the usable bay dimensions of the MNS system.



B	T	H
400		
600	400	2200
800	600	
1000	800	
1200	1000	
	1200	

Dimensions in mm

Fig. 7-14

The most common dimensions of sections of the MNS system
1 to 3 = single control, 4 = double control (duplex),
G = equipment compartment, K = cable terminal compartment, S = busbar compartment (preferred dimensions underlined)

The standardized subdivision of a section into various functional compartments, i.e. equipment compartment, busbar compartment and cable terminal compartment, offers advantages not just for design but also in operation, maintenance, change and also safety.

The basic design of a section with the configuration of the busbars and the distribution busbars for supplying power to fixed, removable or withdrawable parts is shown in Fig. 7-15. A particular advantage of the MNS system is the configuration of the busbars at the rear of the section (in contrast to the formerly common configuration above in the section). It offers supplementary safety for personnel in the event of an accidental arc on the busbar, provides space for two busbar systems if required, enables an advantageous back-to-back configuration with only one busbar system and allows cables to be fed in through cable racks from above.

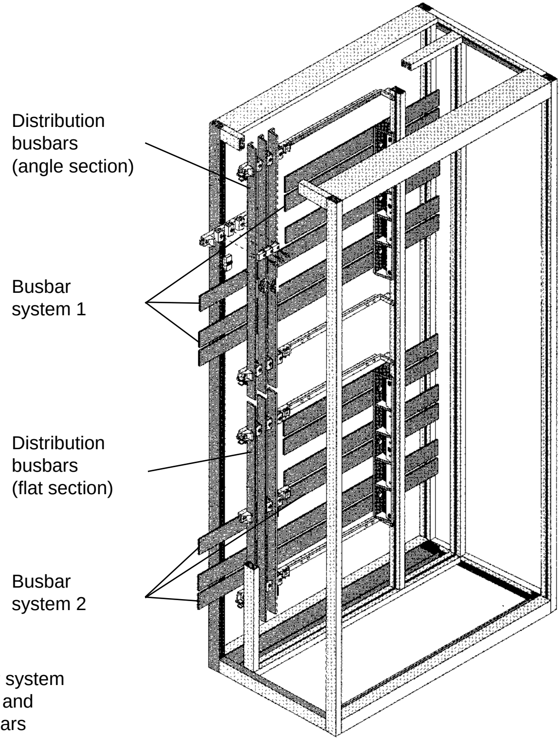


Fig. 7-15

MNS switchgear system
Busbar systems and
distribution busbars

The configuration of the function wall with the access openings for the plug-in contacts is shown in Fig. 7-16. The function wall of the MNS system, as the most important internal subdivision, provides the electric shock protection (IP20) and the arc barrier between equipment compartment and busbar compartment. This is achieved with form-design features only without automatically actuated protective shutters.

When the fixed parts and the withdrawable parts are inserted, labyrinthine insulation configurations are formed around the plug-in contacts, safely preventing flashovers between the conductors.

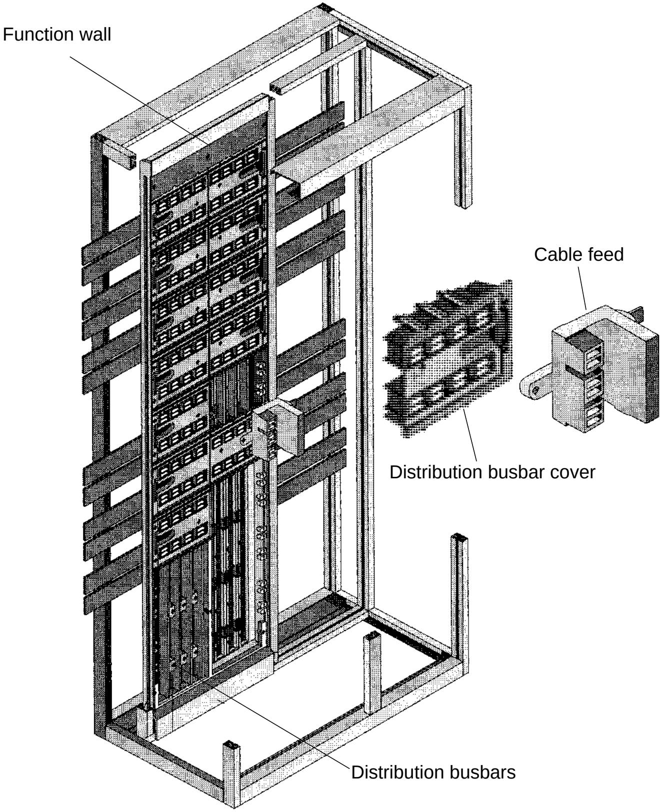
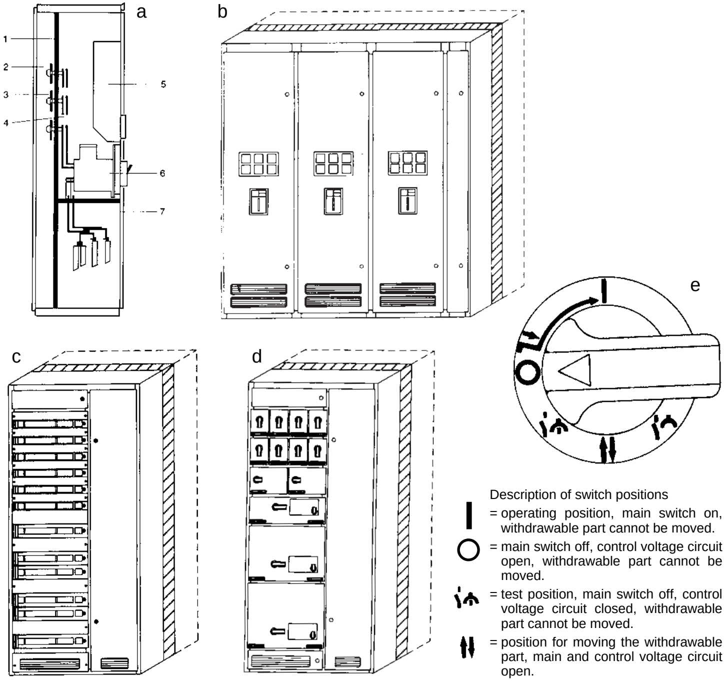


Fig. 7-16

MNS switchgear system
configuration of function wall

Fixed and withdrawable parts basically have plug-in contacts as busbar-side terminals. In fixed parts the equipment is arranged two-dimensionally on the functional units, while it has a three-dimensional design in withdrawable parts with maximum usage of the cabinet depth. With a majority of smaller modules (<7.5 kW), the demands on switch cabinet volume are around 40 % less with the withdrawable part design. The withdrawable part sizes are adjusted to one another to enable small and large modules to be economically combined in one bay (Fig. 7-17). Later changes of the components can be made without accessing the bay function wall. Reliable mechanical and electrical interlocking of the switchgear prevents operating errors when moving the withdrawable parts.



Description of switch positions

I = operating position, main switch on, withdrawable part cannot be moved.

O = main switch off, control voltage circuit open, withdrawable part cannot be moved.

= test position, main switch off, control voltage circuit closed, withdrawable part cannot be moved.

⇅ = position for moving the withdrawable part, main and control voltage circuit open.

= isolated position, withdrawable part withdrawn by 30 mm (to stop), main and control contact open, withdrawable part mechanically locked.

Fig. 7-17

Bay types of the MNS system

a) and b) cutaway view and view of MNS sections with circuit-breakers
1 arc partition, 2 busbar compartment, 3 primary busbar, 4 distribution busbar, 5 instrument recess, 6 circuit-breaker and 7 cable terminal compartment

c) MNS section with power output modules in strip form

d) MNS section with withdrawable units

e) Control switch for withdrawable unit

The circuit diagrams of typical motor starters, which can be obtained as fixed or withdrawable parts, are shown in Fig. 7-18. Tables 7-21 and 7-22 have an initial selection of the associated module sizes. MNS assemblies can be supplied as arc-resistant, shock-resistant, vibration-resistant and earthquake-resistant as required for specific quality demands. Table 7-23 shows an overview of the breadth of application of the system.

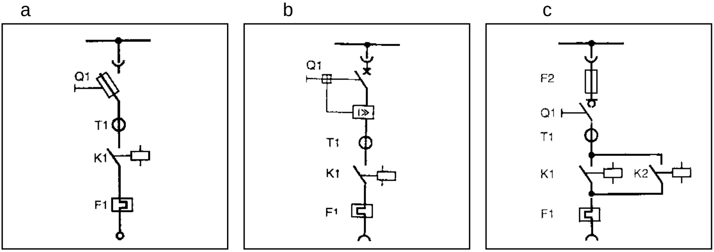


Fig. 7-18

Examples of standard modules with circuit diagrams for motor starter

a) with fuse switch-disconnector and thermal relay (fixed-part technique)

b) with circuit-breaker and thermal relay (withdrawable-part design)

c) with load-break switch, fuse, thermal relay and reversing (withdrawable-part design)

Table 7-21

Standard type program motor starter with HRC fuses, with thermal relay

Rated current I_e (AC3/400 V~) A	Motor ratings under AC3 (occasional jog mode 0.5% under AC4 permissible) at			Module dimensions Height	
	400 V~ kW	500 V~ kW	690 V~ kW	One direction of rotation	With reversing
11.5	5.5	5.5	5.5	5 E	5 E
15.5	7.5	7.5	7.5	5 E	5 E
30	15	15	15	5 E	7 E
44	22	30	30	7 E	9 E
60	30	37	37	7 E	9 E
72	37	45	40	7 E	9 E
85	45	59	–	11 E	11 E
105	55	75	110	17 E	17 E
140	75	90	110	17 E	17 E
205	110	132	160	23 E	23 E
295	160	200	250	29 E	37 E
370	200	250	355	31 E	39 E
460	250	355	355	31 E	–

Basic grid dimension E = 25 mm

Table 7-22

Standard type program motor starter with circuit-breaker, with thermal relay

Rated current I_e	Motor ratings under AC3 (occasional jog mode 0.5% under AC4 permissible) at			Module size Height	
(AC3/400 V~) A	400 V~ kW	500 V~ kW	690 V~ kW	One direction of rotation	With reversing
3.5	1.5	1.5	–	8E/4	8E/4
5	2.2	2.2	–	8E/4	8E/4
11.5	5.5	5.5	–	8E/4	8E/4
15.5	7.5	7.5	–	8E/4	8E/4
30	15	15	–	8E/4	8E/4
44	22	30	–	8E/4	8E/4
60	30	37	–	8E/2	8E/2
72	37	45	40	8E	8E
85	45	59	75	8E	8E
105	55	75	110	16E	16E
140	75	90	110	16E	16E
205	110	132	160	16E	16E
295	160	200	250	24E	24E
370	200	250	355	24E	–
460	250	355	355	24E	–

Basic grid dimension E = 25 mm

Table 7-23

Type-tested switchgear assembly MNS
System characteristic data

Electrical parameters

Rated voltages	rated insulation voltage U_i	1000 V 3~, 1500 V
	rated operational voltage U_a	690 V 3~, 750 V–
	rated impulse withstand voltage U_{imp}	8 kV
	overvoltage category	III
	pollution severity	3
	rated frequency	to 60 Hz
Rated currents	**busbars:**	
	rated current I_e	to 6300 A
	rate peak withstand current I_{pk}	to 250 kA
	rated short-time withstand current I_{cw}	to 100 kA
	distribution busbars:	
	rated current I_e	to 2000 A
	rate peak withstand current I_{pk}	to 165 kA
	rated short-time withstand current I_{cw}	to 86 kA

(continued)

Table 7-23 (continued)

Mechanical parameters

Dimensions	cubicles and supporting structure	DIN 41488
	preferred module sizes, height	**2200** mm
	preferred module sizes, width	400, **600,** 800, **1000**, 1200 mm
	preferred module sizes, depth	400, **600,** 800, **1000**, 1200 mm
	basic grid dimension	E = 25 mm as per DIN 43660
	hinged frame for installation of electronics tiers	DIN 41494, Sheet 1, ASA C 83.9
Surface protection	supporting structure	Al-Zn coating
	internal subdivision	Al-Zn coating
	cross section	galvanised
	enclosure	paint RAL 7032, pebble grey
Degrees of protection	as per IEC 60529 or DIN 40050	IP 00 to IP 54
Plastic parts	CFC and halogen-free, flame-retardant, self-extinguishing	DIN VDE 0304 Part 3
Internal subdivision	section - section busbar compartment-cable terminal compartment busbar compartment-equipment compartment equipment compartment-cable terminal compartment sub-section - sub-section	
Specifications	IEC 60439-1, EN 60439-1, VDE 0660 Part 500, BS5486, UTE63-410	
Special qualification	German Lloyd, Hamburg (shipping) Pehla Test Laboratory, Ratingen (internal arcing as per IEC 60298, Appendix AA and VDE 0660 Part 500 Supplement 2) KEMA, Arnheim NL (internal arcing) Federal Ministry for Regional Planning, Building and Urban Development, Bonn (shelters) ABB testing laboratory, Mannheim (induced vibrations, KTA 2201.1 and 2201.4, DIN IEC 60068 Part 2)	

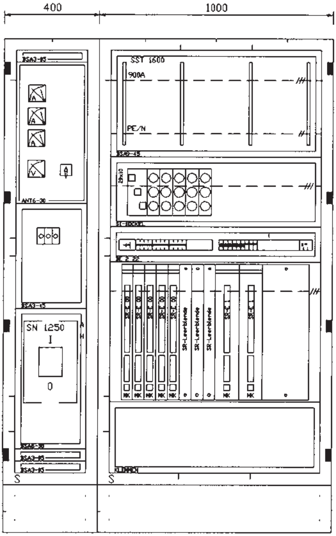
For particularly demanding control tasks in industrial plants with a large number of smaller mechanisms with high switching frequency, such as is found in power plants, ProMNS system withdrawable parts can be used in MNS low-voltage substations. These have thyristor power controllers as primary switching device for power of up to 5.5 kW. This makes them maintenance-free and suitable for virtually unlimited switching frequency. The heat produced by the semiconductor modules is dissipated to the ambient air primarily via cooling fins at the front of the withdrawable part. The withdrawable part also includes fuses as additional short-circuit protection and a switch-disconnector for isolation. For higher outputs, there are also ProMNS withdrawable parts with power contactors instead of the thyristor controllers.

7.2.10 Low-voltage distribution boards in cubicle-type assembly

For smaller distributors with busbar currents to 1600 A, there are specially designed cabinet solutions with sheet steel enclosures (protective earthing, safety class I, Fig. 7-19) and also with insulated enclosures (protective insulation, safety class II, Fig. 7-20). The cabinet and enclosure sizes are modular in design, enabling the elements to be combined economically with one another.

Fig. 7-19

Sheet steel distribution board KNS-S with power output modules in strip form (vertical)



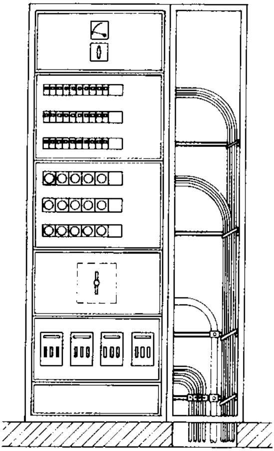


Fig. 7-20

Insulated distribution board KNS-I with cable compartment

Table 7-24 Technical data of KNS-S and KNS-I distribution boards in cubicle-type assembly

		⏚ KNS-S	**⧈ KNS-I**
Electrical parameters	rated operational voltage	690 V 3 ~	690 V 3 ~
	rated insulation voltage	1000 V 3 ~, 1200 V–	1000 V 3 ~, 1200 V–
	rated frequency	to 60 Hz	to 60 Hz
	rated current of the busbars	to 1600 A	to 1250 A
	rated peak-withstand current of the busbars	to 90 kA	to 90 Ka
	rated short-time-withstand current (1s) of the busbars	to 45 kA	to 45 kA
Dimensions	cubicles height	1300, 1900 mm	500, 1000, 2000 mm
	width	400, 700, 1000 mm	350, 650, 950 mm
	depth	300, 400, 600 mm	200, 400 mm
	basic grid dimension	E = 25 mm as per DIN 43660	E = 25 mm as per DIN 43660
Dimensions	– enclosure	sheet steel RAL 7035, light grey	insulation* RAL 9011, black
	– device coverings	fibre glass reinforced polyester RAL 7035, light grey	fibre glass reinforced polyester RAL 7035, light grey
	– rear walls	sheet steel AIZn (Al-Zn)	Resopal RAL 7032, pebble grey
	– base	sheet steel RAL 7035, light grey	sheet steel RAL 7035, light grey sheet steel, aluminium RAL 7035, light grey
Protective measures		safety class I	safety class II
Degrees of protection	as per IEC 60529, DIN 40050	IP 30, IP 40, IP 55	IP 30, IP 40, IP 54
Specifications	type-tested switchgear assembly (TSK) and partially type-tested switchgear assembly (PTSK)	IEC 60439-1, EN 60439-1 VDE 0660 Part 500	IEC 60439-1, EN 60439-1 VDE 0660 Part 500
	fire behaviour		VDE 0304 Part 3, Level BH 2
Shock safety			Application for civil defence shelters to control class RK0.63/6.3 Degree of safety B

* Polyurethane hard integral foam, without CFC component and chlorine-free

7.2.11 Low-voltage distribution boards in multiple box-type assembly

The INS box system has housings of high-quality plastic (polycarbonate), placing it in safety class II. It can be used with busbar currents of up to 1000 A. Fig. 7-21 shows examples of the structure of housings with flange mountings, Table 7-25 shows how the INS system can be used.

1 Wedge
2 Cotter way
3 Self-adhesive gasket
4 Flange mounting

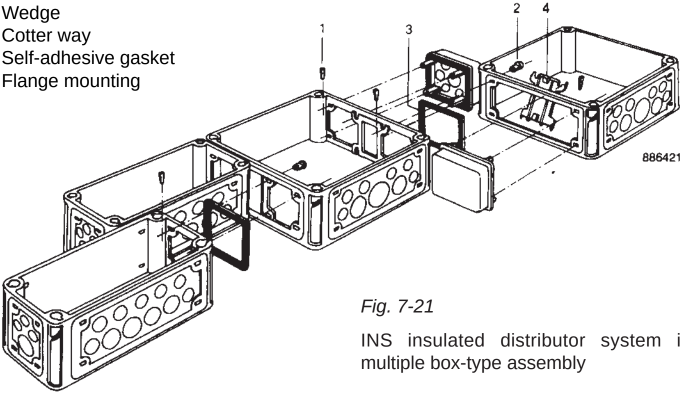


Fig. 7-21

INS insulated distributor system in multiple box-type assembly

Table 7-25

Technical data of the INS insulated distribution board system

Electrical parameters	
Rated insulation voltage	1000 V 3~, 1200 V-
Rated operational voltage	690 V 3~, 800 V–
Rated current of busbars	200 A, 400 A, 630 A, 1000 A
Rated current of incoming units	1000 A
Rated peak withstand current (peak value)	60 kA
Rated short-time-withstand current (1 s)	29 kA
Mechanical parameters	Modular enclosure sizes:
Enclosures (external dimensions)	150 x 300 mm 300 x 300 mm 450 x 300 mm 600 x 300 mm 600 x 600 mm
Basic grid dimension	25 mm
Enclosure	
Box, cover, insertion flange, cable socket etc.	Thermoplast (maintenance-free)
Resistance against:	Inorganic acids, organic acids, oxidation and reduction agents, salt solutions and many fats, waxes and oils.
Colour of housing parts	RAL 7032, pebble grey
Device covering	RAL 2003, pastel orange
Protective measures	Safety class II
Degrees of protection as per IEC 60529/DIN 40050	IP 65: full electric-shock protection, Protection against dust entry (dustproof), Protection against water from all directions (spray water)
Specificatons	
Type-tested	IEC 60439-1, EN 60439-1
Switchgear assembly (TSK)	VDE 0660, Part 500 VDE 0110 as per Group C
Fireproof as per	VDE 0304, Part 3, Level II b
Shock safety	RK 0.63/6.3

The heat generated in the built-in devices (Section 7.3.1) and the heat sources in the surroundings are particularly important with the distribution board in box-type assemblies. For this reason, when operating distribution boards in the open, even under a roof, it should be considered that temperature variations greater than 50 °C may occur. If the distribution board is subject to direct sunlight during the day and cooling at night, condensation is likely to form. This may be a serious danger to the functioning of the equipment and may result in arcing. To prevent such problems, installation of ventilation openings or ventilation inserts is recommended, with due regard to the degree of protection required. This should be considered in the design of the distribution board.

7.2.12 Systems for reactive power compensation

The reactive power modules for the MNS system are designed to conform to the installation dimensions of the system, i.e. they are designed for a 600 mm wide and 400 mm deep equipment compartment. Four or five modules and one controller unit fit into one switchgear cubicle. The direct association of the compensation modules with the electrical equipment (motor feeder modules) enables a very compact design. On the supply side, the plug-in contacts allow the fixed-part modules to be replaced quickly by electrical technicians when necessary. However, the modules are also available in withdrawable part design.

Table 7-26

Technical data of modules for reactive power compensation with dry capacitors

Rated system voltage	Provision with harmonic filter coil	Module output
400 V ~	0%	4 x 10 kvar, 4 x 12.5 kvar, 3 x 20 kvar, 3 x 25 kvar
	5.67%, 7%	2 x 10 kvar, 2 x 12.5 kvar, 2 x 20 kvar, 2 x 25 kvar, 1 x 40 kvar, 1 x 50 kvar
	12.5%, 14%, 15%	2 x 10 kvar, 2 x 20 kvar, 1 x 40 kvar
	5/12.5%, 5.67%/12.5%	1 x 20 kvar, 1 x 40 kvar
500 V ~	0%	4 x 10 kvar, 3 x 20 kvar
	5.67%, 7%	2 x 10 kvar, 2 x 20 kvar, 1 x 40 kvar
	12.5%, 14%, 15%	2 x 10 kvar, 2 x 20 kvar, 1 x 40 kvar
	5/12.5%, 5.67%/12.5%	1 x 20 kvar, 1 x 40 kvar
690 V ~	0%	4 x 10 kvar, 4 x 12.5 kvar, 3 x 20 kvar, 3 x 25 kvar
	5.67%, 7%	2 x 10 kvar, 2 x 12.5 kvar, 2 x 20 kvar, 2 x 25 kvar, 1 x 40 kvar, 1 x 50 kvar
	12.5%, 14%, 15%	2 x 10 kvar, 2 x 20 kvar, 1 x 40 kvar
	5/12.5%, 5.67%/12.5%	1 x 20 kvar, 1 x 40 kvar

7.2.13 Control systems for low-voltage switchgear assemblies

Today's automated, advanced designs for operation of low-voltage systems for power distribution, supply of power for motors and connection to the controls of higher-order control systems require control components based on microprocessors even for low-voltage switchgear installations. ABB supplies the INSUM system as such a control system (Fig. 7-22). The versatile protection and control functions of every single motor starter are controlled by Motor Control Units (MCU) in the INSUM system. The operator at the switchgear assembly can access and read out measured values on a simple menu-controlled operation and display device (Human Machine Interface HMI) to control up to 128 MCUs, i.e. motors. INSUM offers the following functions, which can be used as required:

Protection tasks such as:

- overload protection/automatic restart
- low-load indicator
- off-load protection
- blocking protection
- phase failure monitoring
- autoreclosure blocking
- safety interlocking
- thermal overload protection by thermistor
- loss of supply monitoring/sequential starting of motors after voltage recovery
- earth-fault detector
- cyclic bus monitoring/fault protection

Control functions:

- control of the motor starter/circuit-breaker via the MMI, the local control panel, with the integrated INSUM OS monitor workstation or the higher-order process control system
- test function

Measured and metered value recording, such as:

- phase currents
- voltages
- power outputs
- earth-fault current
- switching cycle counter
- operating hours

Signalling functions:

- status messages and signals
- warning and fault messages in plain text in the local language

Communications functions:

- use of the LON open intersection bus (Local Operating Network)
- direct integration into ABB ADVANT OCS process control system and Freelance 2000 using LON
- protocol converters (gateways) such as for PROFIBUS DP, MODBUS RTU or ETHERNET TCP/IP are available for serial connection to all PLT systems of other manufacturers.
- parameter setting and event logging with trending function with INSUM OS PC control station, monitor workstation or laptop.

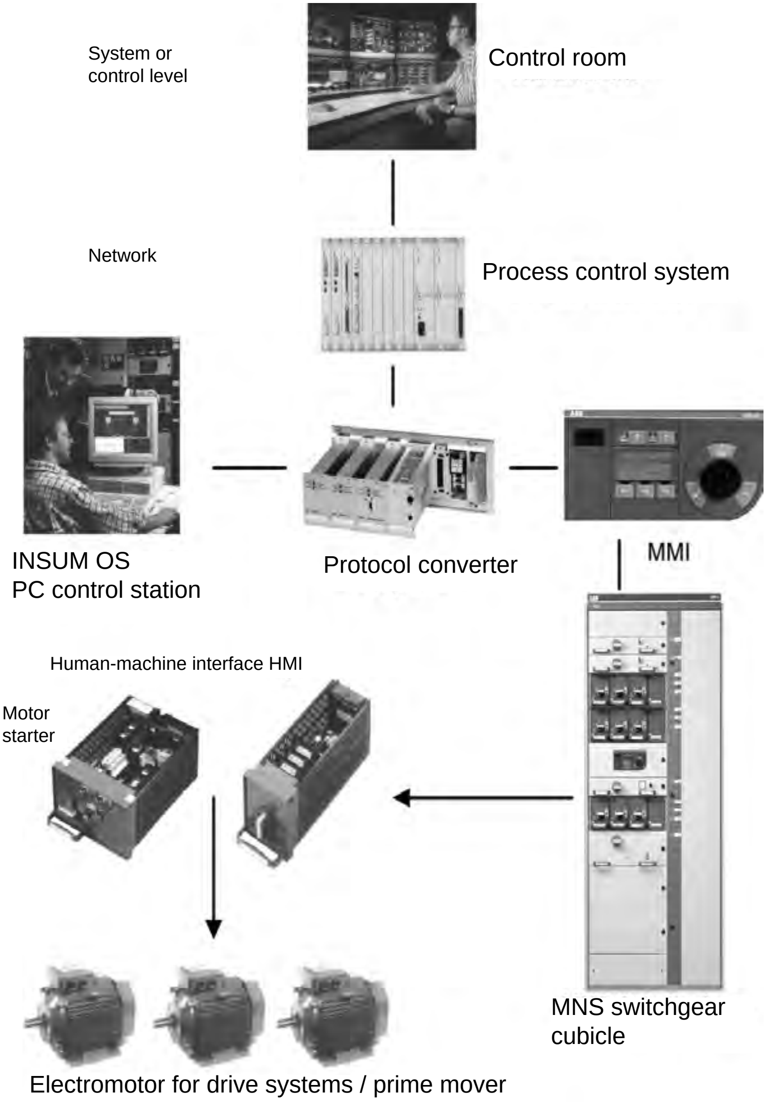


Fig. 7-22

Structure of INSUM control system

Control variants are available for the various types of drive systems such as direct starters, reversible starters, star-delta starting, Dahlander starters, pole-changing switches, servo-motor starting (with or without inching service), soft starters (with or without easy gradient) or latch-locked switches. They are selected in the MCU by the drive-type parameter. The MMI allows the user easy access to the INSUM system. The desired measured values and status can be read out here and switching operations can be conducted. The parameter setting can also be queried or parameters can be set by yourself. Setting parameters means that the characteristic values (e.g. drive-type and motor data of the equipment) are saved in the control system.

INSUM allows the Motor Control Centres to be linked to the higher-order process control system over intersection bus connections (Fig. 7-22). The protocol converters (gateways) adapt to the specific hardware and software requirements of the control system as required.

Implementation of INSUM, integrated over intersection bus connections into the process control system (PCS), has been shown to reduce investment costs significantly. In addition, INSUM makes it easier for the user to operate the system and make any changes and maintenance required. Full monitoring and implementation of maintenance work as required and not to a set period allows significant reduction of operating expenses.

INSUM has already proven itself in mechanical engineering, in the chemical industry, in paper and pulp manufacture, with power supply companies, in balance of powerplant, in sewage treatment systems and even on offshore drill rigs and ships.

In more complex power network systems, there are separate control systems for medium voltage and low voltage and for building services (e.g. AREADAT from ABB). This requires different workstations with different operational philosophies. The ABB INScontrol system enables these subsystems to be integrated. The operator has an overview of the entire structure in one single display and has access to all levels of the network through the system. INScontrol shows the user displays of systems, event lists and alarm lists and prompts the operator when switching operations are required.

INScontrol shows the system structure organized on one bay level and one system level, and also a common control level. At section level, autonomously operating equipment is used, which can be adapted to the specific protection, control, regulation and monitoring tasks with the aid of programmable functions. The system level above the section units in the system hierarchy independently controls and monitors communications, enables system-based process data query and is the link to the next level of the hierarchy. All data from the individual processes is bundled at the control level, allowing the operator to fully monitor and control the entire system (see also Section 14.4).

7.3 Design aids

Some suggestions for the design of low-voltage switchgear assemblies are given below. In every case, they will need to be adapted for the actual system conditions.

7.3.1 Keeping to the temperature rise limit

The limit temperatures that must be maintained for a TTA are listed in Table 2 (DIN EN 60439-1 (VDE 0660 Part 500). An ambient temperature of max. 40 °C or 35 °C in 24-hour equipment is specified as a base. For example, this means that:

- Conductor terminals: 35 °C + 70 K (conductor) = max. 105 °C
- Operating parts: 35 °C + 15 K (metal) or + 25 K (plastic) = max. 50 °C or 65 °C
- Enclosures: 35 °C + 30 K (metal) or + 40 K (plastic) = max. 65 °C or 75 °C

If the system has to be subjected to higher ambient temperatures (export = 55 °C), the same limit temperature must be maintained in the substation design. This is preferably achieved by using a lower component density for the switchgear or by improved ventilation of the cubicles (including forced ventilation).

Table 7-26

Examples of typical power dissipation sources in a section, MNS system, protection class IP40,
I_B = rated current,
I_M = load current,
P_V = rated power loss (load current).

Equipment	**Dimensions**	**I_B**	**I_M**	**P_V**
Motor starter 2 kW	8 E/4	15 A	9 A	9 W
Motor starter 7.5 kW	8 E/4	15 A	10 A	12 W
Motor starter 55 kW	8 E	100 A	80 A	50 W
Moulded case circuit-breaker 400 A	8 E	400 A	400 A	60 W
Load-break switch with fuse 63 A	4 E	63 A	50 A	8 W
Load-break switch with fuse 125 A	4 E	125 A	100 A	25 W
Load-break switch with fuse 250 A	4 E	250 A	200 A	70 W
Load-break switch with fuse 400 A	6 E	400 A	320 A	160 W

Exact values for all installed switchgear, busbar trunking and wiring arrangements must be supplied by the manufacturers/suppliers.

Fig. 7-23 shows the connection between the degree of protection, the heat load of a switchgear cubicle and the influence of the ambient temperature. If the power dissipation generated in a switchgear cubicle reaches the permissible value according to the corresponding curve, an air temperature of 60°C appears in the area of the upper sub-section. The temperature gradients from top to bottom are taken into account by the general rule of installing the functional units for the heavier drives at the bottom and those for the lighter at the top.

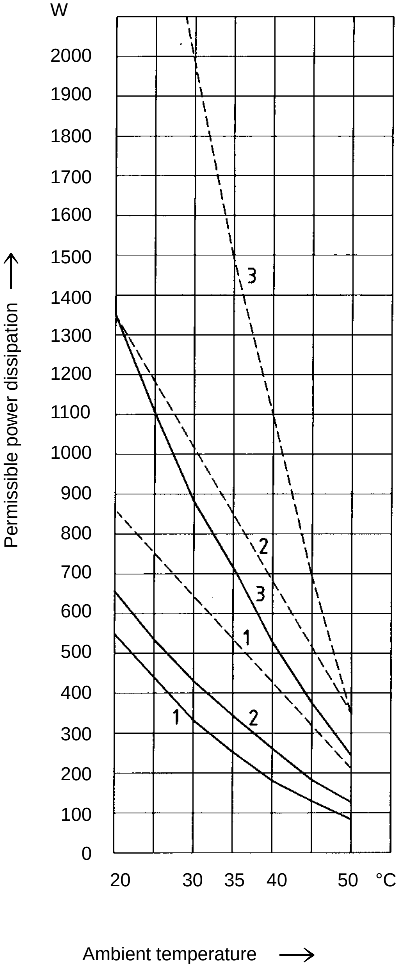


Fig. 7-23

Typical values for the maximum permissible effective power dissipation in an MNS switchgear cubicle

Dimensions of the switchgear cubicle(middle cubicle)
height 2200 mm
width 1000 mm
depth 600 mm

Equipment compartment
width 600 mm

Clearance from wall
8 cm

Legend

______	degree of protection IP52 to IP54
----------	degree of protection IP32 to IP42

1 = Withdrawable-part design
2 = Fixed-part design
3 = Switchgear cubicle with open-type circuit-breakers

7.3.2 Internal arc test

When developing switchgear assembly designs, the primary goal must be to avoid faults that could result in internal arcing.

With this in mind, the design of the electrical and mechanical interlocking (withdrawable-part versus subsection) must be considered with respect to withdrawable-part design. Another important point is the requirement for high availability. This means that even if accidental arcing does occur, the entire assembly should not fail and be damaged but at worst one section – or even better – only the affected withdrawable part will be destroyed. In addition, if such a malfunction occurs, the operating staff should not be endangered.

The occurrence of internal arcing can be greatly restricted with suitable design, such as with internal subdivision of a switchgear cubicle. The effects of accidental arcing can be limited primarily by reducing the duration of arcing.

This can be achieved with the aid of suitable sensors that will react to light, temperature or pressure and trip the backup feeder circuit-breaker, in general the incoming feeder circuit-breaker. This will result in arcing periods of 40 to 80 ms. Three-pole shorting links operating in connection with the incoming feeder circuit-breaker will enable even shorter arcing periods. Both methods have the disadvantage of leaving the entire low-voltage switchgear assembly without power when the incoming feeder circuit-breaker is tripped, with the result that a large part of the system fails.

The better technical solution is to use suitable design measures to ensure that the arc quenches itself after a few milliseconds in the event of such a fault, so only the faulty functional unit will fail. The remainder of the substation will remain in operation. This can be done by selecting suitable layout, configuration and material for the walls comprising the internal subdivisions.

Testing the response of switchgear assemblies to internal arcing – specified for medium voltage assemblies already for many years by a test directive (Section 8.2.3) – is now also regulated for low-voltage assemblies. The new test directive is available as Supplement 2 to DIN EN 60439-1 (VDE 0660 Part 500) or as IEC 61641. The preferred arc duration in the test should be 100 ms. As a maximum, arcing times of up to 500 ms should be considered. The response of the switchgear assembly is assessed by the following criteria:

- Properly secured doors or barriers shall not open.
- Parts that could cause a hazard shall not come loose.
- Arcing must not burn any holes in freely accessible, external parts of the enclosure.
- The vertically installed indicators (black cotton cloth = cretonne) must not ignite.
- The protective-conductor function for the exposed conductive parts of the enclosure must be retained.

7.3.3 Verification of the short-circuit current capability of busbar systems

The most certain way to verify the short-circuit current capability of the busbar systems of a TTA or PTTA is to test them with the rated short-time withstand current. The compact design of the busbar supports would demand relatively complicated and extensive calculations. For this reason, it is recommended that the basic (standard) design of the busbar system be subjected to a type test, ensuring that the TTA is tested for the standard rated currents and standard rated short-circuit withstand current. Special solutions and interim values can then be very easily considered by resorting to an extrapolation procedure in accordance with DIN IEC 61117 (VDE 0660 Part 509). This technical report describes an extrapolation procedure for determining the short-circuit current capability of non type-tested busbar systems (NTS), derived from type-tested busbar systems (TS).

7.3.4 Calculation programs for planning and design of low-voltage substations

Many companies offer calculation programs for the PC for planners. DOC by ABB – Version 020C – is described here as an example. It is designed for IBM-compatible computers. The program is supplied on 3.5" diskettes. They contain the individual program modules, the database and the texts in compressed and encrypted form. The program is currently available in seven languages (German, English, Italian, French, Spanish, Portuguese, Danish).

The required operating system is MS-DOS/PC-DOS 5.0 or higher and code page 437 is necessary. Version 020C was also developed for use in a local area network.

This version includes the following features:

- Rating of cables of low-voltage systems
- Thermal verification of conductors and busbars
- Calculation of short-circuit currents
- Examination of dynamic load on busbars and their supports
- Selection of circuit-breakers
- Starting of motors
- Assignment of circuit-breakers and fuses, contactors and thermal relays
- Assignment of circuit-breakers: selectivity and protective functions
- Examination of outgoing feeder-cable protection
- Calculation and drawing of time-current characteristics
- Power factor correction
- Selective assignment of protection equipment on the low-voltage and medium-voltage side of transformers
- Calculation of overtemperature in switchgear assemblies
- Drawing of general circuit diagrams
- Printing a summary of all completed project planning and engineering
- Data output in special file formats for dialogue with the programs of CAD, CIM
- Individually designed configuration based on the connected hardware (monitor, printer, etc.), the referenced standards and the database of the devices in use

7.4 Rated voltage 690 V

Publications in the 1970s frequently referred to the technical and economic advantages of a higher rated voltage. As early as 1967 IEC Publication 38 listed the voltage level of 660 V as a preferred voltage in comparison to the 500 V level. Particularly in the area of device development, great efforts were made to upgrade them generally for 660 V. Today it can be assumed that almost all switchgear is suitable for this voltage. The higher voltage has become firmly established in the power distribution sector, e.g. in power plants, many industrial plants and for the power supply of high-output motors instead of 3 kV or 6 kV.

The supplementary benefits of the 690 V voltage level for the user is in many cases quite significant, but it needs to be evaluated with reference to the actual implementation. In general, implementation of the 690 V offers the following advantages in comparison to 400 V (and with lower values in comparison to 500 V):

- Reduction of the rated currents
- Reduction of the short-circuit currents
- Reduction of the conductor cross sections for current transmission by 1 to 3 times
- Lower power losses
- Larger cable limit length with reference to voltage drop
- Use of motors of up to 630 kW, i.e. elimination of the 6 kV for this output
- More economical usage of reactive current compensation modules by greater reactive power at 690 V
- Increase in transformer rated power to 3150 kVA
- Operation of 400 V motors (delta) also for 690 V (star)

The 690 V rated voltage today has a fixed position in low-voltage engineering. It has reached a share of as high as 15%. It will soon have replaced the 500 V level completely.

7.5 Selected areas of application

7.5.1 Design of low-voltage substations to withstand induced vibrations

The highest demands for functional safety under the influence of induced vibrations are placed on important switchgear assemblies in particularly stressed buildings or at sites subject to seismic disturbances.

The verification and testing of low-voltage substations under these conditions covers the following loading cases: >earthquake<, >explosive shock wave< and >aircraft impact<. The verification targets are stability, integrity and functional safety of the switchgear cubicles and functional units.

The loading case >earthquake< is a low frequency waveform, which may have an effect for some seconds, thereby distinguishing it from the loading cases of >explosive shockwave< and >aircraft impact<. Both of these loading cases are high-frequency square wave pulses; the oscillations are excited in the millisecond range. To ensure that the loading cases of >explosive shock wave< and >aircraft impact< are covered by the loading case of earthquake, the switchgear assemblies are installed in rooms equipped with resilient floors. These resilient floors sit on suitable schock insulators. They absorb the square wave pulse and balance the waveform of an earthquake. This enables all types of loads, both computed and experimental, to be treated equally. The verifications for the supporting structures and base frames of the switchgear assemblies are generally calculated in accordance with the German nuclear KTA 2201 regulation.

7.5.2 Low-voltage substations in internal arc-proof design for offshore applications

Offshore systems place very high demands on the quality of the technical equipment, because the fixed or floating offshore drill rigs operate autonomously and technical failures can have serious consequences. Repeated faults and personal injuries make particular demands on the user. The low-voltage switchgear assemblies are also included in these demands, because they must continue to function under the severest weather conditions. In addition to the general basic conditions listed below, offshore systems have stringent requirements for internal arc-proof design of the incoming feeder, coupling feeder and also for the switchgear cubicles for the motor control centre (MCC) in withdrawable-part design.

Examples of the general conditions for substation design are listed below:

- All plastic components must be halogen-free
- Plastic support components for live parts must be designed to be creepage-proof in accordance with CTI 300 and must have self-extinguishing properties
- All steel parts must be galvanized
- Substations must be delivered in accordance with IEC 60439-1
- The requirements of IEC 60092 must be met
- The busbars must be isolated
- The switchgear cubicle must be subdivided into separate functional compartments (busbar compartment, equipment compartment, cable terminal compartment)
- The substation must have a minimum weight (busbar, e.g. Cu-Al)

The MNS system corresponds to these general requirements even in its standard design. ABB has supplied electrical equipment and components for more than 1000 ships and offshore units. The request for internal arc-proof design has been taken into account in separate tests. The results from the comprehensive tests confirm the suitability of the equipment. The internal arc-proof capability of the MNS systems has been successfully confirmed in the test. In addition to compliance with the test criteria as specified in the regulations, the following results are important:

- The internal arc self-extinguishes after 1.5 to 100 ms.
- The effects of the internal arc remain restricted to the place where it occurred.
- Neighbouring withdrawable parts remain fully functional.
- Additional equipment enables incoming feeder cubicles to withstand a 50 kA internal arc for 300 ms.
- Additional tests were passed with 40 kA at 720 V.

7.5.3 Substations for shelter

Application approval certification is required for electrical equipment and assemblies intended for installation in shelters. This confirms that the requirements of the relevant technical directives for civil defence construction have been met and that approval for installation in a shelter has been granted. The inspecting authority requires the application approval certification as verification for all protection construction supported by federal funding. The application approval certification is issued by the federal civil defence office (BZS, Bonn) on behalf of the federal ministry for regional planning, building and urban development (BMBAU, Bonn). The BZS is also responsible for testing and verifying the shock safety of equipment installed in shelters. ABB has been awarded the application approval certification for medium-voltage substations, low-voltage substations, INS switchboxes and various switchgear and installed material.

The shock test is conducted on factory-new test samples. The test centre specifies the scope of testing required and the details of the shock test, such as special rigging, number of test objects and testing schedule. Test centres are the German army proving ground in Meppen and the federal office for civil defence experimental establishment at Ahrbrück. The exact testing conditions are specified by the BMBAU and are described in the appendix to the general basic construction standards for shelters, “Verification of Shock Safety of Installed Parts in Shelters”. There are specific control classes for classifying the shock safety, which are defined by recording the main characteristics of the test. The main characteristics are the test parameters of velocity and acceleration of the shock polygon. For example, control class 0.63 / 6.3 refers to a test velocity of 0.63 m/s at an acceleration of 6.3 g.

The shock safety is assessed with degrees of safety A, B and C.

- A: unrestricted shock safety. This means that the installed part must be guaranteed to retain unrestricted function even during the shock effect.
- B: restricted shock safety. This means that the installed part function may only be affected for the duration of the shock effect.
- C: minimum safety. This means that only safety against subsequent damage in the personal and technical environment of the installed parts must be guaranteed.

The INS, KNS and MNS low-voltage substation systems have been subjected to shock testing and have passed the test. The BMBAU has issued an application approval certification for the substations. The certifications are valid for operation in civil shelters up to and including control class RK 0.63/6.3, degree of safety B. Only the wall plugs approved for civil defence shall be used for securing the switchgear cubicles to the building.

8. Switchgear and switchgear installations for high voltage up to and including 52 kV (medium voltage)

8.1 Switchgear apparatus (≤ 52 kv)

This voltage range is generally referred to as “medium voltage”, even though the term has not been standardized anywhere.

The principal terms relating to switchgear are defined in Section 10.1.

8.1.1 Disconnectors

The classic design of the disconnector is the knife-contact disconnector (Fig. 8-1). It has become less common with the increasing use of withdrawable circuit-breakers and switch-disconnectors. This functional principle is now again becoming more frequent in gas-insulated switchboard technology.

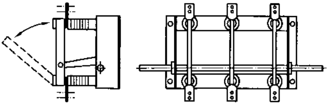


Fig. 8-1
Medium-voltage knife-contact disconnectors

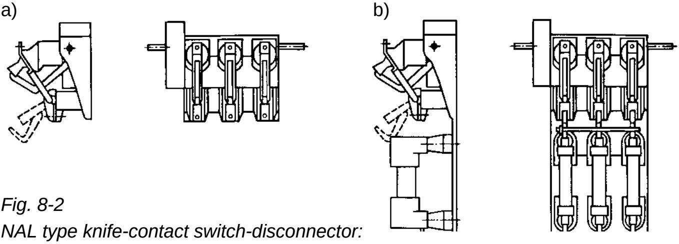
The blades of knife-contact disconnectors installed in an upright or hanging position must be prevented from moving by their own weight.

Disconnectors can be actuated manually and, in remotely operated installations, by motor or compressed-air drives.

8.1.2 Switch-disconnectors

Switch-disconnectors are increasingly being used in distribution networks for switching cables and overhead lines. Switch-disconnectors in connection with HV fuses are used for protection of smaller transformers.

Switch-disconnectors are switches that in their open position meet the conditions specified for isolating distances. General purpose switches can make and break all types of operating currents in fault-free operation and in the event of earth fault. They can also make and conduct short-circuit currents.



a)

b)

Fig. 8-2
NAL type knife-contact switch-disconnector:
a) without and b) with fuse assembly

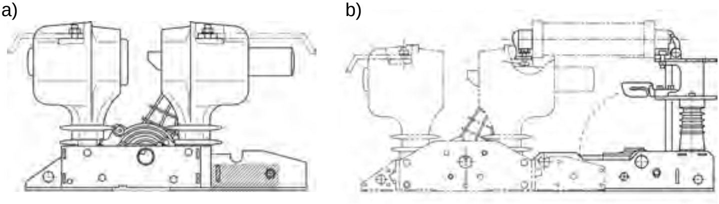


Fig. 8-3
C4 rod-type switch-disconnector: a) without and b) with fuse assembly

Knife-contact switch-disconnectors (Fig. 8-2) and rod-type switch-disconnectors (Fig. 8-3) are actuated in two ways:

a) “Snap-action mechanism”, also referred to as toggle-spring mechanism. With this type of operating mechanism, a spring is tensioned and released shortly before the operating angle is completed and its release force actuates the main contact systems. This is used for both closing and opening.

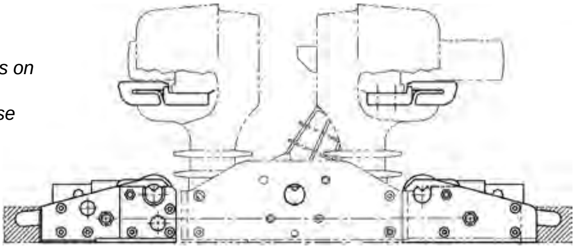
b) “Stored-energy mechanism”. This mechanism has one spring for closing and a second spring for opening. During the closing operation, the opening spring is simultaneously tensioned and latched. The stored energy for the opening operation is released by magnetic trips or the striker pin of the HV fuse.

The rod-type switch-disconnector is particularly suitable for the design of compact switchbays, because the knife-contact switch-disconnector requires a greater depth for the switching zone because of the projecting contact blade in its open state. The rod-type switch-disconnectors also enable very small phase spacings without phase barriers.

8.1.3 Earthing switches

Earthing switches are installed in switchbays primarily near cable boxes, i. e. before the main switching device. However, earthing switches are often specified also for busbar earthing, for example in metering panels. If the main switching device is a switch-disconnector, the earthing switch and the switch-disconnector will often be on a common base frame (Fig. 8-4).

Fig. 8-4
Configuration of earthing switches on the switch-disconnector base frame



Every earthing switch must be capable of conducting its rated short-time current without damage. “Make-proof” earthing switches are also capable of making the associated peak current at rated voltage. For safety reasons, make-proof earthing switches are recommended with air-insulated switchboards because of possible faulty actuations (DIN VDE 0101, Section 4.4). In gas-insulated switchboards, the earthing of a feeder is often prepared by the earthing switch and completed by closing the circuit-breaker. In this case, a make-proof earthing switch is not required.

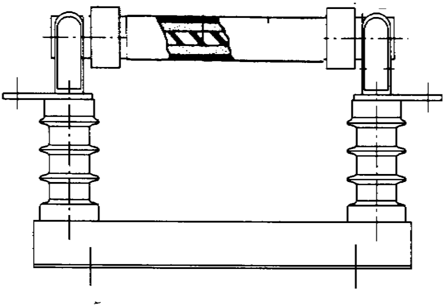
8.1.4 Position indication

Because disconnectors, switch-disconnectors and earthing switches are very important to the safety of the isolation of cables, lines and station components, there are special requirements for their position indication. It is true that the switch contacts themselves no longer need to be visible, but actuation of indicators or control switches must be picked up directly at the switch contacts or at a connecting point downstream of any operating spring on the power kinematic chain. (DIN EN 60 129 (VDE 0670 Part 2 Appendix 4)).

8.1.5 HV fuse links (DIN EN 60 282-1 (VDE 0670 Part 4))

The load current flows in fuse links through narrow silver conductor bands, which are arranged spirally in a sealed dry quartz sand filling in the interior of an extremely thermally resistant ceramic pipe. The conductor bands are designed with a narrower cross-section at many points to ensure that in the event of an overcurrent or short-circuit current, a defined melting will occur at many points simultaneously. The resulting arc voltage ensures current limiting interruption in case of high short-circuit currents.

Fig. 8-5
Fuse base with fuse link



The cap-shaped end contacts of the HV fuse link are picked up by the terminal contacts of the fuse base. HV fuse links can be fitted with indicators or striker pins, which respond when the band-shaped conductors melt through. The striker pin is required for mechanical tripping of the switching device when used in the switch/fuse combination (DIN EN 60 420 (VDE 0670 Part 303)).

Characteristic current values for HV fuse links:

Rated current

The majority of fuse links in operation have a rated current ≤ 100 A. For special applications with smaller service voltages (e.g. 12 kV), fuse links up to 315 A are available. The associated melt-through times of the fusible conductors are found from the melting characteristics (manufacturer information for the range of the interrupting currents) (Fig. 8-6).

Rated breaking current

This value must be provided by the manufacturer of the fuse link. It is influenced by the design for a specified rated current. When selecting fuse links for transformer protection in distribution systems, the maximum breaking current is not a critical quantity.

Rated minimum breaking current

Classification of fuse links into three categories

– <u>*Back-up fuses*</u>
  Smallest breaking current (manufacturer information) in general at 2.5 to 3.5 times rated current. Suited for application in switch/fuse combinations. Very common!

– <u>*General purpose fuses*</u>
  The minimum breaking current is that which results in melt-thRough after 1 hour or more of exposure time (generally twice the rated current).

– <u>*Full-range fuses*</u>
  Every current that results in a melt-through can be interrupted.

Cut-off current characteristic

The maximum value of the current let-through by the fuse depends on its rated current and the prospective short-circuit current of the system. Fig. 8-7 shows a characteristic field.

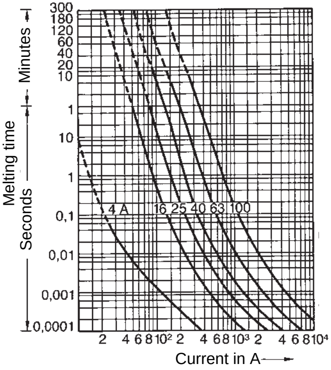


Fig. 8-6
The melting time depending on the overcurrent/short-circuit current

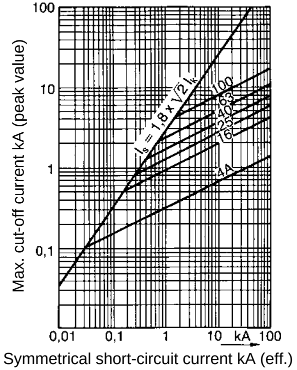


Fig. 8-7
The cut-off current depending on the prospective short-circuit current

Selecting fuse links for specific conditions

When protecting transformers (Table 8-1) and capacitors with fuses, the inrush currents must be taken into account. When protecting transformers, selectivity by making the melting times match of low-voltage fuses and HV fuses is required to ensure that the low-voltage fuses respond first. This is taken into consideration in Table 8-1.

Table 8-1

Approved protection of transformers on the medium-voltage side (fuse-links type CEF) and on the low-voltage side.[1]

Rated voltage (kV)	Rated transformer output (kVA)																
	50	75	100	125	160	200	250	315	400	500	630	800	1000	1250	1600	2000	2500
	High-voltage fuses I_n (A)																
3	25	25	40	40	63	63	63	80	100	100	160	200	200	250[2]	315[2]		
5	16	25	25	25	40	40	63	63	63	80	100	100	160	200	200	250[2]	315[2]
6	16	16	25	25	25	40	40	63	63	63	80	100	100	160	200	200	250[2]
10	10	16	16	16	25	25	25	40	40	63	63	63	80	100	100	160	200
12	10	16	16	16	16	25	25	25	40	40	63	63	80	100	100	160	160
15	10	10	16	16	16	16	25	25	25	40	40	63	63	63	100	100	125
20	10	10	10	16	16	16	16	25	25	25	40	40	63	63	63	80	100
24	10	10	10	10	16	16	16	16	25	25	25	40	40	63	63	63	80
30	10	10	10	10	10	16	16	16	16	25	25	25	40	40	40	2x40	2x40
36	10	10	10	10	10	10	16	16	16	16	25	25	25	40	40	2x40	2x40
Rated voltage (V)	Low-voltage fuses I_n (A)																
220	80	100	125	160	200	250	250	315	400	500	630						
380	50	63	100	100	125	125	200	250	250	350	400	400	500	630			
500	40	50	80	80	100	100	160	160	200	250	350	350	400	500	630		

[1] Maximum rated current of the low-voltage protection that yields selectivity with the high-voltage fuse.

[2] CMF-type fuse link

In capacitor banks the rated current of the HV fuse links should be at least 1.6 times the rated current of the capacitors. Experience has demonstrated that this covers also the influences of possible system harmonics and increased voltage.

When selecting fuse links for protection of high-voltage motors, the starting current and the starting time of the motors must be taken into account. The frequency of startups must also not be neglected if this is frequent enough to prevent the fuses from cooling down between starts.

8.1.6 **I_s-limiter –** fastest switching device in the world

The increasing requirements for energy throughout the world demand higher rated or supplementary transformers and generators and tighter integration of the supply systems. This can also result in the permissible short-circuit currents of the equipment being exceeded and the equipment being dynamically or thermally destroyed.

It is often not technically possible or not economical for the user to replace switchboards and cable connections with new equipment with increased short-circuit current capability. The implementation of I_s-limiters when expanding existing installations and constructing new installations reduces short-circuit currents and costs.

A circuit-breaker does not provide protection against impermissibly high peak short-circuit currents, because it is too slow. Only the I_s-limiter is capable of detecting and limiting a short-circuit current in the initial rise, i.e. in less than one millisecond. The maximum instantaneous current value that occurs remains well below the peak value of the short-circuit current of the system.

Typical I_s-limiter applications (Fig. 8-10):

- in couplings,
- in coupling the public system with a private supply,
- parallel to reactor coils,
  (avoids copper losses and voltage drop at the reactor coils)
- in transformer or generator feeders,
- in outgoing feeders.

The I_s-limiter is a current-limiting switching device, which detects and limits the short-cicuit current in the initial rise. The short-cicuit current through the I_s-limiter is limited so quickly that it does not contribute in any way to the peak value of the short-cicuit current at the fault site.

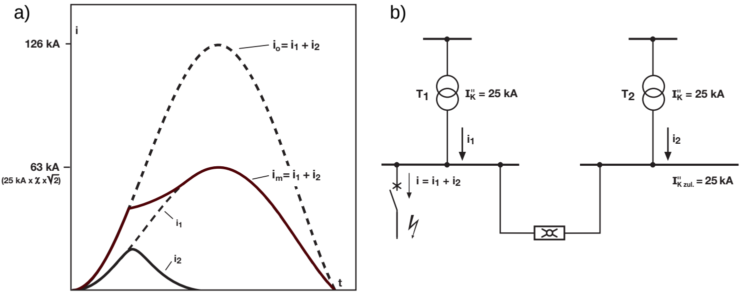


Fig. 8-8

Short-circuit breaking with I_s limiters
a) Current path
i_o Total current without I_s limiter
i_m Total current with I_s limiter
b) Basic layout

In principle, the I_s-limiter consists of an extremely fast switching device that can conduct a high rated current, but has a low switching capacity and a parallel configured fuse with high breaking capacity. To achieve the desired short switching delay, a small charge is used as energy storage for opening the switching device (main current path). Once the main current path has been opened, the current still flows through the parallel fuse, where it is limited within 0.5 ms and then is finally interrupted in the next voltage zero.

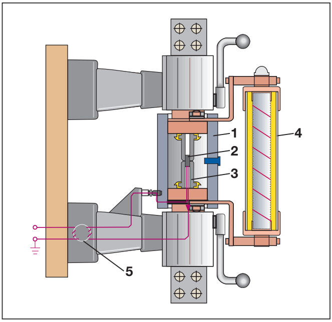


Fig. 8-9

Holder and insert of an I_s-limiter

1 Insulating tube
2 Charge
3 Bursting bridge (main current path)
4 Fuse
5 Insulator with pulse transformer

Table 8-2

Rated voltages and currents for I_s-limiter

Rated voltage kV	Rated current A
0.75	.... 4.500
12.0	.... 4.000
17.5	.... 4.000
24.0	.... 2.500
36.0 (40.5)	.... 2.500

I_s-limiter inserts are parallel connected for higher currents

The I_s-limiter is from all points of view the ideal switching device for solving short-circuit problems in switchboards in power plants, in heavy industry and for power supply companies.

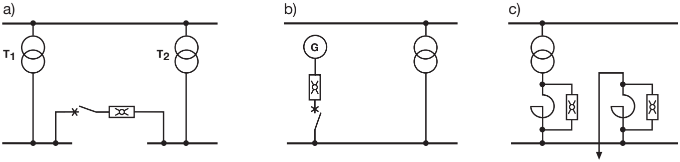


Fig. 8-10

The most common applications for I_s-limiters are:
a) couplings, b) in power supplies, c) parallel to reactors in power supplies and in outgoing feeders.

8.1.7 Circuit-breakers

There are still a number of “small-oil-volume” circuit-breakers in use for rated voltages to 52 kV in systems, but for new installations only vacuum or SF_6 circuit-breakers are used.

Circuit-breakers can be fix-mounted or integrated into the switchbay with appropriate interlocking mechanisms in withdrawable unit design.

Circuit-breakers must be capable of making and breaking all short-circuit and service currents occurring at the operational site. See 10.4.3 for details. The testing conditions for the corresponding verifications can be found in DIN VDE 0670 Part 102 and Part 104.

Vacuum circuit-breakers

Vacuum circuit-breakers of the VD4 type are available from the ABB Calor Emag production range for short-circuit breaking currents up to 63 kA with rated currents from 400 to 3150 A. The VD4 range covers the voltage ranges of 12 kV, 17.5 kV, 24 kV and 36/40 kV.

Fig. 8-11 shows a vacuum circuit-breaker of the VD4 type in column design.

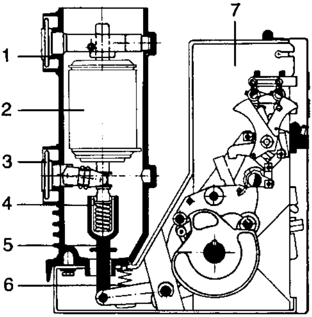


Fig. 8-11

Section through breaker type VD4
1 Upper connection
2 Vacuum interrupter
3 Lower connection
4 Contact pressure spring
5 Insulated coupling rod
6 Opening spring
7 Spring stored-energy operating mechanism

The components of the main circuit are covered by tubular epoxy resin insulators. The VD4 circuit-breaker is therefore particularly suitable for use with compact switchbays of small dimensions.

Fig. 8-12

VD4 circuit-breaker for 12 kV as a withdrawable unit

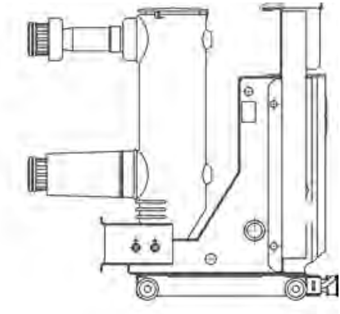


Fig. 8-12 shows the VD4 circuit-breaker with isolating contact arms on the withdrawable module frame for use in air-insulated switchboards, e.g. of type ZS1.

Fig. 8-13

Vacuum interrupter in sectional view, simplified overview

1 Insulator
2 Fixed contact
3 Movable contact
4 Metal bellows
5 Shielding
6 Contact stem
7 Cover
8 Protection guide
9 Central shield

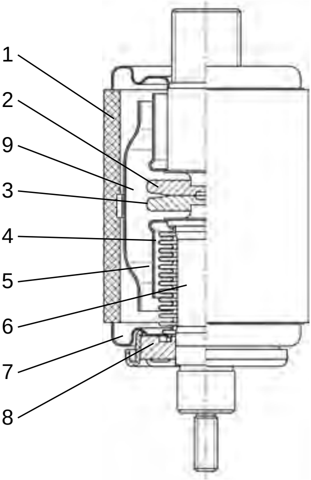


Fig. 8-12 shows the most important components of a vacuum interrupter of the ABB range in sectional view. All joints of the conducting path and of the enclosure are manufactured by brazing in vacuum furnaces with inserted brazing material rings. This results in an extremely reliable and long-lasting seal.

The contacts are a copper/chrome compound material, a copper base containing evenly distributed fine-grained chrome particles, which has a good extinguishing and arc-resistant response when switching short-circuit currents, and is also distinguished by low-chopping current values when breaking small currents.

Switching overvoltages

Switching overvoltages when switching inductive loads with vacuum circuit-breakers have long been a subject of discussion. The introduction of copper/chrome as contact material has significantly reduced the occurence of hazardous overvoltage values. To cover the residual risk, surge arresters based on metal oxide (MO) are recommended for specified applications. Examples of such applications are:

- small motors (with starting current below about 600 A),
- small generators,
- reactor coils for power factor compensation,
- dry-type transformers in industrial application.

Only in special cases (e.g. furnace transformers) are supplementary RC circuits required, preferably in the form of ZO-R-C combinations (zinc oxide+R+C).

Actuating systems

The travel of movable contacts between open and closed position in the vacuum circuit-breaker is between 8 and 14 mm depending on the rated voltage. At the end of the closing stroke, the energy for tensioning the contact pressure springs is required. The relatively low total energy requirement for vacuum circuit-breakers is generally provided by mechanical spring stored energy operating mechanisms, as with the VD4 type. Tripping is initiated by magnetic trips or manually. The mechanical operating mechanism of the VD4 circuit-breaker is always suitable for autoreclosing (0 – t – CO).

Fig. 8-14 shows a new actuating system for the VM1 type circuit-breaker. The movable contacts here are actuated by a permanent magnet mechanism with two stable end stops. The contact movements are initiated by current pulses (approx. 100 Watt / 45 ms), generated by discharge of a capacitor with a charged voltage of 80 V, i.e. with less tripping energy than with magnetic trips of the mechanical mechanism.

1	*Upper connection*
2	*Vacuum interrupter*
3	*Epoxy resin enclosure*
4	*Lower connection*
5	*Flexible connector*
6	*Contact pressure spring*
7	*Insulated coupling rod*
8	*Lever shaft*
9	*Stroke setting*
10	*Sensors for position indication*
11	*ON coil*
12	*Permanent magnets*
13	*Magnet armature*
14	*OFF coil*
15	*Manual emergency trip*
16	*Actuator housing*

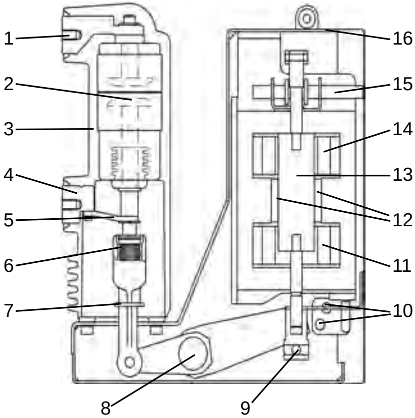


Fig. 8-14

Vacuum circuit-breaker VM1 (dimensions fully compatible to type VD4)

The trip currents are controlled by thyristors and transistors, i.e. exclusively by electronic components. A fixed-programmed logic circuit coordinates the processes and interlock conditions. The contact position is detected by magnetic proximity sensors. The interface to the control system is through binary inputs and outputs.

Because of the extremely small number of individual parts, this actuating system offers significant advantages in reliability, durability (100,000 switching cycles) and manufacturing costs.

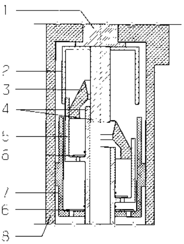
The pole section (Fig. 8-14) with the vacuum switching chamber moulded in epoxy resin has optimum dielectric properties, permanent protection against external influences of all types and because of the small number of parts, very little likelihood of faults occurring. This eliminates the requirement for maintenance of this switching device under standard operating conditions.

SF_6 circuit-breakers

After its successful implementation in the range of transmission voltages (cf. Section 10 and 11!), SF_6 has also become established in the medium-voltage range. The puffer-type arc-quenching principle, which was introduced first, provides an effective arc-quenching gas flow by a mechanically driven piston. However, this requires high-energy driving systems. Hence self-blast arc-quenching systems of different types were developed, where the relative movement between the gas and the arc is provided by the arc itself, either by continuous movement of the arc in a circular route or by pressure built up in a temporarily enclosed volume.

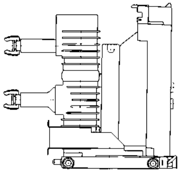
The newest generation of ABB SF_6 circuit-breakers for medium-voltage - type HD4 - makes use of a combination of these two-different arc-quenching principles („Autopuffer"). Circuit-breakers of this type are available for service currents from 630 A to 4000 A and for short-circuit currents up to 50 kA. The arc-quenching system (Fig. 8-15) applies the gas compressed in the lower chamber to interrupt small currents with overvoltage factors < 2.5 p.u. even in case of small inductive currents. High short-circuit currents are interrupted by the self-blast effect applying the pressure built up in the moving chamber by the arc energy.

Fig. 8-15: SF_6 circuit-breaker type HD4



1 Upper terminal
2 Main contact
3 Nozzle
4 Arcing contact
5 Moving chamber
6 Valves
7 Lower chamber
8 Insulating housing
left: closed
right: open

"Autopuffer"-arc quenching system



Circuit-breaker on switch truck, side view

8.1.8 Vacuum contactors

Vacuum contactors, in connection with HV fuses, are particularly suitable for operational switching of motors with very high switching frequency, e.g. medium-voltage motors for pumps, fans, compensators and capacitors. HV fuses provide protection for cables and circuit components in case of a short circuit.

Vacuum contactors have a life expectancy (electrical) of 1•10^6 switching cycles, and can handle a switching frequency up to 1200 on/off operations per hour. The V-contact type vacuum contactors (Fig. 8-16) have the performance data listed in Table 8-3. However, the table does not note whether suitable fuses are available to take advantage of the listed performance ranges.

Table 8-3

Performance data of type V-contact vacuum contactors

Rated voltage Rated current	kV A	3,6 400	7.2 400	12 400
Suited for				
– Motors of up to	kW	1 500	3 000	5 000
– Capacitors of up to	kVAr	1 500	3 000	4 800

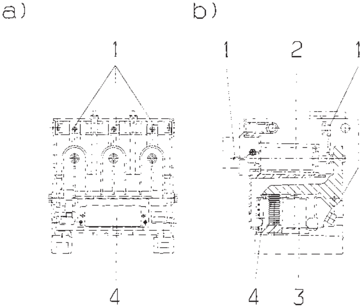


Fig. 8-16

Vacuum contactor, type V-Contact

a) front view
a) section view

1 connection terminals
2 vacuum interrupter
3 contactor coil
4 auxiliary contacts

8.2 Switchgear installations (≤ 52 kv)

8.2.1 Specifications covering HV switchgear installations

This voltage range – generally referred to as medium voltage – covers switchbays in use and on the market that can be classified as per one of the two following specifications:

DIN VDE 0101 or
DIN EN 60298 (VDE 0670 Part 6)

8.2.2 Switchgear as per DIN VDE 0101

Switchgear installations as per DIN VDE 0101 are designed to comply with fixed minimum clearances of live components from one another, from earth potential and from protecting barriers. They can basically be manufactured at the site where they will be operated. Current-carrying capacity for service and short-circuit currents must be verified by calculation (cf. Section 4. also). Type testing is not required.

Vacuum contactors have a life expectancy (electrical) of 1•10^6 switching cycles, and can handle a switching frequency up to 1200 on/off operations per hour. The V-contact type vacuum contactors (Fig. 8-16) have the performance data listed in Table 8-3. However, the table does not note whether suitable fuses are available to take advantage of the listed performance ranges.

Table 8-3

Performance data of type V-contact vacuum contactors

Rated voltage	kV	3,6	7.2	12
Rated current	A	400	400	400
Suited for				
– Motors of up to	kW	1 500	3 000	5 000
– Capacitors of up to	kVAr	1 500	3 000	4 800

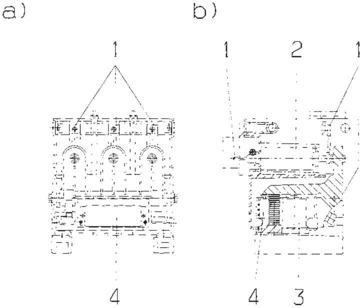


Fig. 8-16

Vacuum contactor, type V-Contact

a) front view
a) section view

1 connection terminals
2 vacuum interrupter
3 contactor coil
4 auxiliary contacts

8.2 Switchgear installations (≤ 52 kv)

8.2.1 Specifications covering HV switchgear installations

This voltage range – generally referred to as medium voltage – covers switchbays in use and on the market that can be classified as per one of the two following specifications:

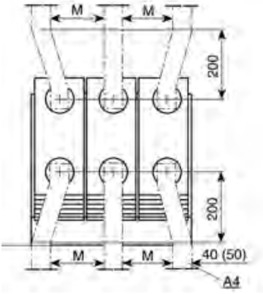
DIN VDE 0101 or
DIN EN 60298 (VDE 0670 Part 6)

8.2.2 Switchgear as per DIN VDE 0101

Switchgear installations as per DIN VDE 0101 are designed to comply with fixed minimum clearances of live components from one another, from earth potential and from protecting barriers. They can basically be manufactured at the site where they will be operated. Current-carrying capacity for service and short-circuit currents must be verified by calculation (cf. Section 4. also). Type testing is not required.

When setting up these installations in electrical equipment rooms with restricted accessibility, protection against accidental contact with live components, e.g. screens or rails, is sufficient. The bays can also be designed with sheetmetal walls and doors (minimum height 180 cm) (cf. Section 4.5; 4.6 and 5.2). Reinforced wallboard is also frequently encountered as a wall material. The bays can also be completely enclosed for full protection for operation outside locked premises.

The use of insulating materials and intelligent design will allow smaller clearances, particularly in the terminal zone of circuit-breakers and switch-disconnectors, than the specified minimum clearances as per DIN VDE 0101 (cf. Table 4-12:). A device of this kind must be tested with connected conductors in the zone in which the permissible minimum clearances are not met. This zone is referred to as the "tested terminal zone" (see DIN VDE 0101). It must be included in the user manual for the switching devices with the main dimensions (Fig. 8-17).



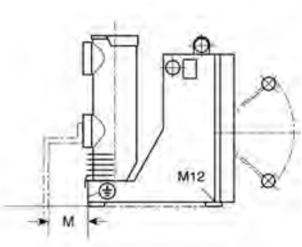


Fig. 8-17

Tested terminal zone as per DIN VDE 0101
M = minimum clearance as per DIN VDE 0101
here: tested terminal zone = 200 mm
A4 = connecting bar as per DIN 46433

Today, switchbays as per DIN VDE 0101 are mainly encountered in individual installation design on site or are manufactured by smaller companies without in-house test laboratories.

DIN VDE 0101 also includes basic specifications for the general design of a substation, including the structural requirements. They are also applicable for the installation of type-tested switchgear as per DIN EN 60298 (VDE 0670 Part 6).

8.2.3 Metal-enclosed switchgear as per DIN EN 60298 (VDE 0670 Part 6)

Metal-enclosed switchboards are generally assembled from type-tested panels these days. As per DIN EN 60298 (VDE 0670 Part 6) metal-enclosed switchgear installations must be designed so that their insulation capacity, degree of protection, current-carrying capacity, switching capacity and mechanical function conform to the requirements set by the testing provisions. This is verified by a type test on a prototype unit. In addition, a routine test is made on every completed panel or every transport unit.

Note: As well as DIN EN 60298 (VDE 0670 Part 6), the higher-order specification DIN EN 60694 (VDE 0670 Part 1000) must also be observed.
Type-tested switchgear installations with insulated enclosures are subject to IEC 60466. However, there is no longer a corresponding European or German standard.

Rated voltage

The rated values for the insulation level of a switchgear installation must be selected on the basis of the requirements of the system at the installation site from the selection tables in DIN EN 60 694 (VDE 0670 Part 1000).

Table 10-1 (Section 10) shows the selection values for the range of rated voltages up to 52 kV. The voltage values “over the isolating distance” only apply for switching devices with which the safety requirements for the open contacts of disconnectors must be met.

Table 10-1 lists two value pairs that can be selected for the rated lightning impulse voltage level for almost all rated voltages. The options correspond to the former subdivision in list 1 and list 2.

When making the selection, the degree of danger from lightning and switching overvoltages, the type of neutral treatment and, if applicable, the type of overvoltage protection should be considered. The higher value pairs in each case are the ones to be selected for installations and equipment exposed to atmospheric overvoltages, e.g. by direct connection to overhead lines. The lower value pairs can be used for installations that are not exposed to atmospheric overvoltages or are protected from these overvoltages by arresters.

Gaseous insulating materials

DIN EN 60298 covers switchgear in which atmospheric air acts as the gaseous insulation within the enclosures and also those in which a gas other than the atmospheric air is used (e.g. SF_6)(air-insulated/gas-insulated).

Degree of protection for metal-enclosed switchgear

The metallic and earthed enclosure protects personnel against approach to live components and against contact with moving parts. It also protects the installation against the penetration of foreign bodies. One of three different degrees of protection may be selected for switchgear as per DIN EN 60298. The difference is whether the enclosure is suitable for repelling fingers or similar objects (IP 2X), rigid wires more than 2.5 mm in diameter (IP 3X) or rigid wires more than 1 mm in diameter (IP 4X).

Compartmentalization

The general term “metal-enclosed” is used in DIN EN 60298 for three different categories depending on the design of the internal compartmentalization

– “metal-clad” switchgear has separate compartments for the main switching device and the two adjacent zones, i.e. in general three compartments (for circuit-breaker, busbar system and cable terminal zone). The compartment walls are metal and are earthed.

- “compartmented” switchgear has the same degree of bay subdivision as “metal-clad” switchgear, but the compartment walls are of insulating material.
- “cubicle” switchgear is defined as all switchgear whose compartmentalization does not meet the requirements of the two above categories (e.g. only two compartments), but this also includes all switchgear that does not have internal compartmentalization.

The decision on which of these installation categories is to be used in any specific case is up to the user, with most attention paid to safety of personnel during maintenance and cable work inside the switchbay. Restricting the effects of faults is important only when the resistance of the compartment walls to arcing has been verified and when the compartmentalization forms a true potential separation.

Internal arcing

All specialists are in basic agreement that manufacturers and users must make every effort to prevent under all circumstances faults in switchgear installations in which internal arcing occurs. However, it is also acknowledged that such faults cannot be completely prevented in all cases. For this reason, it is expected that current switchgear designs have been tested for response to internal arcing.

Internal short-circuit arcs during operation can occur by overvoltage, faulty insulation or improper control. The test consists of inducing the arc with an ignition wire connected over all three phases. The arc has temperatures of around 4000 K in the area of its footing points and around 10 000 K or more in the area of the arc column. Immediately after the arc has been ignited, the gas in in the immediate vicinity of the arc heats up instantly, causing a very steep rise in pressure in the compartment concerned. This pressure increase would continue to the load limit of the enclosure if pressure relief vents were not built into it. The sealing covers or membranes of these vents respond in ca. 5 to 15 ms and open the path to allow the heated gases to vent (Fig. 8-18). This characteristic process is not determined only by the response time of the pressure relief valves but it also results from the mechanical inertia of the heated gas mass.

The maximum pressure reached is dependent on the volume of the compartment where the fault occurs and on the magnitude of the short-circuit current. The greatest quantity of heated gases is given off into the area around the switchboard during the expansion phase. The pressure stress on the panel exceeds its high point as early as about 15 ms, that of the building has reached its maximum stress after 40 ms at the latest. A powerful ejection of still heated gases of low density and glowing particles occurs in the subsequent emission phase and in the thermal phase.

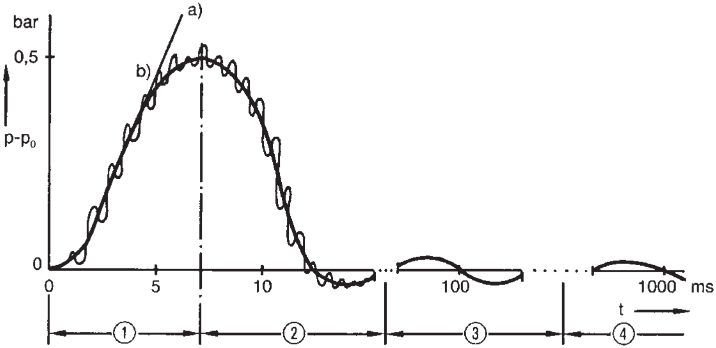


Fig. 8-18

Pressure development in the faulty panel caused by internal arcing, 1 Compression phase (pressure build-up), 2 Expansion phase (pressure relief), 3 Emission phase (hot gases released), 4 Thermal phase (ejection of glowing particles). a) isochorous pressure rise, b) opening of pressure relief valves.

Guidelines for testing metal-enclosed switchgear for their response to internal arcing can be found in Appendix AA of DIN EN 60298 (VDE 0670 Part 6). PEHLA Guide no. 4 contains relevant supplementary provisions.

The specified test sequence requires the internal arcing to be ignited with a thin ignition wire in the test compartment of a switchbay. The short-circuit test plant supplying the test object must have sufficient power to allow a short-circuit current as high as the short-time withstand current to flow in three phases over the internal arcing during the agreed duration of the test. The test generally lasts 1 second. This will cover the longest protection grading times that can be still expected in practice – at full short-circuit current. The test with a short-circuit duration of 0.1 second may be of interest for special protection concepts. With this short-circuit duration, the test result is restricted to the question of whether the tested compartment withstands the stress caused by the internal overpressure.

During the test, fabric indicators (black, cretonne or cotton-wool batiste) are stretched vertically at a defined spacing on metal frames in front of the accessible walls of the switchboards and horizontally at 2 m height above the zone where personnel would be when operating the installation (Fig. 8-19).

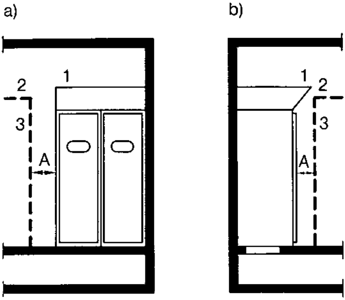


Fig. 8-19

Test structure: thermal effects

a) Front view; b) Side view; 1 Discharge plate; 2 Horizontal indicators at 2.0 m height; 3 Vertical indicators at distance A from test object; A = 300 mm for electrical equipment rooms with restricted accessibility; A = 100 mm for generally accessible rooms.

After the short-circuit test, the test engineer records the response of the switchbay(s) tested based on six criteria. The following points are recorded:

1. doors and screens have not opened,
2. no hazardous parts were ejected,
3. arcing did not cause any holes,
4. none of the vertical fabric indicators in front of walls and doors ignited,
5. none of the horizontal fabric indicators at a height of 2 m above the control zone ignited,
6. all earth connections are still effective.

High-speed film or video cameras can also provide additional information on what occurs during the test. They are therefore strongly recommended.

The test objects are not assessed with “pass/fail”. This allows the user to approve switchbays for one application, even though a positive observation was not registered for every one of the above criteria.

This freedom to interpret the results is particularly significant with reference to criteria 4 and 5, because in the event of ejection of hot gases, the switchbay itself is not primarily relevant for the effects. Reflection from the ceilings and walls in the emission phase and the thermal phase (Fig. 8-18) can divert the hot gases coming from the pressure relief vents into zones accessible for personnel and cause hazardous conditions there. The highest degree of damage also occurs during this period inside the switchbay. The ejection of very hot gas reaches its most hazardous amount under the condition when caused by the direction of supply (from below) the electromagnetic forces compel the arc to persist in the immediate vicinity of the pressure relief vent. A switchbay type may be considered fully tested only after this case has been considered.

Countermeasures for protection of personnel against these effects can be as simple as installing screens or discharge plates. At high short-circuit currents, hotgas conduits with blow-out facilities using absorbers discharging into the switchgear installation room are the perfect solution. However, even better results without additional installations can be achieved if it is possible to limit the arc duration to approximately 100 ms by appropriate trip times. Because the grading times of the system protection do not generally allow such a short-term tripping of the feeder circuit-breaker, additional sensors are required, such as the I_{th}-limiter. When one of the pressure relief valves opens and there is simultaneous persistent short-circuit current, it initiates an undelayed trip command to the feeder circuit-breaker. This quenches the internal arc in less then 100 ms.

The pressure load on walls, ceilings, doors and windows of the switchgear installation room is the result of the gas ejection during the expansion phase (Fig. 8-18). The withstand can generally not be verified by testing. All major manufacturers provide calculation programs for determining the pressure development in the switchgear installation compartment to find out whether pressure relief vents are required for the installation room.

8.2.4 Metal-enclosed air-insulated switchgear as per DIN EN 60298 (VDE 0670 Part 6)

Switchgear of this design have the largest market share throughout the world.

Metal-clad switchgear

Fig. 8-20 shows an example of metal-enclosed and metal-clad switchgear of type ZS1.

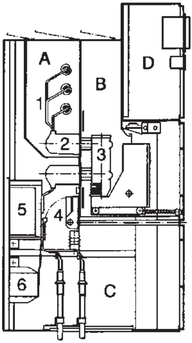


Fig. 8-20

Type ZS1 switchbgear
A busbar compartment; B main switching device compartment; C cable terminal compartment; D low-voltage compartment;
1 busbar; 2 isolating contacts;
3 circuit-breaker; 4 earthing switch;
5 current transformer;
6 voltage transformer

The circuit-breaker of this type of switchgear can be moved when the door is closed between the operating position and test position. Because vacuum circuit-breakers under normal operating conditions are maintenance-free, the door to the circuit-breaker compartment can remain permanently closed. However, if it should be necessary to remove the switch from the switchbay, this can be done without problems on a service truck that can be adjusted for height to the exact position.

Access to the cable boxes can be made much easier by removing the circuit-breaker and also removing the partition between compartments B and C.

Compartment C has room for the cable boxes of several parallel cables. Metallic oxide arresters for overvoltage protection of inductive consumers can also be installed here.

When the circuit-breaker is in test position and the switchbay doors are closed, the cables can be earthed via the permanently installed earthing switch (with short-circuit making capacity). In order to check that the cables are dead voltage indicator plugs can be inserted into test sockets at the front of the switchboards. The test sockets are connected to the terminals of capacitive deviders, which are integrated into the current transformer.

Instead of the vacuum circuit-breaker, an SF_6 circuit-breaker of the HD4 type with identical main dimensions can be installed in this switchgear type.

The ZS-1 switchgear shown in Fig. 8-20 is available with the technical data and bay dimensions shown in Table 8-4.

Table 8-4

Technical limit data and associated minimum bay dimensions of the ZS1 metal-enclosed metal-clad switchgear design series

Rated voltage	kV	12	17.5	24
Rated short-duration power-frequency withstand voltage	kV	28	38	50
Rated lightning impulse withstand voltage	kV	75	95	125
Rated current				
– of the busbars	A	... 4 000	... 4 000	... 4 000
– of the feeders	A	1250/ ... 4 000	1250/ ... 4 000	1250/ ... 2 500
Rated short-time withstand current (3 s)	kA	31.5/... 50	25/... 40	... 25/... 25
Minimum bay dimensions				
– width	mm	650/1 000	650/1 000	800/1 000
– depth	mm	1 300/1 350	1 300/1 350	1 500/1 500
– height	mm	2 200	2 200	2 200

In addition to the standard switchgear panel with draw-out circuit-breaker, there are variations for sectionaliers, metering panels and bays with permanently installed switch-disconnectors for substation power supply transformers. Double busbar installations are designed in accordance with the two circuit-breaker methods in back-to-back or front-to-front configurations (Fig. 8-21).

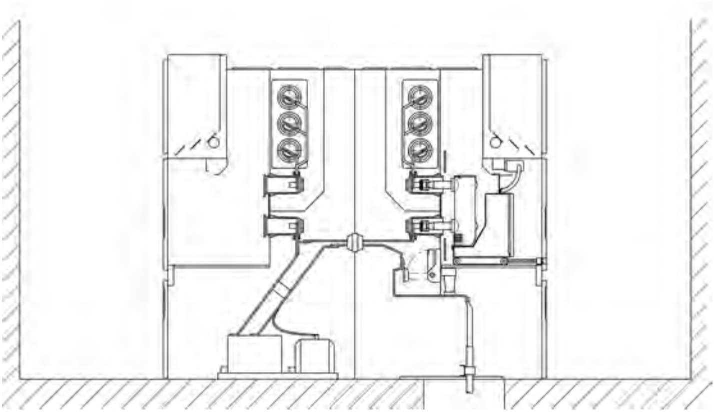


Fig. 8-21

Double busbar switchgear installation ZS1, switchbays in back-to-back configuration

Cubicle switchgear

Fig. 8-22 shows metal-enclosed cubicle switchgear of type ZS8. Below are switchbays with permanently installed switch-disconnectors for switching cables and overhead lines and with HV fuses for protection of distribution transformers. The switch-disconnectors can be remote-controlled with the motor-operated mechanism. In the circuit-breaker bays, the VD4 and VM1 vacuum circuit-breakers are withdrawable units that can be moved when the panel door is closed.

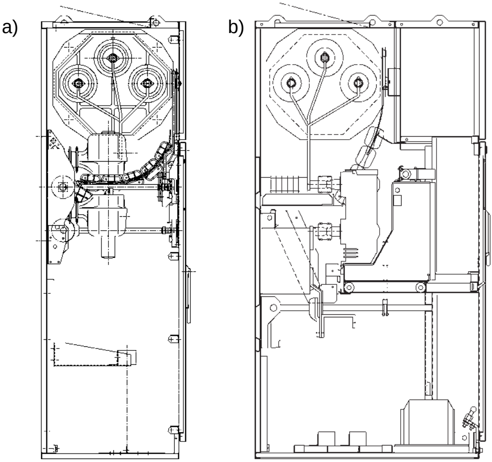


Fig. 8-22

ZS8 *metal*-enclosed *cubicle switchgear:*

a) switch-disconnector panel

b) circuit-breaker panel

All bay types of the ZS8 design series can be queued up in spite of varying dimensions. The switch-disconnector bay can also be supplied in the same depth as the circuit-breaker bay. The most important dimensions of these bays and their rating data are shown in Table 8-5.

Table 8-5

Technical limit data and associated minimum bay dimensions of the ZS8 cubicle switchgear

Rated voltage	kV	12	17.5	24
Rated short-duration power frequency withstand voltage	kV	28	38	50
Rated lightning impulse withstand voltage	kV	75	95	125
Rated current				
– of the busbars	A	... 1 250	... 1 250	... 1 250
– of the switch-disconnector feeders	A	... 630	... 630	... 630
– of the circuit-breaker feeders	A	... 1 250	... 1 250	... 1 250
Rated short-time withstand current (3 s)	kA	... 25	... 20	16 1)/... 25
Minimum bay dimensions				
– width of switch-disconnector bay	mm	600	650	600
– depth of switch-disconnector bay without/with branch compartmentalization	mm	600/1 200	1 000/–	800/1 200
– width of circuit-breaker bay	mm	650	650	800
– depth of circuit-breaker bay without/with branch compartmentalization	mm	1 000/1 200	1 000/1 200	1 200/1 200
– height	mm	1 900	1 900	1 900

1) switch-disconnector bay for 24 kV only up to 16 kA

ZS8 switchbays are not subdivided by metallic earthed compartment walls, as required for the “metal-clad” category. For this reason, they must be classified in the “cubicle” category.

ZS8 switchbays are equipped with earthing switches (with short-circuit making capacity) for feeder earthing. The earthing switches can only be closed when the switch-disconnector is open or the circuit-breaker withdrawable unit is in isolated position. There is an insulating plate integrated in every switchbay, which slides into the open break of the switch-disconnector or in front of the busbar-side slide-in contacts of the circuit-breaker compartment. This assures protection against accidental approach to live components during work in the bay, e.g. at the cable terminals. There are also ZS8 panels with “tee-off partitions” (Fig. 8-23). These bays have earthed metallic partition, which separate the busbar system from the areas of switching devices and cable terminals. The electric protection against approach to the slide-in contacts installed in epoxy resin spouts is provided by earthed metallic shutters that swings in front of the epoxy resin spouts in these bays. The panel doors can only be opened after closing the protection shutter in all ZS8 type switchgear.

Checking that the cables are dead can be made with conventional voltage indicators or by using voltage indicator plugs at externally accessible test sockets. Measurements using sockets require installation of capacitive divider devices in the epoxy resin insulators of the switch-disconnector or in the current transformer of the circuit-breaker panels.

Panel variations of the ZS8 series in addition to the panels with switch-disconnectors or circuit-breakers include sectionalizers, busbar risers and metering panels.

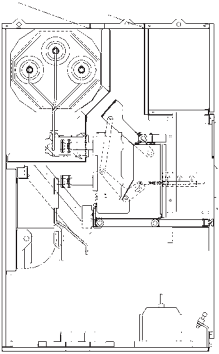


Fig. 8-23

ZS8 switchgear with tee-off partition

8.2.5 Metal-enclosed gas-insulated switchgear

as per DIN EN 60298 (VDE 0670 Part 6)

The same standard as for the air-insulated switchgear described in Section 8.2.4 also applies to the gas-insulated switchgear of the medium-voltage area. The term “gas-insulated” refers to the fact that atmospheric air is not used as the gaseous insulating material inside the switchbays, i.e. the enclosure of the installation must be gas-tight against the environment.

The gas currently used in most gas-insulated designs is a synthetic electronegative gas, SF_6, with almost three times the dielectric resistance of air. See also Section 16.3! The insulating gas can also be nitrogen, helium or even air dried for the purpose and at a higher pressure level.

The decisive advantage of a gas-insulated switchgear compared to an air-insulated installation is its independence from environmental influences such as moisture, salt fog and pollution. This results in less maintenance, increased operational safety and high availability. The smaller dimensions due to compact design and increased dielectric resistance of the gaseous insulating material are also advantages. Gas-insulated switchgear technology in the medium-voltage area has become increasingly significant over the last 15 years.

The numerous designs available on the market can be generally classified into three different application groups:

- switchgear with circuit-breakers
- switchgear with switch-disconnectors and circuit-breakers
- ring-main units

One technical solution for each of these application groups is described below as an example.

Gas-insulated switchgear with circuit-breakers

Fig. 8-24 shows switchgear type ZX1 (for 12, 17.5 and 24 kV) with the versatile options offered by the advanced technology of these new switchgear designs.

The principles used for the application are:

High-precision housing

- The gas-tight housing of the live components is manufactured of stainless steel using laser technology for high-precision cutting and welding. This not only ensures that the housing is gas-tight but also allows the bays to be queued up on site without problems.

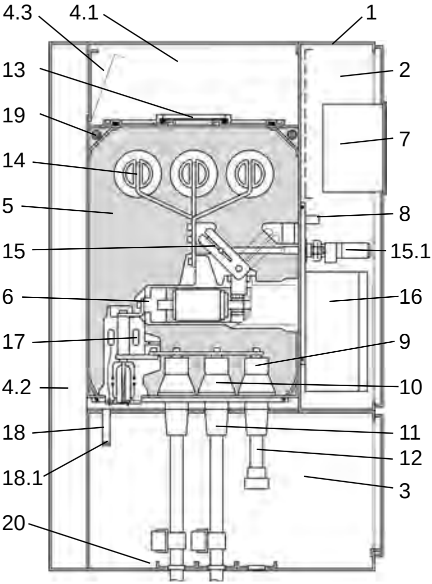


Fig. 8-24 Metal-enclosed gas-insulated switchgear type ZX1 with single busbar system

1	*Panel enclosure, complete*
2	*Secondary compartment*
3	*Cable terminal compartment*
4.1	*Integrated pressure release duct*
4.2	*Pressure release duct, cable terminal compartment*
4.3	*Pressure relief flap*
5	*Core module*
6	*Circuit breaker pole*
7	*Bay control and protection unit REF542*
8	*Pressure sensor*
9	*Cable and test socket*
10	*Cable socket*
11	*Cable plug*
12	*Surge arrester (as example)*
13	*Pressure release plate*
14	*Busbar*
15	*Transfer switch*
15.1	*Transfer switch mechanism*
16	*Circuit-breaker mechanism*
17	*Combined current/voltage sensor with capacitive tap*
18	*Main earthing conductor*
18.1	*Bay/bay earthing connection strap*
19	*Bag of desiccating agent*
20	*Base plate, divided*
▨	*Insulation gas in core module and inside c.-b. pole tube*

Vacuum switching technology

- The application of vacuum switching technology as the quenching principle of the circuit-breaker meets a primary requirement for gas-insulated switchgear: the interruptor unit must be maintenance-free. So far, this requirement is really only met by vacuum interrupters, because of their low contact wear and their high electrical durability. Gas-insulated switchgear for this voltage range with SF_6 circuit-breakers is also available.

Plug connector technology

- The application of plug-in technology is essential for ensuring short assembly times when setting up installations. Several parallel cables can be connected to the commercially available internal conical sockets in the baseplate of the core module. The plug-in technology in the area of the busbar bushings is new but based on the same technology as the cable connectors. These bushings designed as plug connectors are the most important requirement for easy installation of the completed panels. There are additional plug connectors in the supply lines for auxiliary power and in the fibre-optic connections to the higher-order control system, if present.

Sensors for measured quantities and states

- The combined current/voltage sensor has three functions. For current measurement, it has a Rogowski coil, which gives a voltage signal that has a linear dependency on the current and therefore can be used in a very broad current range (e.g. to 1250 A in one type). This not only simplifies planning but also increases the flexibility when modifying installations that are already operating.

  A high-resistance (200 MΩ) voltage divider is used as a voltage sensor. Two bell-shaped screening electrodes ensure equal distribution of the electric field along the resistance. The voltage signal captured at the subresistance of the devider is fed to the bay control unit.

  The earth side of the two screening electrodes is simultaneously used as a capacitive tap to the voltage indicator plugs. It is connected with test sockets on the front of the switchboard to allow checking that the cables are dead independently of the functional availability of the bay control unit.

  The positions of the two switching devices and the ‘ready for switching’ indication of the circuit-breaker mechanism are detected by inductive proximity sensors. A temperature-compensated pressure sensor signals three pressure/density levels, i.e. fill pressure at 20°C, lower operational pressure limit and pressure with internal arcing. All sensor information goes directly to the bay control unit and is displayed and processed there.

Digital bay control and protection unit

- The digital REF542 bay control and protection unit is the base of the intelligence and communications interface of the new switchgear (see also Section 14!)

It has the following functions:

- on site and remote actuation
- display of positions, measured values, protective parameters
- interlocking, internal and external
- protection (all protective functions except for cable differential protection)
- storage of events
- information transmission to a higher-order control system
- monitoring its own functions and the tripping circuits

Faults in the sequence of actuation of circuit-breaker and disconnector/earth switch function of the transfer switch are prevented by interlocking in the REF542. The earthing process can be automatically run by the REF542 as a programmed sequence while retaining the “five rules of safety”. Any required protective functions can be programmed in as software before delivery. Software changes can be made on site at any time with a laptop computer. Parameter changes can be made by pressing buttons on the device itself.

Personnel safety design

A switchgear design such as that of the ZX1 makes the occurrence of faults with internal arcing unlikely from the start. However, the ZX1 offers complete personnel protection in the event of internal arcing. In the case of a fault in the area of the insulating gas, the housing is relieved from excessive stress by the response of the pressure release plate in the pressure release duct, which runs horizontally through all bays and at the end of the installation releases the gas into the open air through an outside wall or into the switchgear installation room via an absorber. The response of the pressure sensor at 0.6 bar overpressure can be used to trip the feeder circuit-breaker immediately without requiring additional components, thereby reducing the arcing time to less than 100 ms. In the event of a fault in the cable terminal area, the pressure is relieved through the back channel into the horizontal pressure release duct.

Double busbar switchgear installations can be designed with the panel type ZX1, in accordance with the two-circuit-breaker method in back-to-back or front-to-front arrangement. Bay variations such as sectionalizer, busbar riser and metering panel are also available.

The most important rating data and the main dimensions of the ZX1 switchgear are shown in Table 8-6.

Table 8-6

Technical limit data and associated minimum panel dimensions of ZX1 type metal-enclosed gas-insulated switchgear

Rated voltage	kV	12	17.5	24
Rated short-duration power-frequency withstand voltage	kV	28	38	50
Rated lightning impulse withstand voltage	kV	75	95	125
Insulating gas	–	N_2	SF_6	SF_6
Rated fill pressure, absolute	bar	1.3	1.3	1.3
Rated current				
– of the busbars	A	... 2000	... 2 000	... 2 000
– of the feeders	A	1 250/2 000	1 250/2 000	1 250/2 000
Rated short-time withstand current (3 s)	kA	... 40	25	25
Minimum panel dimensions				
– width	mm	600/800	600/800	600/800
– depth	mm	1 250/1 300	1 250/1 300	1 250/1 300
– height	mm	1 950	1 950	1 950

As shown in Table 8-6, with 17.5 kV and 24 kV, SF_6 is used as insulating gas while with 12 kV nitrogen (N_2) is used. Nitrogen has the advantage over air that it prevents oxidation of contact surfaces and lubricants.

The switchgear type ZX2 (Fig. 8-25) is suited for "conventional" double busbar substations that have two busbar systems for every switchbay. This switchgear has the same advanced features as described for switchgear type ZX1.

Table 8-7 shows the technical data implemented to date with the associated main dimensions.

Table 8-7

Technical limit data and associated minimum panel dimensions of the ZX2 type metal-clad gas-insulated switchgear

Rated voltage	kV	12	17.5	24	36
Rated short-time power-frequency withstand voltage	kV	28	38	50	70
Rated lightning impulse withstand voltage	kV	75	95	125	170
Insulating gas	–	N_2	SF_6	SF_6	SF_6
Rated fill pressure, absolute	bar	1.3	1.3	1.3	1.3
Rated current					
– of the busbars	A	... 2 500	... 2 500	... 2 500	... 2 500
– of the feeds	A		800/1250/...2500	1250/...2500	
Rated short-time withstand current (3 s)	kA	... 40	... 40	... 40	... 40
Minimum panel dimensions					
– width	mm		400/600//800		600/800
– depth	mm	1 710	1 710	1 710	1 710
– height	mm	2 300	2 300	2 300	2 300

Single-busbar switchgear in the ZX2 design can also be manufactured without the rear busbar system to make full use of the advanced technical data.

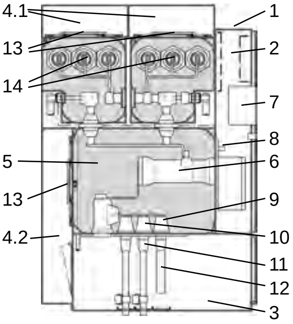


Fig. 8-25 Metal-clad gas-insulated switchgear with double busbar system type ZX2

1	*Panel enclosure, complete*
2	*Secondary compartment*
3	*Cable terminal compartment*
4.1	*Integrated pressure release duct*
4.2	*Integrated pressure release duct*
5	*Core module*
6	*Circuit-breaker pole*
7	*Bay control and protection unit REF542*
8	*Pressure sensor*
9	*Cable and test socket*
10	*Cable socket*
11	*Cable plug*
12	*Surge arrester (as example)*
13	*Pressure release plate*
14	*Busbar systems* ▨ *Insulating gas*

Gas-insulated switchgear with switch-disconnectors and circuit-breakers

Gas-insulated switchgear technology is becoming the subject of increasing interest for distribution systems and smaller industrial consumers. Because the high performance data are not required as with the installations described in the previous section, special switchgear series have been developed for this application. A major characteristic of this application is the use of switch-disconnectors for feeders with cables and overhead lines and in combination with fuses for protection of smaller transformers.

Fig. 8-26 shows cross-sections through variations of the switchgear series ZX0. SF_6 is used as insulating gas and quenching medium for the switch-disconnectors for all rated voltages.

The switch-disconnectors integrated into the panels include the function of the earthing switch for the feeder as a combination device. The contact blades are actuated by the same mechanism for one or the other function depending on the actuation direction. The combination device as switch-disconnector meets the same requirements as a switch-disconnector tested and manufactured as a single unit as per DIN EN 60265-1 (VDE 0670 Part 301). The requirements of DIN EN 60129 (VDE 0670 Part 2) apply for the earthing function (with short-circuit current-making capacity).

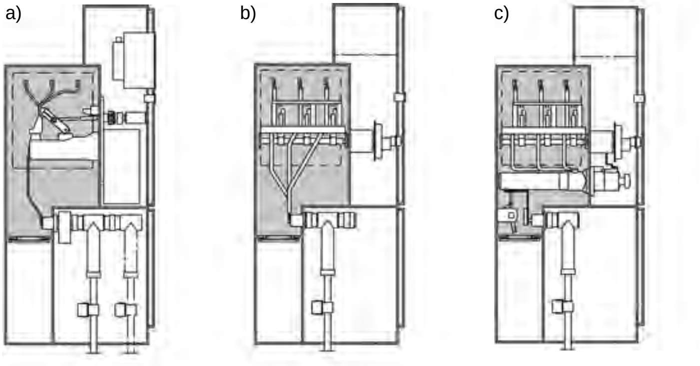


Fig. 8-26

Metal-enclosed gas-insulated switchgear system type ZXO

a) circuit-breaker panel b) switch-disconnector panel c) switch-disconnector panel with fuses

In order to check that the cables are dead before earthing voltage indicator plugs can be inserted into test sockets at the front of the switchboard. These sockets are connected to the taps of field grading electrodes inside the cable-plug bushings.

The circuit-breaker bays of this type of switchgear have vacuum interrupters with a resin coating as arc-quenching systems. This also forms the pivot of the 3-position switch for disconnecting and earthing.

The connected cables are therefore earthed via the circuit-breakers. The REF542 digital bay control and protection unit also controls the actuation, interlocking, display and protection functions in the circuit-breaker panel of the switchgear system ZX0.

Table 8-8 shows limit data and dimensions of the ZX0 type switchgear system.

Table 8-8

Technical limit data and associated minimum panel dimensions of the ZX0 metal-enclosed gas-insulated switchgear system

Rated voltage	kV	12	17.5	24
Rated short-duration power-frequency withstand voltage	kV	28	38	50
Rated lightning impulse withstand voltage	kV	75	95	125
Insulating gas	–	SF_6	SF_6	SF_6
Rated fill pressure, absolute	bar	1.3	1.3	1.3
Rated current				
– of the busbars	A	1 250	1 250	1 250
– of the switch-disconnect. feeder	A	800	800	800
– of the switch-disconnect. feeder with HV fuses	A	200	100	100
– of the circuit-breaker feeder	A	630	630	630
Rated short-time withstand current (3 s)	kA	... 25	... 20	... 20
Panel dimensions				
– width	mm	400	400	400
– depth	mm	850	850	850
– height	mm	1650[1)]/1950[2)]	1650[1)]/1950[2)]	1650[1)]/1950[2)]

[1)] For switchboards without circuit-breaker panels

[2)] For all panels of a switchboard with circuit-breaker panels

Ring-main units for distribution systems

There are two basic designs in use for this purpose:

- modular switchboards with the option of later expansions,
- switchboards with a common gas volume inside a common enclosure with a preset number (e.g. 3 or 4) of feeders.

Fig. 8-27 shows such a type CTC switchboard with common enclosure for all three feeders.

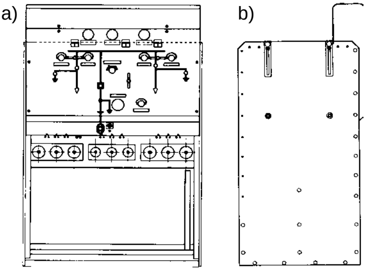


Fig. 8-27

Front view a) and side view b) of the ring-main switchboard type CTC.

SF_6 switch-disconnectors are also used here for switching the connected cables and overhead lines. For protection of transformers, either a vacuum circuit-breaker with electronic protection (type CTC-V, Fig. 8-27) or a switch-disconnector in combination with HV fuses (type CTC-F, same dimensions as CTC-V) can be supplied.

Every switchbay has an earthing switch with specified making capacity to earth the connected cables. In order to check that the cables are dead before earthing voltage indicator plugs can be inserted into test sockets at the front of the switchboard. These sockets are connected to the taps of field grading electrodes inside the cable-plug bushings.

The switch-disconnectors and circuit-breakers of the switchboards can be remotely actuated with motor-operated mechanisms. Table 8-9 shows limit data and dimensions of the CTC gas-insulated ring-main unit.

Table 8-9

Technical limit data and dimensions of the CTC metal-enclosed gas-insulated ring-main unit

Rated voltage	kV	12	17.5	24
Rated short-duration power-frequency withstand voltage	kV	28	38	50
Rated lightning impulse withstand voltage	kV	75	95	125
Insulating gas	–	SF_6	SF_6	SF_6
Rated fill pressure, absolute	bar	1.4	1.4	1.4
Rated current				
– of the cable ring feeder	A	630	400	400
– of the transformer feeder (CTC-F)	A	200	100	100
– of the transformer feeder	A	630	400	400
Rated short-time withstand current (3 s)	kA	20	16	16
Switchboard dimensions				
– width	mm	1 000	1 000	1 000
– depth	mm	760	760	760
– height	mm	1 500	1 500	1 500

8.2.6 Control systems for medium-voltage substations

Conventional secondary technology

A wide range of devices for protection, control and monitoring tasks is available for conventional secondary technology in medium-voltage switchgear installations. The planning engineer selects the required single units and combines them into one installation.

The information on measured values, switchgear status and interference messages is transmitted through parallel wiring from the various medium-voltage bays to a main control desk or a telecontrol system. Records, data storage, graphical measured value processing, help information when faults occur and self-monitoring functions are not possible with this technology.

Microprocessor control systems

The implementation of digital system designed for the requirements of medium-voltage networks allows a number of much more powerful solutions at moderate expense. A system of this type is divided into the bay level, the switchboard level and the control room level (see also Section 14.4!).

At the bay level autonomously operating, modular and multifunction devices that can be adapted for the required protection, control and regulating tasks by appropriate software are used. These monitoring devices are installed directly in the secondary compartment of the medium voltage switchbays. Here, all measured values, switch positions and messages from the bays are acquired, processed and sent over a serial (unified) interface. The device, which operates independently of the next hierarchy level, combines the protective functions, the switching position display, the measured value display and the local operation of the switchgear, which is protected against faulty operation, in one single housing. Its modular design makes it adaptable for the bay-specific protection tasks and selectively or in combination controls functions such as motor protection, overcurrent definite-time protection, over and undervoltage protection, earth fault detection, distance protection, differential protection and alarm description. It has comprehensive self-monitoring functions and also allows events to be sorted by time with real-time stamping.

The REF542 bay control and protection unit is a device of this type. It can optionally be implemented autonomously for one switchbay only or integrated into a higher-order automation control system.

8.3 Terminal connections for medium-voltage installations

8.3.1 Fully insulated transformer link with cables

Plastic-insulated cables and fully insulated (plug-in) cable terminals provide a number of operational improvements in substation design when consistently used at the interfaces between cables and station components. The key component for a new type of cable link, Fig. 8-28, between the power transformer and the switchboard is a multiple transformer terminal, Fig. 8-29, for four parallel power cables. The multiple terminal is designed for a rated voltage of up to 36 kV and enables rated currents of up to 3150 A. It can be retrofitted to all power transformers. In addition to the operational advantages, this technology offers savings because the transformer no longer requires a cable rack. For more information on plug connectors for power cables, see Section 13.2.8.

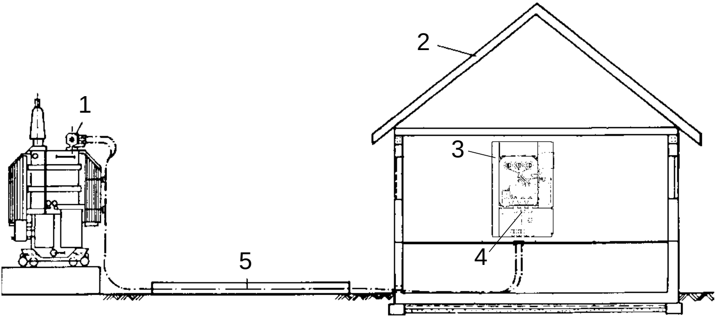


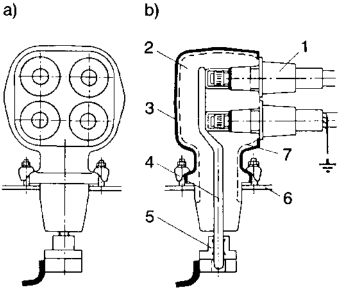
Fig. 8-28

Substation design with fully insulated cable link to the transformer, 1 transformer multiple terminal, 2 substation building, 3 switchboard, 4 cable plug, 5 cable link in protective conduit

Fig. 8-29

View a) and section b) of a transformer multiple terminal

1 Cable connector
2 Moulded resin body with sockets
3 Metal housing
4 Conductor bar
5 Contact system
6 Transformer housing
7 Control shield



8.3.2 SF$_6$-insulated busbar connection

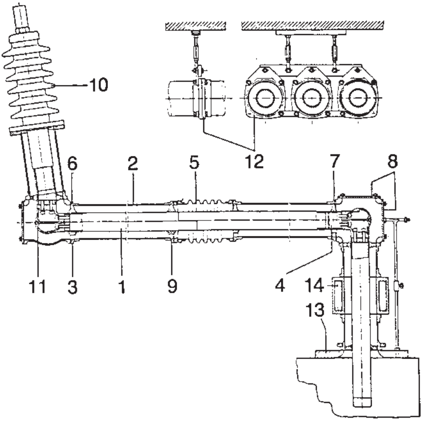
The busbar shown below in Fig. 8-30 is designed for a rated voltage of up to 36 kV and rated currents of up to 3150 A.

The busbar system consists of several individual parts that can be combined to make all required connections. It is suitable for combining busbars of different sections of switchboards and for making connections to power transformers. Use at 12 kV is also possible with the use of N$_2$ as insulating gas.

Fig. 8-30

Sectional view of an SF$_6$-insulated busbar

1. *Inner conductor*
2. *Outer tube*
3. *Flange joint with insulator*
4. *Internal expansion joint*
5. *External expansion joint (metal bellows)*
6. *T-junction enclosure*
7. *Cross-junction enclosure*
8. *Cover with and without connection*
9. *Insulating flange*
10. *Outdoor bushing*
11. *Conductor elbow joint*
12. *Suspension*
13. *Mounting flange*
14. *Current transformer*



8.3.3 Solid-insulated busbar connection

Another option for making busbar connections with low space requirements is to use epoxy-resin-insulated capacitor-controlled single-phase conductors. They are available for service voltage of up to 72.5 kV and for operating current of up to 5000 A.

Design of the busbar system

The preferred conductor material is an aluminium alloy with high mechanical strength and low weight. The insulation (Fig. 8-31) is in direct contact with the conductors, with capacitive control provided by conducting layers at the ends. The covering layer at earth potential is fully embedded in the insulation. For outdoor use the bars are also enclosed in a protective tube.

The bar section lengths are up to 12 m. Single or multiple bends are available as required made to fit the assembly and connection dimensions. The bars are connected rigidly or flexibly to the devices with screw or plug-type joints. Individual lengths are joined with an insulating cylinder. The recommended phase clearances, e.g. 200–300 mm at 2500 A, correspond to the phase spacings of the switchgear. Standard support structures and clamps withstand the short-circuit forces. The earth connections comply with the relevant specifications.

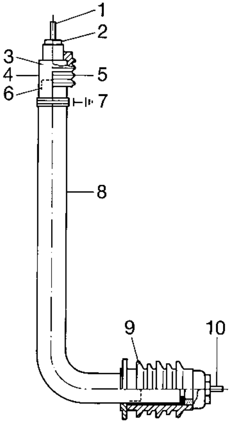


Fig. 8-31

Design of the DURESCA bar for indoor or outdoor use. 1 Indoor connection, 2 Conductor, 3 Insulation, 4 Busbar termination with standard creepage distance, 5 Busbar termination with extended creepage distance, 6 Earth potential layer, 7 Earth connection, 8 Surface finish for indoors: without protective cover, optionally with protective tube or corrugated pipe;
for outdoors: with protective tube or corrugated pipe, 9 Porcelain insulating cover, 10 Outdoor connection

9 High-current switchgear

9.1 Generator circuit-breaker

Generator circuit-breakers are switchgear in the high-current connection between generator and generator transformer. The electrical requirements on generator circuit-breakers are higher in many respects than for breakers in the network. These requirements are specified in the (unique in the world) "IEEE" C37.013 standard in detail (ANSI). The following list summarizes the most important areas of application and the advantages.

Functions	Advantages
Isolate generator from station services infeed	Station services fed via main transformer. No longer requires the formerly standard starting transformers and the associated switchgear components and changeover facilities (see Fig. 9-1a).
Synchronization on the low voltage side of the main transformer	Eliminates voltage transformers on the h.v. side of the main transformer. Possibility of connecting two generators via two separate transformers or one three-winding transformer to one overhead cable simplifies power-plant design (see Fig. 9-1).
Disconnection of a fault in the main transformer or in the station service transformer.	Effects of faults much more restricted than with high-speed de-excitation because it trips in less than 60 ms.
Disconnection of a fault in the generator	Station services remain on the network without interruption, resulting in higher availability. Safe handling of load imbalances.
Disconnection of faults on the overhead lines from the power plant to the next transformer station or substation.	HV circuit-breaker no longer required in power plant if transformers or switchgear installations are near power plant.
Implementation in nuclear power plants.	Significantly improved security of uninterruptable station services supply.
Implementation in pumped-storage power stations.	Switching between pump and generator operation without problem.
Automation of the power plant.	Only 1 switching operation to synchronize or disconnect the generator, instead of 5-7 switching operations when synchronizing on the HV side, resulting in reduction of the danger of switching faults.

In specific cases there can be economic, operational and technical reasons for implementing such breakers.

Fig. 9-1 shows examples of unit connections with generator circuit-breakers. The various types show how these breakers ensure maximum possible availability of station services in the event of a fault for large units with several main and station transformers.

Conventional power plants and nuclear power plants with high unit capacity and special requirements for safety and availability are preferred areas of application for generator circuit-breakers.

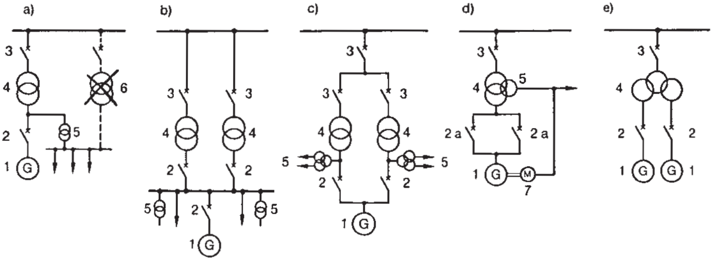


Fig. 9-1

Unit connections of power plants
a) Basic circuit diagram, b) and c) Large generators with part-load transformers, d) Pumped storage block, e) Hydro power plant;
1 Generator, 2 Generator breaker, 2a 5-pole generator breaker for switchover between motor and generator operation, 3 High-voltage circuit-breaker 4 Main transformer, 5 Station services transformer, 6 Starting transformer, 7 Starting motor

The use of generator circuit-breakers must be considered in the early stages of designing a power plant. The following requirements are important when designing the structure:

a) Space required for breaker
   Breaker dimensions; phase spacing (note minimum clearances); transport; access and space for maintenance. Expansion of air-pressure wave (DR-breaker type only).

b) Space required for auxiliaries
   Cooling unit (5-10 m^2, at higher rated currents)
   Control cubicle (2.5-5 m^2)
   Air-compressor plant (10-30 m^2)(DR-breaker type only).
   The auxiliaries must be in the immediate vicinity of the generator circuit-breaker.

c) Structural requirements
   Stable foundation (attend to reaction forces)
   Maintenance pit (under DR-breaker only)
   Lifting gear for installation and maintenance.

Today, generator circuit-breakers are not generally offered as single unit but as a functional unit, which contains the current and voltage transformers required for generator and unit protection inside single-phase enclosures, with disconnectors, shorting links and earthing switches, and also start-up disconnectors, surge arresters and protection capacitors.

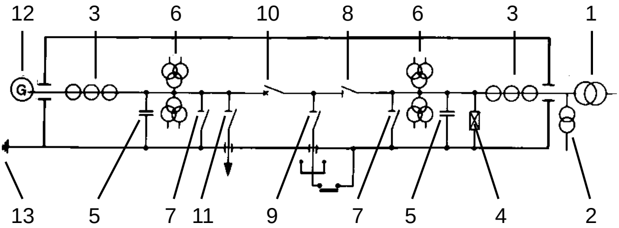
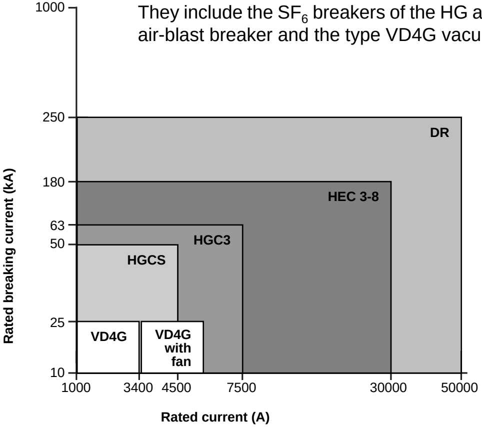


Fig. 9-2

Single-line diagram of a generator circuit-breaker system
1 Main transformer, 2 Station services transformer, 3 Current transformer, 4 Surge arrester, 5 Protection capacitor, 6 Voltage transformer with 1 or 2 secondary windings, 7 Earthing switch, motor-actuated, 8 Series disconnector, motor-actuated, 9 Short-circuit connection with clip for earth connection, 10 Circuit-breaker, 11 Starting circuit-switch, motor-actuated, 12 Generator, 13 Earth

9.1.1 Selection criteria for generator circuit-breakers

Apart from the rated voltage, the most important criteria are the rated current and the rated breaking current of the power unit. ABB supplies several types of generator circuit-breaker, which can be used depending on the unit capacity. They include the SF_6 breakers of the HG and HE range, the DR type air-blast breaker and the type VD4G vacuum breaker.



Rated voltages (IEC)

VD4G:	17.5 kV
HGCS:	17.5 kV
HGC3:	17.5 kV
HEC:	24 - 36 kV
DR:	36 kV

Fig. 9-3 Selection table for generator circuit-breakers

9.1.2 Generator circuit-breaker type ranges HG... and HE...(SF$_6$ gas breaker)

These breaker systems are designed for generator capacities of 100-1000 MVA and – depending on the type – can be used for the voltage levels 17.5-36 kV.
They are suitable for both indoor and outdoor installation.

The power-interruptor chambers of these breakers are filled with SF$_6$ gas as the quenching and insulation material. The arc is interrupted with the proven ABB self-blasting principle: The arc that is generated when the contacts open heats the SF$_6$ gas, increases the pressure and generates a stronger gas flow, which blasts the arc and extinguishes it.
The rotating arc reduces the contact erosion.

The contacts, which carry current continuously, are placed separately from the interrupting contacts, guaranteeing optimum current transfer at all times.

The voltage-carrying components are air-insulated against earth.
The 3-pole design on a common base frame makes installation very simple. Special foundations are not required.

The power chambers are actuated by the proven ABB type AHMA spring mechanism. The energy storage capacity is rated for 2 switching cycles ON-OFF. Disconnector, earthing switch and start-up switch have electric motor-operated mechanisms. They are controlled in accordance with the current requirements in power plant design with conventional relay technology.

The modular design makes it possible to expand the generator circuit-breakers to very compact functional systems with disconnectors, earth switches, transformers etc. (see Figs. 9-2, 9-4). Production and testing of the complete system in factoy greatly reduces the time and expense of assembly and testing at the construction site.

The service intervals, in compliance with the demands of modern power plant design, have been extended to 15 years operational life or 10,000 switching cycles (mechanical). The single-line breaker enclosure is welded to the busduct enclosure. The live parts are bolted to the high-current busduct conductor by way of flexible copper extension straps.

Table 9-1

Technical data for generator circuit-breakers type HG ... and HE ... (SF_6 gas breaker)

Type designation	kV	HGCS	HGC3	HEC3	HEC4	HEC5	HEC6	HEC7	HEC8	HGI2	HGI3	HEK3
Rated voltage as per IEEE/ANSI	kV	15.8	15.8	27.5	27.5	27.5	27.5	27.5	27.5	15.8	15.8	24
Rated voltage as per IEC	kV	17.5	17.5	24	24	24	24	36	36	17.5	17.5	
Rated short-time power frequency withstand voltage												
50/60 Hz 1 min, against earth	kV	50	50	60	60	60	60	80	80	50	50	80
over isolating distance 1)	kV	55	55	70	70	70	70	88	88	–	–	–
Rated lightning impulse withstand voltage												
1.2/50 µs against earth	kV	110	110	125	125	125	125	150	150	110	110	150
over isolating distance 1)	kV	121	121	145	145	145	145	165	165	–	–	–
Rated current,2) 3) natural cooling, 50 Hz	A	4,500	7, 500	12,000	13,000	12,000	13,000	24,000	–	6,300	8,000	11,000
Rated current,2) 3) natural cooling, 60 Hz	A	4, 500	7,300	11,500	12,500	11,500	12,500	24,000	–	–	–	11,000
Rated current,3) with forced ventilation, at 50 +60 Hz	A	–	–	–	24,000	–	24,000	–	28,000	–	–	16,500
Breaking current	kA	50	63	100	100	120	120	160	160	50	63	100
Making current	kA	138	173	300	300	360	360	440	440	138	170	300

1) Only valid for models with disconnector
2) Rated current information corresponding to ambient temperature: max. 40 °C
3) Temperature of the high-current bus ducts at the breaker terminals: conductor max. 90 °C; encapsulation max. 65 °C

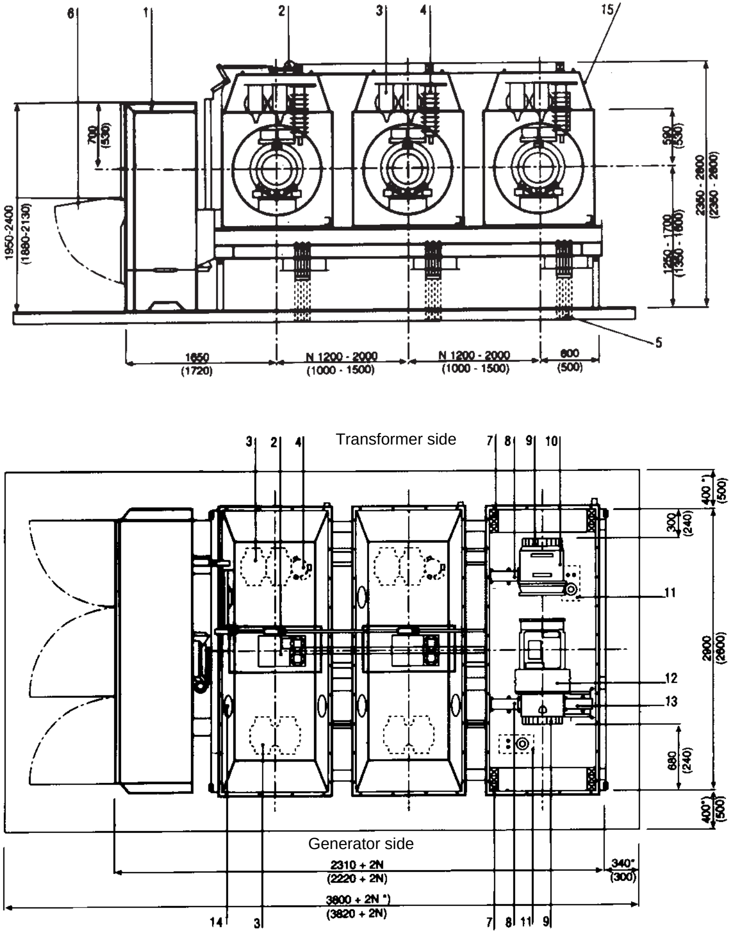


Fig. 9-4

Generator circuit-breaker systems of the HGC (dimensions in parentheses) and HEC range – outline drawing
1 Control cubicle, 2 Short-circuit connection with disconnector, 3 Voltage transformer, 4 Surge arrester, 5 Cable feed to start-up feed, 6 Opening shutter panel to mechanism compartment, 7 Toroidal-core current transformer, 8 Earthing switch, 9 High-current terminal, 10 Series disconnector, 11 Capacitor, 12 SF_6 circuit-breaker, 13 Disconnector to start-up feed, 14 Inspection glass for visual position check, 15 Removable covers for breaker encapsulation, N Variable phase clearance

The HGCS generator circuit-breaker system has a different design from the other systems of this range. It has a switchbay compartmented by phases with all apparatus permanently installed. The circuit-breakers can be slid out.

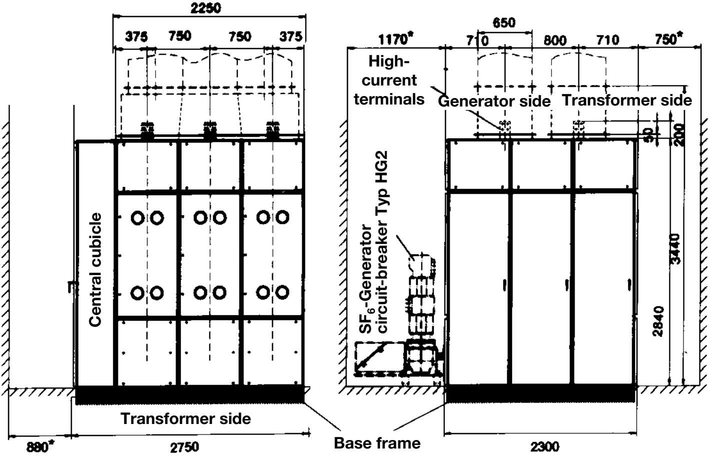


Fig. 9-5 HGCS generator circuit-breaker system/outline diagram
**= Minimum clearances*

The generator circuit-breaker of the **HEK 3** type is particularly well suited for integration into encapsulated busbar systems when retrofitting existing installations. The generator circuit-breakers of the **HGI 2** and **HGI 3** types are available when retrofitting open indoor busbar systems.

9.1.3 Generator circuit-breaker type DR (air-blast breaker)

This breaker type is designed for very large unit capacities up to 2000 MVA and above. The type DR generator circuit-breaker is single-line metal-clad and can be directly integrated into the high-current bus ducts. Both the breaker encapsulation and the breaker live parts are connected to the high-current bus ducts with flexible copper expansion straps.

The cooling components are 100% redundant, so in the event of faults, they can be switched immediately to the standby unit and the power plant can continue operating.

Table 9-2

Technical data for generator circuit-breaker type DR
(see Fig. 9-6)

Type designation		DR 36 v 1750 D
Rated voltage	kV	36
Rated short-time power-frequency withstand voltage 50 Hz, 1 min. against earth	kV	75
Over open isolating distance	kV	100
Rated lightning impulse withstand voltage 1.2/50 µs against earth	kV	170
Over open isolating distance	kV	195
Rated frequency	Hz	50/60
Rated current		
– self-cooling	A	up to 11 000
– forced cooling	A	up to 50 000
Breaking current	kA	250
Making current (peak value)	kA	400-750

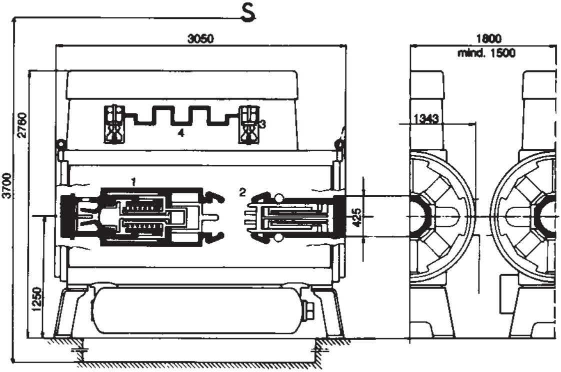


Fig. 9-6
Generator circuit-breaker type DR/outline diagram

1 Circuit-breaker, 2 Linear-travel disconnector, 3 Auxiliary chamber, 4 Low-resistance resistivity

9.1.4 Generator circuit-breaker type VD 4 G (vacuum breaker)

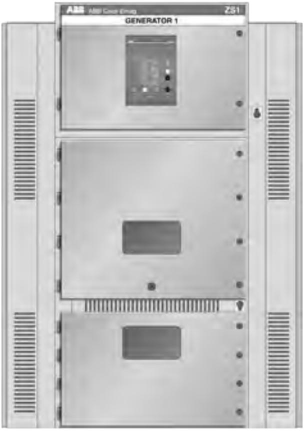
Vacuum circuit-breakers from standard ranges can also be used as generator circuit-breakers with smaller generators (up to 100 MW). These breakers allow very compact solutions. They are used as a fixed-mounted single unit or as a draw-out device within a functional system with metallic compartment walls, earthing switch and disconnector function (segregation) (Fig. 9-5). Current and voltage transformers and surge arresters can also be integrated.

The technical data listed in the following table are based on testing in accordance with ANSI standard IEEE C 37.013-1997.

Table 9-3

Technical data generator circuit-breaker type VD4 G

Type designation		VD4G	
Rated voltage (IEC)		kV	17.5
Rated voltage (ANSI/IEEE)		kV	15.8
Rated short-time power-frequency withstand voltage		kV	50
Rated lightning impulse withstand voltage		kV	(95) 110
Rated current (at 40°C max.)	without fan	A	3400
	with fan	A	5000
Rated breaking current	(system source, symm.)	kA	40
	(generator source)	kA	25/18.5
Rated making current		kA	110



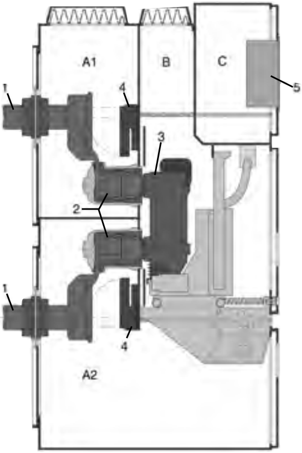


Fig. 9-7 Generator circuit-breaker VD4G

A1	Upper terminal compartment (e.g. transformer)
A2	Lower terminal compartment (e.g. generator)
B	Circuit-breaker compartment
C	Low-voltage compartment

1	Terminal lead
2	Isolating contacts
3	Circuit-breaker
4	Earthing switch
5	Bay control and protection unit REF 542

9.2 High-current bus ducts (generator bus ducts)

9.2.1 General requirements

The high-current bus ducts with all their branches are a component of the electrical installation in the power plant.

The high-current bus duct and switchgear generally serve the following functions (Fig. 9-8).

- Connection between generator and main transformer(s) including generator neutral.
- Branch connections to station services and excitation transformers as well as voltage transformer cubicles.
- Design and connection of measuring, signalling and protection devices for current, voltage and other operating data.
- Installation and connection of high-current switching devices such as generator circuit-breakers with high-current disconnectors and earth disconnectors.
- Additional facilities, e.g. for protection and working earthing, pressure-retaining systems or forced cooling.

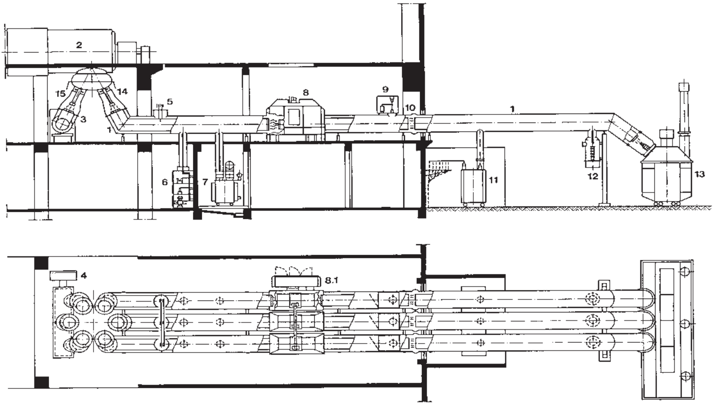


Fig. 9-8 High-current switchgear installation

1 High-current bus duct, 2 Generator, 3 Generator neutral point, 4 Neutral earthing cubicle, 5 Short-circuiting facility (temporary), 6 Voltage transformer cubicle, 7 Excitation transformer, 8 Generator circuit-breaker, HEC type with 8.1 control cubicle, 9 Voltage and capacitor cubicle, 10 Expansion joint, 11 Station auxiliary transformer, Main transformer, 14 Current transformer / feeder side, 15 Current transformer/neutral side

Note: The voltage transformers (6 and 9), the capacitors (9), the earth switch, the short-circuiting facility (5) and the surge arrester (12) can also be installed in the generator terminals.
The configuration of the current transformers (14) must be specified: a) at the generator feed, b) in the busbar run or c) in the generator circuit-breaker, to enable the short-circuiting facility to be located at the proper position.
Consultation with the supplier of the generator circuit-breaker is required.

Technical requirements

The design of the largest generators with nominal voltages of up to 27 kV and power up to 1600 MVA yields operating currents of up to 36 kA. For the high-current bus duct, this means that the generated heat in conductors and enclosure and the significant magnetic field effects in the installation and its environment must be controlled.

With the stated unit capacities and the high network outputs, short-circuit currents of up to approximately 750 kA peak value may occur in the high-current bus ducts and high-current switchgear. In the branches, peak short-circuit currents of more than 1000 kA may occur. And of course the safety and availability of a high-current bus duct must correspond with the high standard of the other power-plant components.

The high-current bus ducts must therefore comply with specified requirements:
- Adherence to preset temperature limits,
- Adequate short-circuit current carrying capability, (thermal and mechanical strength with short-circuits),
- Adequate magnetic shielding,
- Safe insulation, i.e. protection against overvoltages, moisture and pollution.

9.2.2 Types, features, system selection

Types

In smaller power plants (hydropower, CHP stations) with a load current of up to approximately 2.5 kA (5 kA), the bus ducts can still have the "classic" busbar design. The simplest designs are flat and U-shaped busbars of Al or Cu (sometimes also tubular conductors, in Al only). Exposed busbars are used with small generator ratings only because they require locked electrical equipment rooms. In contrast, laying the busbars in a common rectangular aluminium duct provides protection against contact and pollution. Aluminium partitions between the phases provide additional protection. This prevents direct short-circuits between the phases. In the event of short-circuit currents flowing, the compartment walls reduce the short-circuit forces (shielding) on insulators and busbars.

Single-phase systems can be supplied in single-insulator or triple-insulator designs.

The ABB standard is the single-phase system with the following variations:
- up to 5.5 kA in single-insulator design (type HS 5500)
- up to 40 kA in triple-insulator design (type HA)

Features

ABB high-current bus ducts in single-phase enclosure.

The single-phase enclosure is the most commonly supplied and the most technically advanced model. The conductors and the concentrically arranged enclosure around the conductor consist of aluminium tubes and are insulated from each other by an air gap and resin insulators (Fig. 9-9)

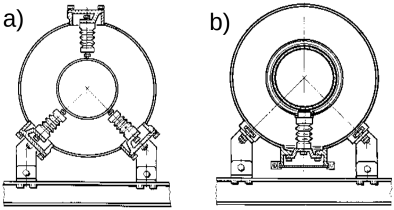


Fig. 9-9
ABB high-current bus duct

a) Single-phase design with three insulators

b) Single-phase design with one insulator

An important technical feature is the single-phase enclosure short-circuited over the three phases at both ends. This enables the enclosures to form a transformer secondary circuit to the conductors. The current flowing in the enclosure – opposite to the conductor current – reaches approximately 95% of the conductor current depending on the system configuration and the impedance of the short-circuit connection between the enclosures (Fig. 9-10)

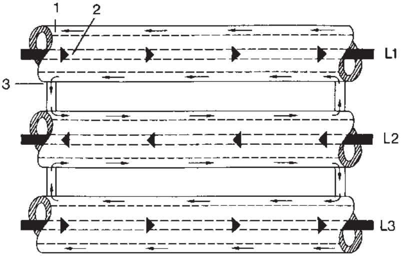


Fig. 9-10

Principle of the high-current bus duct with electrically continuous enclosure,

1 Enclosure current,
2 Conductor current,
3 Enclosure connection

The magnetic field outside the enclosure is almost completely eliminated, thereby eliminating the ambient losses.

This type has the following important features:
- Proof against contact, making locked electrical equipment rooms unnecessary,
- Protection against pollution and moisture, maintenance limited to visual checks,
- No magnetic field outside the enclosure (no induction losses in adjacent conductive material such as screens, railings, concrete reinforcement, pipes etc.),
- Reduced likelihood of ground faults and short-circuits,
- Single-phase high-current switching devices can be incorporated in the bus duct.

The HA type range includes 5 voltage levels – types HA 01 to 05 – for rated current intensities of 3 to 31 kA in self-cooling design (Table 9-5) and currents of up to about 50 kA with forced cooling.

Types HS 5500 for 2 voltage levels, rated currents intensities up to 5.5 kA (Table 9-4) Table 9-6 is applicable for structural planning.

Table 9-4 Single-phase high-current bus ducts types HS 5500

General table for system selection based on current and voltage (natural cooling)

Rated current	Conductor dia. mm	Enclosure dia. mm	Conductor/Enclosure			
			Rated short-time p.-f. withstand voltage 50 (60) Hz 1 min in kV		Rated lightning impulse withstand voltage 1.2/50 µs in kV	
	Type HS 5500	Type HS 5500	Type HS 5500		Type HS 5500	
kA	01 and 02	01 and 02	01	02	01	02
				(36)		(95)
5.5	150	480	28	38	75	95

Notes: For explanations, see Table 9-5
For main dimensions, see Table 9-6

Table 9-5 Single-phase high-current bus ducts type HA

General table for system selection based on current and voltage (natural cooling)

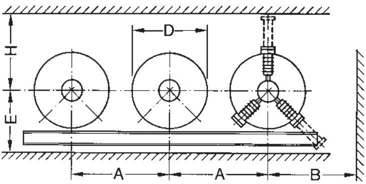
Rated current	Conductor Ø mm	Enclosure Ø mm					Conductor/enclosure Rated short-time p.-f. withstand voltage 50 (60) Hz 1 min in kV					Rated lightning impulse withstand voltage 1.2/50 ms, in kV				
kA	Type HA 01 to 05	Type HA 01	02	03	04	05	Type HA 01	02	03	04	05	Type HA 01	02	03	04	05
3	100	460	460	550	640	730										
5	190	550	550	640	730	820										
8	280	640	640	730	820	910										
10	370	730	730	820	910	1 000		(36)	(60)	(80)	(80)		(95)	(110)	(150)	(150)
12	460	820	820	910	1 000	1 090	28	38	50	70	70	75	95	125	145	170
15	550	—	910	1 000	1 090	1 180										
17	640	—	1 000	1 090	1 180	1 270										
20	730	—	1 090	1 180	1 270	1 360										
22	820	—	—	1 270	1 360	1 450										
24	910	—	—	1 360	1 450	1 540										
26	1 000	—	—	1 450	1 540	1 630										
30	1 000	—	—	—	—	1 720										

Note: test voltages as per DIN EN 60071-1 (VDE 0111, Part 1), Table 2; IEC 600 71-1, Table 2;
( ) values in parentheses according to ANSI C 37.23.
A cooling system is required for currents over 31 kA.

Table 9-6

Main dimensions of the high-current bus duct

Dimension A for
HGCS breaker: 650 mm
HEK 3 breaker: 1400 mm
HEC breaker: 1200 to 2000 mm
DR breaker: 1800 mm and over



Current	Type HA				Type HA					
kA	01 to 05				01	02	03	04	05	05E
	D	A	B	E	H	H	H	H	H	H
	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm
0- 3	460	750	700	500	600	600	—	—	—	—
3- 5	550	850	750	550	650	650	650	—	—	—
3- 8	640	950	800	600	650	650	700	750	—	—
3-10	730	1 000	900	650	700	700	750	800	850	—
3-10	820	1 100	950	700	750	750	800	850	900	950
5-12	910	1 200	1 000	750	800	800	850	900	950	1 000
8-15	1 000	1 300	1 050	800	850	850	900	950	1 000	1 050
10-17	1 090	1 400	1 100	850	900	900	950	1 000	1 050	1 100
12-17	1 180	1 500	1 150	900	950	950	1 000	1 050	1 050	1 100
15-20	1 270	1 600	1 200	950	1 000	1 000	1 050	1 100	1 100	1 150
17-22	1 360	1 700	1 250	1 000	1 050	1 050	1 050	1 100	1 150	1 200
20-24	1 450	1 800	1 300	1 050	1 100	1 100	1 100	1 150	1 200	1 250
22-26	1 540	2 000	1 400	1 100	1 100	1 100	1 150	1 200	1 250	1 300
24-26	1 630	2 100	1 450	1 150	1 150	1 150	1 200	1 250	1 300	1 350
26-30	1 720	2 300	1 500	1 200	1 200	1 200	1 250	1 300	1 350	1 400
	Type HS 5500									
to 5.5	480	600	700	500	650	650	—	—	—	—

9.2.3 Design dimensions

Criteria for rating a high-current bus duct:

- service voltage
- load current
- operating temperatures
- insulation level
- short-circuit current carrying capability
- supplementary requirements for installed components and equipment
- climatic conditions

The dielectric strength (rated short-time p.-f. withstand and rated lightning impulse withstand voltage) is assured by standardized type-sized air clearances between conductor and enclosure, and by standard insulators as per VDE, DIN and IEC and the assigned voltage levels with the test voltages as per DIN EN 600 71-1 (VDE 0111 Part 1).

The test voltages for BS and ANSI are covered by the clearances provided (Table 9-4, 9-5).

The standardized type range and the connections at components of the power plant such as generator and transformer are rated for minimum clearances as per VDE and IEC. Verification by test is not required.

Computers are used for optimum and economical design of sizes and wall thicknesses for conductor and enclosure on the basis of a comprehensive heat network; with full or partial ventilation of the bus duct, this program is also used to design the cooling system. The standard rating is based on maximum limit temperatures with an ambient temperature of 40°C:

Enclosure 65 °C – 80 °C; conductor 90 °C – 105 °C.

These values comply with all corresponding VDE, IEC and ANSI standards.

The short-circuit current carrying capability of the bus duct includes adequate provision for peak short-circuit and short-time current. Only one short-circuit current – either from the generator or from the system side – can occur on the main conductor, but in the branches, the sum of the two short-circuit currents must be taken into account. The single-phase enclosure design reduces the likelihood of a short-circuit by many times.

The main duct design for the rated current inevitably has a short-circuit current carrying capability by that far exceeds the rated value dynamically and thermally.

However, the branch ducts are dimensioned primarily for peak and short-time current withstand in compliance with the ABB short-circuit calculations and the requirements of the relevant standards (Section 3 and 4). This automatically ensures compliance with the permissible temperatures at load current.

9.2.4 Structural design

Conductors and enclosure are of Al 99.5% sheet (DIN 40501), which is rolled and submerged-arc welded. Conductors of up to 370 mm diameter are used in the form of extruded aluminium tubes only. To improve thermal dissipation, the conductors are painted on the outside and the enclosures inside and outside.

The prefabricated assemblies have a maximum length of about 12 m. The length depends on the feasibility of transport and the access and installation conditions on the construction site.

Each support of the conductor consists of one or three post insulators – in exceptional cases of four –, which are mounted from outside. Sliding surfaces or fixed pins on all insulators of each support and a spring arrangement on one insulator per support allow relative axial movements between the conductor and the enclosure.

The single-insulator system has been designed to carry currents in the range of 3 to 5.5 kA with the greatest possible safety with the compact design requiring the smallest possible space. The single-insulator system offers all the advantages of single-phase enclosed bus ducts (three-insulator system). In addition, the use of one freely accessible post insulator around the enclosure makes the assembly easier in very small spaces.

Post insulators and holder ring are manufactured from moulded resin and provide support for the conductor and retain the air gap between conductor and enclosure.

The enclosure supports are independent of the support of the conductor and are designed as sliding or fixed-point, fastened directly to the support structure. The tube profile allows distances of enclosure supports of 10-20 m depending on the system.

All connections to the generator, to transformers and switchgear not only ensure secure electrical connection but also allow adjustment, accommodation of thermal movements and access to the junction points. The enclosure structure is particularly important at the generator terminals because of the small spaces between them. In small and medium-sized installations, three-phase terminal and neutral compartments with hatches and viewing windows allow inspection and access to the connections. At higher rated currents, only the single-phase enclosed bus duct construction provides sufficient magnetic field compensation, prevents eddy currents and therefore ensures controlled temperature conditions.

The conductors are connected to the generator, transformers and switchgear terminals with flexible press-welded copper straps fastened with bolts. Spring washers with high spring travel and force guarantee the required contact pressure and prevent unacceptable temperature rise. The contact surfaces are silver-coated if required by the conductor limit temperature (IEC and ANSI).

Current transformers for measurement and protection of the toroidal core type are either installed at the generator terminal bushings or integrated into the bus duct at a suitable point. Detachable connections are then to be integrated into the main conductor for installation and removal. Voltage transformers can be incorporated into the bus duct or installed in separate instrument cubicles connected by branch ducts. The same applies for protection capacitors for limiting capacitively transmitted voltages.

Surge arresters protect bus duct and generator, even in the event of flashover in the transformer, but are then usually overstressed. The use of housings with pressure relief will ensure the safety of personnel and the installation.

9.2.5 Earthing system

The design of earthing systems for high-current bus ducts is based on VDE 0141 and more recently VDE 0101, which also comply with the other national and international standards (such as IEC, ANSI, BS). The maximum anticipated double ground-fault current can be calculated as follows:

$$I''_{\mathrm{K\,EE}} = \frac{\sqrt{3}}{2} \cdot I''_{\mathrm{K\,3}}$$

The minimum cross section A_E for the main earthing conductor as per VDE 0103 is calculated as follows:

$$A_{\mathrm{E\,min.}} = \frac{I''_{\mathrm{K\,EE}} \cdot 10^3 \cdot \sqrt{m+n}}{S_{\mathrm{thn}} \cdot \sqrt{\frac{1}{T_K}}}$$

The earthing system of the ABB high-current bus duct uses the enclosure of the three phases as the earthing conductor. The separate conductors are restricted to connecting the enclosure to the earth terminals on the generator, the transformers and the connection to the power plant earthing system. All components outside the busbar run such as cubicles etc. are connected to the enclosure and so are earthed "by spurs". See Section 5.3 for additional information on earthing.

Note:

When installing generator circuit-breakers, the earth switch and the short-circuiting facility are integrated into the generator circuit-breaker.
For detailed information, see generator circuit-breakers in Section 9.1!

9.2.6 Air pressure/Cooling system

Operational reliability can be further improved by supplying the high-current bus duct with filtered dry air. The resulting overpressure of 500 Pa (max. 2000 Pa) allows air in the bus duct to pass from inside to outside only, preventing contamination. The dry air also prevents the formation of condensation. The incoming air is drawn through a reducing valve and a gas meter from the power plant compressed-air system with or without a dryer and water separator, or from a circuit-breaker compressor, see also Section 15.5 Compressed-air system.

Forced ventilation of the high-current bus duct at 31 to max. 50 kA is of the closed loop type with an air-water heat exchanger for cooling. The ABB cooling unit is installed under the bus duct as close to the middle as possible. The air is blown into the outer phases by fans and diverted to the middle phase at the end by control dampers and deionizing screens via a connecting duct, in which it flows back to the cooling unit at twice the speed. The closed circuit air-cooling system is 100% redundant, allowing the system to be switched to the standby fan and cooler immediately when necessary. If the cooling system fails, the availability of the high-current bus duct is still 50–70%, depending on the design. Fig. 9-11 shows the air flow diagram of a high-current bus duct.

The limited space in the generator terminal area and the requirement to be able to work with smaller dimensions may require cooling with a single-pass airflow below 31 kA.

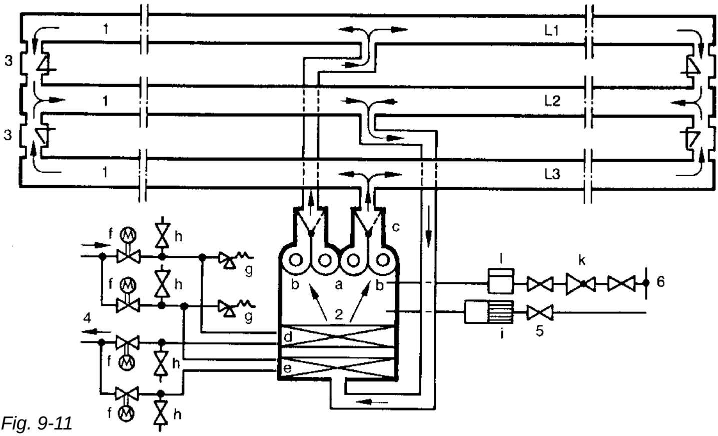


Fig. 9-11

Cooling-air flow diagram for a high-current bus duct, 1 High-current bus duct, 2 Cooling unit with fans a; Standby fans b; Dampers on standby fan c; Cooler d and standby cooler e; 3 Damper valves for flow distribution, deionization screens, 4 Cooling water circulation with motor-operated valves f for cooler and standby cooler (flow and return) with safety valves g; Vent and discharge valves h; 5 Make-up air with filter-dryer element i; 6 Alternative to 5: Make-up air from the compressed air system via reducing valve k and air meter l.

10 High-voltage apparatus

10.1 Definitions and electrical parameters for switchgear

Disconnectors are mechanical switching devices which provide an isolating distance in the open position. They are capable to open or close a circuit if either a negligible current is switched or if there is no significant change in voltage between the terminals of the poles. Currents can be carried for specified times under normal operating conditions and under abnormal conditions (e.g. short circuit). Currents of negligible quantity have values $\leqq$ 0.5 A; examples are capacitive charging currents for bushings, busbars, connections, very short lengths of cable and currents of voltage transformers.

Isolating distances are gaps of specified dielectric strength in gases or liquids in the open current paths of switching devices. They must comply with special conditions for the protection of personnel and installations and their existence must be clearly perceptible when the switching device is open.

Switches are mechanical switching devices, which not only make, carry and interrupt currents under normal conditions in the network but also must carry for a specific time and possibly make currents under specified abnormal conditions in the network (e.g. short circuit).

Switch disconnectors are switches which satisfy the requirements for an isolating distance specified for a disconnector in their open position.

Circuit-breakers are mechanical switching devices able to make, carry and interrupt currents occurring in the circuit under normal conditions, and can make, carry for a specified time and break currents occurring in the circuit (e.g. short circuit) under specified abnormal conditions.

Earthing switches are mechanical switching devices for earthing and short-circuiting circuits. They are capable of carrying currents for a specified time under abnormal conditions (e.g. short circuit). They are not required to carry normal operating currents. Earthing switches for transmission networks may also be required to make, carry and break induced currents (capacitive and inductive) under normal circuit conditions. Earthing switches with short circuit making capability shall be able to make the short-circuit current.

Fuses are switching devices that open the circuits in which they are installed by the melting of one or more parts specified and designed for the purpose of breaking the current when it exceeds a given value for a sufficiently long period.

Auxiliary switches must be rated for a continuous current of at least 10 A and be capable to break the current of the control circuits. The manufacturer must provide details. In the absence of such information, they must be capable of breaking at least 2 A at 220 V d.c. at a minimum circuit time constant of 20 ms. The terminals and wiring in auxiliary circuits must be designed for at least 10 A continuous current. The auxiliary switches that are actuated in connection with the main contacts must be directly actuated in both directions.

Electrical characteristics

(Peak) making current: peak value of the first major loop of the current in one pole of a switching device during the transient period following the initiation of current during a making operation.

Peak current: peak value of the first major loop of current during the transient period following initiation.

Breaking current: current in one pole of a switching device at the instant of initiation of an arc during a breaking process.

Breaking capacity: value of the prospective breaking current that a circuit-breaker or load switch can break at a given voltage under prescribed conditions for application and performance; e.g. overhead line (charging current) breaking capacity.

Short-line fault: short circuit on an overhead line at a short but not negligible distance from the terminals of the circuit-breaker.

Out of phase (making or breaking) capacity: making or breaking capacity for which the specified conditions for use and behaviour include the loss or the lack of synchronism between the parts of an electrical system on either side of the circuit-breaker.

Applied voltage: voltage between the terminals of a circuit-breaker pole immediately before making the current.

Recovery voltage: voltage occurring between the terminals of a circuit-breaker pole after interruption of the current.

Opening time: interval of time between application of the auxiliary power to the opening release of a switching device and the separation of the contacts in all three poles.

Closing time: interval of time between application of the auxiliary power to the closing circuit of a switching device and the contact touch in all poles.

Break time: interval of time between the beginning of the opening time of a switching device and the end of the arcing time.

Make time: interval of time between application of the auxiliary power to the closing cuircuit of a switching device and the instant in which the current begins to flow in the main circuit.

Rated value: value of a characteristic quantity used to define the operating conditions for which a switching device is designed and built and which must be verified by the manufacturer.

Rated normal current: the current that the main circuit of a switching device can continuously carry under specified conditions for use and behaviour. See below for standardized values.

Rated short-time withstand current: current that a switching device in closed position can carry during a specified short time under prescribed conditions for use and behaviour. See below for standardized values.

Rated voltage: upper limit of the highest voltage of the network for which a switching device is rated. See below for standardized values.

Additional rated values:
rated withstand current,
rated making current,
rated short-circuit breaking capacity etc.

Standard value: rated value based on official specifications to be used for designing a device.

Standardized rated voltages: 3.6; 7.2; 12; 17.5; 24; 36; 52; 72.5; 100; 123; 145; 170; 245; 300; 362; 420; 550; 800 kV.

Standardized rated normal currents: 200; 250; 400; 500; 630; 800; 1000; 1250; 1600; 2000; 2500; 3150; 4000; 5000; 6300 A.

Standardized rated short-time currents: 6.3; 8; 10; 12,5; 16; 20; 25; 31,5; 40; 50; 63; 80; 100 kA.

Rated insulation level: standardized combination of the rated values for the lightning impulse withstand voltage, the switching impulse withstand voltage (if applicable) and the short-time power frequency withstand voltage assigned to a rated voltage. As standardized insulation level, only combinations of values from one and the same line of Table 10-1 are valid.

Rated short-duration power frequency withstand voltage: rms value of the sinusoidal a.c. voltage at operating frequency that the insulation of a device must withstand under the specified test conditions for 1 minute.

Rated lightning impulse withstand voltage: peak value of the standard voltage surge 1.2/50 µs that the insulation of a device must withstand.

Rated switching impulse withstand voltage: peak value of the unipolar standard voltage surge 250/2500 µs which the insulation of a device with a rated voltage of 300 kV and above must withstand.

Note:

For disconnectors and specific (asynchronous) circuit-breakers for rated voltages of 300 kV and above, the isolating distances or breaker gaps are tested with combined voltage so that the power frequency test voltage (Table 10-1, peak values in parentheses) is applied at one terminal and the counterpolar test surge voltage (lightning or switching) occurs in the time range of the maximum voltage at the other terminal. The test with combined voltage was originally known as the bias test.

Table 10-1

Standardized rated insulation level for disconnectors, switches, circuit-breakers and earthing switches according to DIN EN 60 694 (VDE 0670 Part 1000)

Rated voltage kV (rms value)	Rated short-duration power frequency withstand voltage kV (rms value)		Rated lightning impulse withstand voltage kV (peak value)	
	Phase to earth, between the phases and across the open breaker gap	Across the isolating distance	Phase to earth, between the phases and across of the open breaker gap	Across the isolating distance
1	*2*	*3*	*4*	*5*
3.6	10	12	20	23
			40	46
7.2	20	23	40	46
			60	70
12	28	32	60	70
			75	85
17.5	38	45	75	85
			95	110
24	50	60	95	110
			125	145
36	70	80	145	165
			170	195
52	95	110	250	290
72.5	140	160	325	375
100	150	175	380	440
	185	210	450	520
123	185	210	450	520
	230	265	550	630
145	230	265	550	630
	275	315	650	750
170	275	315	650	750
	325	375	750	860
245	360	415	850	950
	395	460	950	1 050
	460	530	1 050	1 200

(continued)

Table *10-1 (continued)*

Rated voltage kV (rms value)	Rated short-duration power frequency withstand voltage kV (rms value)		Rated lightning impulse withstand voltage kV (peak value)		Rated switching impulse withstand voltage kV (peak value)		
	Phase to earth and between the phases	Across the open breaker gap and/or isolating distance	Phase to earth and between the phases	Across the open breaker gap and/or isolating distance	Phase to earth and across the open breaker gap	Between the phases	Across the isolating distance
1	*2*	*3*	*4*	*5*	*6*	*7*	*8*
300	380	435	950	950 (+ 170)	750	1 125	700 (+ 245)
			1 050	1 050 (+ 170)	850	1 275	
362	450	520	1 050	1 050 (+ 205)	850	1 275	800 (+ 295)
			1 175	1 175 (+ 205)	950	1 425	
420	520	610	1 300	1 300 (+ 240)	950	1 425	900 (+ 345)
			1 425	1 425 (+ 240)	1 050	1 575	
550	620	800	1 425	1 425 (+ 315)	1 050	1 680	900 (+ 450)
			1 550	1 550 (+ 315)	1 175	1 760	
800	830	1 150	1 800	1 800 (+ 455)	1 300	2 210	1 100 (+ 650)
			2 100	2 100 (+ 455)	1 425	2 420	

The values in parentheses are the peak values of the a.c. voltage applied to the opposite terminal.

10.2 Disconnectors and earthing switches

Disconnectors are used for galvanic isolation of networks or sections of switchgear installations. As an independent air-insulated device, they form a visible isolating distance in their open position. They are suitable for switching small currents (< 0.5 A) or also larger currents if the voltage does not change significantly between the contacts of a disconnector pole during switching (commutation currents).

Disconnectors can carry currents under operating conditions continuously and under abnormal conditions, such as short circuit, for a specified time (1s, 3s).

More than 10 different designs are in use around the world. The most important are rotary disconnectors, two-column vertical break disconnectors and single-column disconnectors.

Earthing switches are used for earthing and short-circuiting deenergized station components. Earthing switches can withstand currents during a specified time (1s, 3s) under abnormal conditions, such as a short circuit, but they are not required to carry continuous operating currents.

In general, earthing switches are combined with the adjacent disconnectors to form one unit. However, earthing switches can also be installed separately.

The applicable standard for disconnectors is DIN EN 60 129 (VDE 0670 Part 2). IEC 61128 is specifically applicable for switching commutation currents with disconnectors.

DIN EN 60 129 (VDE 0670 Part 2) is also applicable for earthing switches. In addition, DIN EN 61 129 (VDE 0670 Part 212) shall be considered with reference to switching induced currents.

Selection of the disconnector design is primarily guided by the layout of the installation (structural design), see Section 11.3.3. The ABB disconnector range can cover virtually all important layout variations in the ranges 72.5 to 800 kV, (rated voltage), 1250 to 4000 A (rated current) and 63 to 160 kA (rated peak withstand current).

10.2.1 Rotary disconnectors

Two-column rotary disconnectors SGF

This disconnector type is used by ABB for rated voltages of 72.5 to 420 kV (in individual cases also for 525 kV), preferably in smaller installations and also in larger switchgear installations as incoming feeder or sectionalizing disconnector. An earthing switch can be installed on both sides.

As shown in Fig. 10-1, the two rotating bases are mounted on a sectional steel frame and connected by a braced tie-rod. The insulators (post insulators) are fixed to the rotating bases and carry the swivel heads with the arms and the high-voltage contacts. Both arms swivel 90 degrees with their insulators during the switching movement.Two-column rotary disconnectors in their open position form a horizontal isolating distance. The rotary bases are weather protected and have maintenance-free ball bearings. The rotary bases are fastened on stay bolts, which allow precise adjustment of the contact system after the lines have been rigged and also compensate the insulator tolerances.

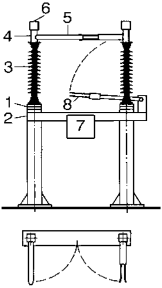


Fig. 10-1

Two-column rotary disconnector type SGF 123 kV, 1 Rotating base, 2 Frame, 3 Post insulator, 4 Rotating head, 5 Contact arm, 6 High-voltage terminal, 7 Mechanism, 8 Earthing switch

The swivel arms are an aluminium-welded construction with non-corroding contact joints, thereby eliminating any long-term changes in resistance. Disconnectors ≥ 170 kV have an interlocking mechanism (pawl and pin). This prevents the contacts from opening at high short-circuit currents. The current in the maintenance-free swivel heads, which are protected against external influences, is transferred via contact fingers arranged in a tulip shape around two contact pins, or for operating currents > 2500 A via tapered roller contacts. The high-voltage contacts can be rotated 360 degrees, allowing the tube or wire runs to be connected in any direction. The contact system has separately sprung contact fingers with no exposed springs.

The disconnectors and earthing switches have an operating mechanism with dead-centre interlocking. This prevents its position from being changed by extreme external influences, such as short circuits, earthquake or high winds. Disconnectors and earthing switches have separate mechanisms. For rated voltages of up to 300 kV, a three-pole disconnector or earthing switch group is generally actuated with one mechanism each. The individual poles of one group are mechanically linked by a connecting rod. The torque is transferred by the mechanism to a rotating base and rotates it by 90 degrees. The tie-rod rotates the second rotating base simultaneously. The contacts make both a rotary and a sliding movement when opening and closing the disconnector. This easily breaks heavy icing. The torque of the earthing switch is transferred to the shaft of the earthing switch. On closing, the arm of the earthing switch swivels upwards and meets the earthing contact attached to the swivel arm.

Three-column rotary disconnectors TDA

These ABB disconnectors are primarily used outside Europe with a side-by-side configuration of the three poles of a group. In comparison to two-column rotary disconnectors, they allow smaller pole spacings and higher mechanical terminal loads.

The two outer insulators are fixed to the base frame and carry the contact system (Fig. 10-2). The middle insulator is fastened to a rotating base and carries the one-piece arm, which rotates approximately 60 degrees during a switching operation and engages the contact systems on the outer insulators. The earthing contacts of the earthing switches, which can be mounted on either side, are located at the fixed contact system.

The three-column rotary disconnectors have the same components as the two-column rotary disconnectors described above. The same information applies for contact arm, swivel bases, contact system and interlocking mechanism, centre-point interlock, earthing switch and mechanical connection of the poles.

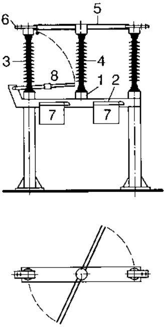


Fig.10-2

Three-column rotary disconnector type TDA, 145 kV, 1 Swivel base, 2 Frame, 3 Post insulator, 4 Rotating insulator, 5 Contact arm, 6 High-voltage terminal, 7 Mechanisms, 8 Earthing switch

10.2.2 Single-column (pantograph) disconnector TFB

In installations for higher voltages (≥ 170 kV) and multiple busbars, the single-column disconnector (also referred to as pantograph or vertical-reach disconnector) shown in Fig. 10-3 requires less space than other disconnector designs. For this reason and because of the clear station layout, it is used in many switchgear installations. The switch status is clearly visible with the vertical isolating distance.

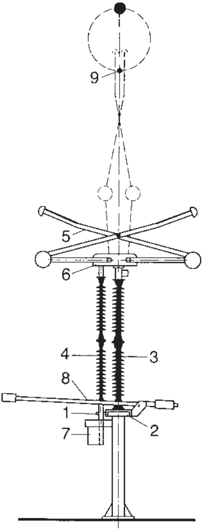


Fig.10-3

Single-column disconnector type TFB 245 kV, 1 Rotating bearing, 2 Frame, 3 Post insulator, 4 Rotating insulator, 5 Pantograph, 6 Gearbox, 7 Mechanism, 8 Earthing switch, 9 Fixed contact

The base of the disconnector is the frame, which holds the post insulator carrying the head piece with the pantograph and the gearbox. The actuating force is transferred through the rotating insulator to the gearbox. The suspended contact is mounted on the busbar situated above the disconnector. On closing, it is gripped between the pantograph arms. During the closing movement, the pantograph arms swivel through a wide range and are therefore capable of carrying the fixed contact even under extreme position changes caused by weather conditions. The feeder line is connected to the high-voltage terminal of the gearbox. In general, the single-column disconnector allows higher mechanical terminal loads than the two-column rotary disconnector.

The frame with the rotary bearing for the rotating insulator is fastened to the support with four stay bolts. They allow the disconnector to be accurately adjusted relative to the suspended contact.

The pantograph is a welded aluminium construction. It is fixed to the gearbox with the pantograph shaft by pins, preventing the pantograph unit from moving during the entire lifetime. This also ensures long-term high contact pressure between the contacts of the pantograph and the fixed contact. A contact force of 700 to 1500 N (depending on the pantograph design) not only ensures secure current transfer but also breaks heavy icing. Tapered roller contacts transfer current from the gearbox to the lower pantograph arms and make the connection from the lower to the upper pantograph arm.

The contact bars on the top of the pantographs and the fixed contact are silver-coated copper, for heavy duty or special cases they have a fine silver inlay. This results in low contact erosion, good current transfer and long service intervals.

Disconnectors for high short-circuit currents have a damping device between the arm joints. In the event of a short circuit, it prevents any reduction in the contact pressure and damps the oscillations of the pantograph caused by the short-circuit current.

The single-column disconnectors have a centre-point interlock in the gearbox and therefore cannot change their position spontaneously. It retains the switch position in any case, even if the rotating insulator breaks or if the disconnector is subjected to extreme vibrations caused by earthquakes or short-circuit forces. Anti-corona fittings on the ends of the arms act as a stop for the suspended contact if it moves in a vertical direction. Even under high tensile forces, it is securely held in the contact zone in the event of a short circuit.

Special designs of single-support disconnectors have been used in installations for high-voltage direct current transmission (HDVC) for many years.

A rotary-linear earthing switch (Section 10.2.4) can be installed on every disconnector pole.

In general, single-column disconnectors and the associated earthing switches are actuated by one mechanism each per pole.

Suspended contact for commutating current switching with single-column disconnector (bus-transfer current switching)

When switching between busbars without current interruption in outdoor switchgear installations, commutation currents occur during the switching operation and cause increased contact erosion on the contact bars of the disconnector and on the suspended contact. The height of the currents depends on the distance of the switching location from the power supply and the type of switchover, i.e. whether between busbars or switch bays, with the latter causing the higher stress. The commutation voltage can be calculated.

Commutation processes occur both on closing and opening. Closing causes bouncing between the contact bars and the suspended contact, which causes only slight arcing and a low degree of contact erosion. However, opening causes arcing between the opening contact bars that continues until the inverse voltage for quenching the arc has been generated. Because of the slow start of the movement of the contact bars, this process lasts for several cycles and causes significant stress on the disconnector contacts. Heavy-duty 420-kV outdoor switchgear installations can have commutation voltages up to 300 V and commutation currents to approximately 1500 A.

The ABB-developed commutation suspended contact for single-column disconnectors has two independently operating enclosed auxiliary switching systems. This ensures proper function in every case, regardless of which of the two contact bars on the pantographs is first to touch or last to leave the suspended contact. The most important components are illustrated in Figs. 10-4 and 10-5. The auxiliary switching system built into an anti-corona hood consists of a spring contact – connected to the auxiliary contact bar by a toggle lever – and a deion arc-quenching device. The spring contact is opened and closed independently of the switching speed at a defined position of the auxiliary contact bar.

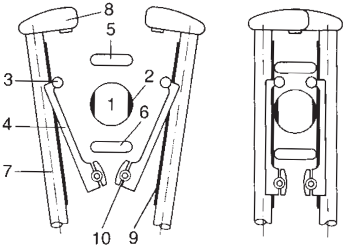


Fig.10-4

Commutating suspended contact, operating principle of guide strips,
1 Main contact support, 2 Main contact bar, 3 Auxiliary contact bar, 4 Toggle lever, 5 Upper guide strip, 6 Lower guide strip, 7 Pantograph arm, 8 Catch device, 9 Pantograph contact bar, 10 Insulated pivot with reset spring

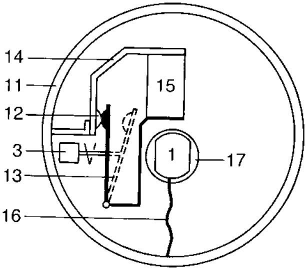


Fig.10-5

Commutating suspended contact, schematic diagram of auxiliary switching chamber,
1 Main contact support, 3 Auxiliary contact bar, 11 Anti-corona hood, 12 Fixed contact, 13 Spring contact, 14 Arc-deflecting baffle, 15 Deion arc-quenching plates, 16 Flexible connection for equipotential bonding, 17 Rotary bearing

Because the arc only lasts for about 25 ms on average during opening, the contact erosion on the spring contact system remains slight and the current is safely interrupted before the pantograph contact bar separates. Separating the main and auxiliary contact systems keeps the latter completely free from the effects of forces resulting from a short circuit. Short-circuit testing has confirmed a peak withstand current strength of 200 kA. Each switching system can take at least 350 switching cycles at commutation currents up to 1600 A and commutation voltages up to 330 V.

Installing commutation suspended contacts provides the system operator with flexibility and reliability of operation. Older installations can be upgraded by replacing the suspended contacts. Installations with switchgear from other manufacturers can also be retrofitted with ABB commuting suspended contacts.

10.2.3 Two-column vertical break disconnectors

This type of disconnector is preferred for higher voltages (≥ 170 kV) as a feeder or branch disconnector (at 1 1/2 circuit-breaker structure, Section 11.3.3). It differs from two-column rotary disconnectors by smaller phase spacings (with side-by-side configuration) and higher mechanical terminal loads. In its open state, there is a horizontal isolating distance with the contact arm open upwards.

As shown in Fig. 10-6, the two post insulators are mounted on a frame. The gearbox with contact arm and high-voltage terminal and the fixed contact with high-voltage terminal are mounted on them. The rotating insulator fastened to the rotary bearing transfers the actuating force to the gearbox, which transmits the force into a torque for opening the contact arm.

Each side of the disconnector can be fitted with an earthing switch (Section 10.2.4) depending on the requirements. The associated earthing contacts are installed on the gearbox or on the fixed contact.

For rated voltages of up to 245 kV one mechanism per three-phase disconnector or earthing switch group is sufficient, at higher nominal voltages one mechanism per pole is generally used.

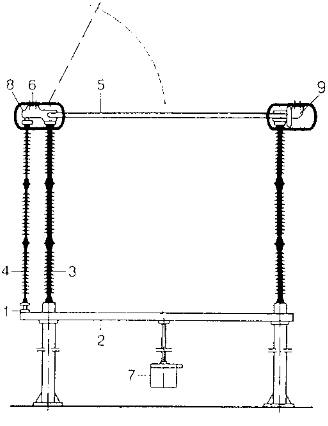


Fig.10-6

Vertical break 525 kV,
1 Rotary bearing, 2 Frame, 3 Post insulator, 4 Rotating insulator,
5 Contact arm, 6 High-voltage terminal, 7 Mechanism, 8 Gearbox,
9 Fixed contact

As with the other disconnector types, the post insulators are also fixed to stay bolts, which enable precise adjustment of the contact arm and equalization of the insulator tolerances after the lines have been fastened.

The contact arm of the vertical break disconnectors is also a welded aluminium design. The contacts are silver-coated copper. The current in the gearbox is carried by tapered roller contacts.

A tie-rod transmits the actuating force from the mechanism to the contact arm with rotary bearings, rotating insulator and gearbox. This tie-rod, like the tie-rods in the gearbox, passes though the centre point shortly before reaching the end position,ensuring that the centre-point is interlocked against spontaneous changes of position under extreme external conditions. At high voltages and high short-circuit currents, or when ice loads have to be broken, a rotary movement of the contact arm around the longitudinal axis (approx. 25°) after reaching the “On” position provides a higher contact pressure, an additional interlock or frees the contacts from ice.

10.2.4 Single-column earthing switches

In outdoor switchgear installations, earthing switches are required not only directly adjacent to the disconnectors but also at other positions in the installation, e.g. for earthing individual busbar sections. Single-column earthing switches are used for this purpose, and they can be simultaneously used as supports for tubular busbars.

The components of the earthing switches are the same for mounting on disconnectors or separate single-column configuration. The only exceptions are the frame and support for the earthing contact.

The insulator is supported by a base frame with the operating mechanism (Fig. 10-7). It supports the contact holder with the earthing contact.

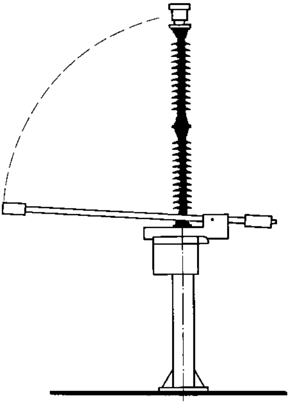


Fig.10-7

Single-column earthing *switch,*
type TEB, 420 kV

Two designs are available for the different requirements: a) Vertical-reach earthing switches for low rated voltages and rated currents, b) rotary-linear earthing switches for higher rated voltages and currents. They differ in the design of the earthing mechanism and hence in the switching movement of the contact arm.

On the vertical-reach earthing switch, the contact arm swivels on the shaft and only rotates around a switching angle of about 90 degrees. In the closed position, the earthing contact is situated between the contact fingers and these are against a spring stop. On the other hand, the rotary-linear earthing switch has a more complex mechanism. The contact arm first executes a rotary movement similar to that of the vertical-reach earthing switch and towards the end of the rotary movement moves on a straight line into the earthing contact. The contact blade on the contact arm is fixed in the earthing contact so the connection can withstand even high peak currents.

10.2.5 Operating mechanisms for disconnectors and earthing switches

Disconnectors are almost entirely actuated by motor-driven operating mechanisms, but manual mechanisms are also used for earthing switches. The operating mechanism is either mounted directly on the base frame of the disconnector or earthing switch or placed at operator level (1.20 m above ground level). Motor-operated mechanisms may also have an emergency manual actuator in case of failure of auxiliary power or for adjustments.

The operating mechanism housing has the position indicator switches for showing the switching position and for control and interlocking, and the motor-operated mechanisms also have contactors, etc. for controlling the actuators. The controllers are designed so that only one switching impulse is necessary to start the mechanism. They shut down automatically when the end position is reached. In the event of an emergency manual operation, the control circuit of the motor-operated mechanism is interrupted by a safety contact, making a simultaneous actuation from the control room impossible. The motor-operated mechanisms can also be fitted with pushbuttons for local control.

The mechanisms of the disconnectors and earthing switches can be interlocked relative to each other and to the associated circuit-breakers to prevent maloperation. Motor-operated mechanisms have an indicator switch contact for the relevant device incorporated into the control circuit of the mechanism. Manual and motor-operated mechanisms can also be fitted with a locking solenoid, which prevents manual switching when there is no power and also breaks the control circuit of the motor mechanism with a separate auxiliary contact. Mechanical interlocking between disconnectors and earthing switches is also possible with directly mounted earthing switches.

The mechanical actuation energy is transmitted from the motor to the actuation shaft by a spindle gear, which has an increased torque on closing and opening the main contact point to break ice loads.

Disconnectors and earthing switches have an operating mechanism with centre-point interlocking, which prevents any spontaneous changes of position under extreme external influences, such as short circuits, earthquakes or hurricanes.

Future generations of mechanisms will be motor-operated mechanisms with semiconductor controls and electronic indication of switch position.

10.3 Switch disconnectors

High-voltage switch disconnectors are switching devices that make, carry and break operating currents and also carry and in part also make short-circuit currents. In their open position, they also form an isolating distance.

The relevant standards are the following:

- DIN EN 60 265-1 (VDE 0670 Part 301) for rated voltages of 1 kV to 52 kV
- DIN EN 60 265-2 (VDE 0670 Part 302) for rated voltages of 52 kV and above

  Note: the standards also cover switches, i.e. devices whose open switching gap does not meet the special requirements of an isolating distance. In practice, equipment of this type is no longer used in central Europe.

The two above standards classify the switch disconnectors into the following by their usage:

- general-purpose switch disconnectors,
- switch disconnectors for limited applications and
- switch disconnectors for special applications.

General-purpose switch disconnectors must be capable of making and breaking the load current for which their current path is designed (rated current) and of carrying and making (at the same level) short-circuit currents for a specified time (1s, 3s). These devices have a very wide application. They are encountered with rated voltages of 12 kV, 24 kV and 36 kV in varying designs, primarily for operating currents to 630 A, but also for 1250 A (Section 8.1.2). Switch disconnectors with this versatility are found in the area of transmission voltages only as integrated devices in SF_6-insulated switchgears.

Switch disconnectors are available for special applications in the area of air-insulated switchgear technology in the range up to 245 kV. They are capable of carrying high operating currents (up to 2000 A) and short-circuit currents, but can only make and break much lower currents.

These devices are used as follows:

- Transformer switches for smaller power supplies in the distribution network for switching magnetizing currents and commutation currents (e.g. 100 A at up to 2.5 kV voltage difference) when changing transformers or the power supply,
- Line switches at one end of an overhead line
- Busbar section switches
- Switches for short cable length (I_c < 3A).

While the switch disconnector is the most common switching device in many distribution networks, it is much less common in transmission networks, in spite of its much lower costs compared to circuit-breakers.

10 High-voltage apparatus

10.1 Definitions and electrical parameters for switchgear

Disconnectors are mechanical switching devices which provide an isolating distance in the open position. They are capable to open or close a circuit if either a negligible current is switched or if there is no significant change in voltage between the terminals of the poles. Currents can be carried for specified times under normal operating conditions and under abnormal conditions (e.g. short circuit). Currents of negligible quantity have values ≦ 0.5 A; examples are capacitive charging currents for bushings, busbars, connections, very short lengths of cable and currents of voltage transformers.

Isolating distances are gaps of specified dielectric strength in gases or liquids in the open current paths of switching devices. They must comply with special conditions for the protection of personnel and installations and their existence must be clearly perceptible when the switching device is open.

Switches are mechanical switching devices, which not only make, carry and interrupt currents under normal conditions in the network but also must carry for a specific time and possibly make currents under specified abnormal conditions in the network (e.g. short circuit).

Switch disconnectors are switches which satisfy the requirements for an isolating distance specified for a disconnector in their open position.

Circuit-breakers are mechanical switching devices able to make, carry and interrupt currents occurring in the circuit under normal conditions, and can make, carry for a specified time and break currents occurring in the circuit (e.g. short circuit) under specified abnormal conditions.

Earthing switches are mechanical switching devices for earthing and short-circuiting circuits. They are capable of carrying currents for a specified time under abnormal conditions (e.g. short circuit). They are not required to carry normal operating currents. Earthing switches for transmission networks may also be required to make, carry and break induced currents (capacitive and inductive) under normal circuit conditions. Earthing switches with short circuit making capability shall be able to make the short-circuit current.

Fuses are switching devices that open the circuits in which they are installed by the melting of one or more parts specified and designed for the purpose of breaking the current when it exceeds a given value for a sufficiently long period.

Auxiliary switches must be rated for a continuous current of at least 10 A and be capable to break the current of the control circuits. The manufacturer must provide details. In the absence of such information, they must be capable of breaking at least 2 A at 220 V d.c. at a minimum circuit time constant of 20 ms. The terminals and wiring in auxiliary circuits must be designed for at least 10 A continuous current. The auxiliary switches that are actuated in connection with the main contacts must be directly actuated in both directions.

Electrical characteristics

(Peak) making current: peak value of the first major loop of the current in one pole of a switching device during the transient period following the initiation of current during a making operation.

Peak current: peak value of the first major loop of current during the transient period following initiation.

Breaking current: current in one pole of a switching device at the instant of initiation of an arc during a breaking process.

Breaking capacity: value of the prospective breaking current that a circuit-breaker or load switch can break at a given voltage under prescribed conditions for application and performance; e.g. overhead line (charging current) breaking capacity.

Short-line fault: short circuit on an overhead line at a short but not negligible distance from the terminals of the circuit-breaker.

Out of phase (making or breaking) capacity: making or breaking capacity for which the specified conditions for use and behaviour include the loss or the lack of synchronism between the parts of an electrical system on either side of the circuit-breaker.

Applied voltage: voltage between the terminals of a circuit-breaker pole immediately before making the current.

Recovery voltage: voltage occurring between the terminals of a circuit-breaker pole after interruption of the current.

Opening time: interval of time between application of the auxiliary power to the opening release of a switching device and the separation of the contacts in all three poles.

Closing time: interval of time between application of the auxiliary power to the closing circuit of a switching device and the contact touch in all poles.

Break time: interval of time between the beginning of the opening time of a switching device and the end of the arcing time.

Make time: interval of time between application of the auxiliary power to the closing cuircuit of a switching device and the instant in which the current begins to flow in the main circuit.

Rated value: value of a characteristic quantity used to define the operating conditions for which a switching device is designed and built and which must be verified by the manufacturer.

Rated normal current: the current that the main circuit of a switching device can continuously carry under specified conditions for use and behaviour. See below for standardized values.

Rated short-time withstand current: current that a switching device in closed position can carry during a specified short time under prescribed conditions for use and behaviour. See below for standardized values.

Rated voltage: upper limit of the highest voltage of the network for which a switching device is rated. See below for standardized values.

Additional rated values:
rated withstand current,
rated making current,
rated short-circuit breaking capacity etc.

Standard value: rated value based on official specifications to be used for designing a device.

Standardized rated voltages: 3.6; 7.2; 12; 17.5; 24; 36; 52; 72.5; 100; 123; 145; 170; 245; 300; 362; 420; 550; 800 kV.

Standardized rated normal currents: 200; 250; 400; 500; 630; 800; 1000; 1250; 1600; 2000; 2500; 3150; 4000; 5000; 6300 A.

Standardized rated short-time currents: 6.3; 8; 10; 12,5; 16; 20; 25; 31,5; 40; 50; 63; 80; 100 kA.

Rated insulation level: standardized combination of the rated values for the lightning impulse withstand voltage, the switching impulse withstand voltage (if applicable) and the short-time power frequency withstand voltage assigned to a rated voltage. As standardized insulation level, only combinations of values from one and the same line of Table 10-1 are valid.

Rated short-duration power frequency withstand voltage: rms value of the sinusoidal a.c. voltage at operating frequency that the insulation of a device must withstand under the specified test conditions for 1 minute.

Rated lightning impulse withstand voltage: peak value of the standard voltage surge 1.2/50 µs that the insulation of a device must withstand.

Rated switching impulse withstand voltage: peak value of the unipolar standard voltage surge 250/2500 µs which the insulation of a device with a rated voltage of 300 kV and above must withstand.

Note:

For disconnectors and specific (asynchronous) circuit-breakers for rated voltages of 300 kV and above, the isolating distances or breaker gaps are tested with combined voltage so that the power frequency test voltage (Table 10-1, peak values in parentheses) is applied at one terminal and the counterpolar test surge voltage (lightning or switching) occurs in the time range of the maximum voltage at the other terminal. The test with combined voltage was originally known as the bias test.

Table 10-1

Standardized rated insulation level for disconnectors, switches, circuit-breakers and earthing switches according to DIN EN 60 694 (VDE 0670 Part 1000)

Rated voltage kV (rms value)	Rated short-duration power frequency withstand voltage kV (rms value)		Rated lightning impulse withstand voltage kV (peak value)	
	Phase to earth, between the phases and across the open breaker gap	Across the isolating distance	Phase to earth, between the phases and across of the open breaker gap	Across the isolating distance
1	*2*	*3*	*4*	*5*
3.6	10	12	20	23
			40	46
7.2	20	23	40	46
			60	70
12	28	32	60	70
			75	85
17.5	38	45	75	85
			95	110
24	50	60	95	110
			125	145
36	70	80	145	165
			170	195
52	95	110	250	290
72.5	140	160	325	375
100	150	175	380	440
	185	210	450	520
123	185	210	450	520
	230	265	550	630
145	230	265	550	630
	275	315	650	750
170	275	315	650	750
	325	375	750	860
245	360	415	850	950
	395	460	950	1 050
	460	530	1 050	1 200

(continued)

Table *10-1 (continued)*

Rated voltage kV (rms value)	Rated short-duration power frequency withstand voltage kV (rms value)		Rated lightning impulse withstand voltage kV (peak value)		Rated switching impulse withstand voltage kV (peak value)		
	Phase to earth and between the phases	Across the open breaker gap and/or isolating distance	Phase to earth and between the phases	Across the open breaker gap and/or isolating distance	Phase to earth and across the open breaker gap	Between the phases	Across the isolating distance
1	*2*	*3*	*4*	*5*	*6*	*7*	*8*
300	380	435	950	950 (+ 170)	750	1 125	700 (+ 245)
			1 050	1 050 (+ 170)	850	1 275	
362	450	520	1 050	1 050 (+ 205)	850	1 275	800 (+ 295)
			1 175	1 175 (+ 205)	950	1 425	
420	520	610	1 300	1 300 (+ 240)	950	1 425	900 (+ 345)
			1 425	1 425 (+ 240)	1 050	1 575	
550	620	800	1 425	1 425 (+ 315)	1 050	1 680	900 (+ 450)
			1 550	1 550 (+ 315)	1 175	1 760	
800	830	1 150	1 800	1 800 (+ 455)	1 300	2 210	1 100 (+ 650)
			2 100	2 100 (+ 455)	1 425	2 420	

The values in parentheses are the peak values of the a.c. voltage applied to the opposite terminal.

10.2 Disconnectors and earthing switches

Disconnectors are used for galvanic isolation of networks or sections of switchgear installations. As an independent air-insulated device, they form a visible isolating distance in their open position. They are suitable for switching small currents (< 0.5 A) or also larger currents if the voltage does not change significantly between the contacts of a disconnector pole during switching (commutation currents).

Disconnectors can carry currents under operating conditions continuously and under abnormal conditions, such as short circuit, for a specified time (1s, 3s).

More than 10 different designs are in use around the world. The most important are rotary disconnectors, two-column vertical break disconnectors and single-column disconnectors.

Earthing switches are used for earthing and short-circuiting deenergized station components. Earthing switches can withstand currents during a specified time (1s, 3s) under abnormal conditions, such as a short circuit, but they are not required to carry continuous operating currents.

In general, earthing switches are combined with the adjacent disconnectors to form one unit. However, earthing switches can also be installed separately.

The applicable standard for disconnectors is DIN EN 60 129 (VDE 0670 Part 2). IEC 61128 is specifically applicable for switching commutation currents with disconnectors.

DIN EN 60 129 (VDE 0670 Part 2) is also applicable for earthing switches. In addition, DIN EN 61 129 (VDE 0670 Part 212) shall be considered with reference to switching induced currents.

Selection of the disconnector design is primarily guided by the layout of the installation (structural design), see Section 11.3.3. The ABB disconnector range can cover virtually all important layout variations in the ranges 72.5 to 800 kV, (rated voltage), 1250 to 4000 A (rated current) and 63 to 160 kA (rated peak withstand current).

10.2.1 Rotary disconnectors

Two-column rotary disconnectors SGF

This disconnector type is used by ABB for rated voltages of 72.5 to 420 kV (in individual cases also for 525 kV), preferably in smaller installations and also in larger switchgear installations as incoming feeder or sectionalizing disconnector. An earthing switch can be installed on both sides.

As shown in Fig. 10-1, the two rotating bases are mounted on a sectional steel frame and connected by a braced tie-rod. The insulators (post insulators) are fixed to the rotating bases and carry the swivel heads with the arms and the high-voltage contacts. Both arms swivel 90 degrees with their insulators during the switching movement.Two-column rotary disconnectors in their open position form a horizontal isolating distance. The rotary bases are weather protected and have maintenance-free ball bearings. The rotary bases are fastened on stay bolts, which allow precise adjustment of the contact system after the lines have been rigged and also compensate the insulator tolerances.

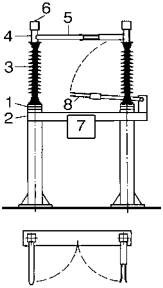


Fig. 10-1

Two-column rotary disconnector type SGF 123 kV, 1 Rotating base, 2 Frame, 3 Post insulator, 4 Rotating head, 5 Contact arm, 6 High-voltage terminal, 7 Mechanism, 8 Earthing switch

The swivel arms are an aluminium-welded construction with non-corroding contact joints, thereby eliminating any long-term changes in resistance. Disconnectors ≥ 170 kV have an interlocking mechanism (pawl and pin). This prevents the contacts from opening at high short-circuit currents. The current in the maintenance-free swivel heads, which are protected against external influences, is transferred via contact fingers arranged in a tulip shape around two contact pins, or for operating currents > 2500 A via tapered roller contacts. The high-voltage contacts can be rotated 360 degrees, allowing the tube or wire runs to be connected in any direction. The contact system has separately sprung contact fingers with no exposed springs.

The disconnectors and earthing switches have an operating mechanism with dead-centre interlocking. This prevents its position from being changed by extreme external influences, such as short circuits, earthquake or high winds. Disconnectors and earthing switches have separate mechanisms. For rated voltages of up to 300 kV, a three-pole disconnector or earthing switch group is generally actuated with one mechanism each. The individual poles of one group are mechanically linked by a connecting rod. The torque is transferred by the mechanism to a rotating base and rotates it by 90 degrees. The tie-rod rotates the second rotating base simultaneously. The contacts make both a rotary and a sliding movement when opening and closing the disconnector. This easily breaks heavy icing. The torque of the earthing switch is transferred to the shaft of the earthing switch. On closing, the arm of the earthing switch swivels upwards and meets the earthing contact attached to the swivel arm.

Three-column rotary disconnectors TDA

These ABB disconnectors are primarily used outside Europe with a side-by-side configuration of the three poles of a group. In comparison to two-column rotary disconnectors, they allow smaller pole spacings and higher mechanical terminal loads.

The two outer insulators are fixed to the base frame and carry the contact system (Fig. 10-2). The middle insulator is fastened to a rotating base and carries the one-piece arm, which rotates approximately 60 degrees during a switching operation and engages the contact systems on the outer insulators. The earthing contacts of the earthing switches, which can be mounted on either side, are located at the fixed contact system.

The three-column rotary disconnectors have the same components as the two-column rotary disconnectors described above. The same information applies for contact arm, swivel bases, contact system and interlocking mechanism, centre-point interlock, earthing switch and mechanical connection of the poles.

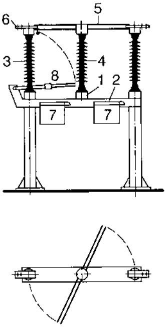


Fig.10-2

Three-column rotary disconnector type TDA, 145 kV, 1 Swivel base, 2 Frame, 3 Post insulator, 4 Rotating insulator, 5 Contact arm, 6 High-voltage terminal, 7 Mechanisms, 8 Earthing switch

10.2.2 Single-column (pantograph) disconnector TFB

In installations for higher voltages (≥ 170 kV) and multiple busbars, the single-column disconnector (also referred to as pantograph or vertical-reach disconnector) shown in Fig. 10-3 requires less space than other disconnector designs. For this reason and because of the clear station layout, it is used in many switchgear installations. The switch status is clearly visible with the vertical isolating distance.

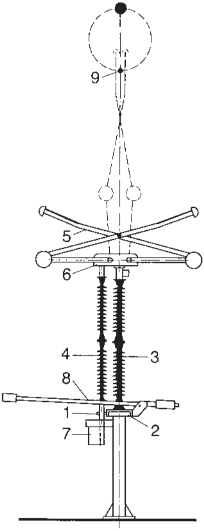


Fig.10-3

Single-column disconnector type TFB 245 kV, 1 Rotating bearing, 2 Frame, 3 Post insulator, 4 Rotating insulator, 5 Pantograph, 6 Gearbox, 7 Mechanism, 8 Earthing switch, 9 Fixed contact

The base of the disconnector is the frame, which holds the post insulator carrying the head piece with the pantograph and the gearbox. The actuating force is transferred through the rotating insulator to the gearbox. The suspended contact is mounted on the busbar situated above the disconnector. On closing, it is gripped between the pantograph arms. During the closing movement, the pantograph arms swivel through a wide range and are therefore capable of carrying the fixed contact even under extreme position changes caused by weather conditions. The feeder line is connected to the high-voltage terminal of the gearbox. In general, the single-column disconnector allows higher mechanical terminal loads than the two-column rotary disconnector.

The frame with the rotary bearing for the rotating insulator is fastened to the support with four stay bolts. They allow the disconnector to be accurately adjusted relative to the suspended contact.

The pantograph is a welded aluminium construction. It is fixed to the gearbox with the pantograph shaft by pins, preventing the pantograph unit from moving during the entire lifetime. This also ensures long-term high contact pressure between the contacts of the pantograph and the fixed contact. A contact force of 700 to 1500 N (depending on the pantograph design) not only ensures secure current transfer but also breaks heavy icing. Tapered roller contacts transfer current from the gearbox to the lower pantograph arms and make the connection from the lower to the upper pantograph arm.

The contact bars on the top of the pantographs and the fixed contact are silver-coated copper, for heavy duty or special cases they have a fine silver inlay. This results in low contact erosion, good current transfer and long service intervals.

Disconnectors for high short-circuit currents have a damping device between the arm joints. In the event of a short circuit, it prevents any reduction in the contact pressure and damps the oscillations of the pantograph caused by the short-circuit current.

The single-column disconnectors have a centre-point interlock in the gearbox and therefore cannot change their position spontaneously. It retains the switch position in any case, even if the rotating insulator breaks or if the disconnector is subjected to extreme vibrations caused by earthquakes or short-circuit forces. Anti-corona fittings on the ends of the arms act as a stop for the suspended contact if it moves in a vertical direction. Even under high tensile forces, it is securely held in the contact zone in the event of a short circuit.

Special designs of single-support disconnectors have been used in installations for high-voltage direct current transmission (HDVC) for many years.

A rotary-linear earthing switch (Section 10.2.4) can be installed on every disconnector pole.

In general, single-column disconnectors and the associated earthing switches are actuated by one mechanism each per pole.

Suspended contact for commutating current switching with single-column disconnector (bus-transfer current switching)

When switching between busbars without current interruption in outdoor switchgear installations, commutation currents occur during the switching operation and cause increased contact erosion on the contact bars of the disconnector and on the suspended contact. The height of the currents depends on the distance of the switching location from the power supply and the type of switchover, i.e. whether between busbars or switch bays, with the latter causing the higher stress. The commutation voltage can be calculated.

Commutation processes occur both on closing and opening. Closing causes bouncing between the contact bars and the suspended contact, which causes only slight arcing and a low degree of contact erosion. However, opening causes arcing between the opening contact bars that continues until the inverse voltage for quenching the arc has been generated. Because of the slow start of the movement of the contact bars, this process lasts for several cycles and causes significant stress on the disconnector contacts. Heavy-duty 420-kV outdoor switchgear installations can have commutation voltages up to 300 V and commutation currents to approximately 1500 A.

The ABB-developed commutation suspended contact for single-column disconnectors has two independently operating enclosed auxiliary switching systems. This ensures proper function in every case, regardless of which of the two contact bars on the pantographs is first to touch or last to leave the suspended contact. The most important components are illustrated in Figs. 10-4 and 10-5. The auxiliary switching system built into an anti-corona hood consists of a spring contact – connected to the auxiliary contact bar by a toggle lever – and a deion arc-quenching device. The spring contact is opened and closed independently of the switching speed at a defined position of the auxiliary contact bar.

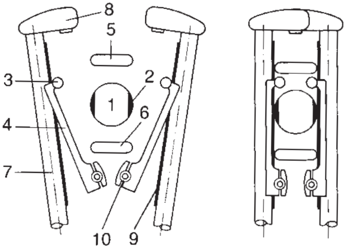


Fig.10-4

Commutating suspended contact, operating principle of guide strips,
1 Main contact support, 2 Main contact bar, 3 Auxiliary contact bar, 4 Toggle lever, 5 Upper guide strip, 6 Lower guide strip, 7 Pantograph arm, 8 Catch device, 9 Pantograph contact bar, 10 Insulated pivot with reset spring

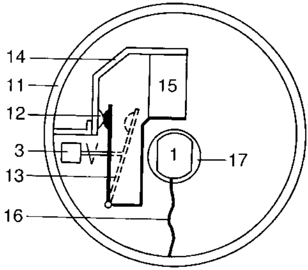


Fig.10-5

Commutating suspended contact, schematic diagram of auxiliary switching chamber,
1 Main contact support, 3 Auxiliary contact bar, 11 Anti-corona hood, 12 Fixed contact, 13 Spring contact, 14 Arc-deflecting baffle, 15 Deion arc-quenching plates, 16 Flexible connection for equipotential bonding, 17 Rotary bearing

Because the arc only lasts for about 25 ms on average during opening, the contact erosion on the spring contact system remains slight and the current is safely interrupted before the pantograph contact bar separates. Separating the main and auxiliary contact systems keeps the latter completely free from the effects of forces resulting from a short circuit. Short-circuit testing has confirmed a peak withstand current strength of 200 kA. Each switching system can take at least 350 switching cycles at commutation currents up to 1600 A and commutation voltages up to 330 V.

Installing commutation suspended contacts provides the system operator with flexibility and reliability of operation. Older installations can be upgraded by replacing the suspended contacts. Installations with switchgear from other manufacturers can also be retrofitted with ABB commuting suspended contacts.

10.2.3 Two-column vertical break disconnectors

This type of disconnector is preferred for higher voltages (≥ 170 kV) as a feeder or branch disconnector (at 1 1/2 circuit-breaker structure, Section 11.3.3). It differs from two-column rotary disconnectors by smaller phase spacings (with side-by-side configuration) and higher mechanical terminal loads. In its open state, there is a horizontal isolating distance with the contact arm open upwards.

As shown in Fig. 10-6, the two post insulators are mounted on a frame. The gearbox with contact arm and high-voltage terminal and the fixed contact with high-voltage terminal are mounted on them. The rotating insulator fastened to the rotary bearing transfers the actuating force to the gearbox, which transmits the force into a torque for opening the contact arm.

Each side of the disconnector can be fitted with an earthing switch (Section 10.2.4) depending on the requirements. The associated earthing contacts are installed on the gearbox or on the fixed contact.

For rated voltages of up to 245 kV one mechanism per three-phase disconnector or earthing switch group is sufficient, at higher nominal voltages one mechanism per pole is generally used.

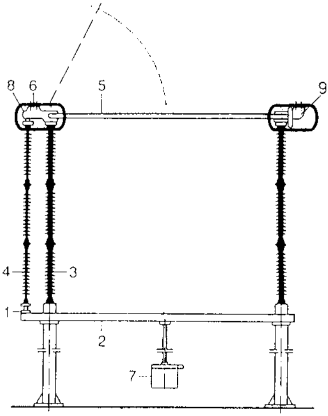


Fig.10-6

Vertical break 525 kV,
1 Rotary bearing, 2 Frame, 3 Post insulator, 4 Rotating insulator,
5 Contact arm, 6 High-voltage terminal, 7 Mechanism, 8 Gearbox,
9 Fixed contact

As with the other disconnector types, the post insulators are also fixed to stay bolts, which enable precise adjustment of the contact arm and equalization of the insulator tolerances after the lines have been fastened.

The contact arm of the vertical break disconnectors is also a welded aluminium design. The contacts are silver-coated copper. The current in the gearbox is carried by tapered roller contacts.

A tie-rod transmits the actuating force from the mechanism to the contact arm with rotary bearings, rotating insulator and gearbox. This tie-rod, like the tie-rods in the gearbox, passes though the centre point shortly before reaching the end position,ensuring that the centre-point is interlocked against spontaneous changes of position under extreme external conditions. At high voltages and high short-circuit currents, or when ice loads have to be broken, a rotary movement of the contact arm around the longitudinal axis (approx. 25°) after reaching the “On” position provides a higher contact pressure, an additional interlock or frees the contacts from ice.

10.2.4 Single-column earthing switches

In outdoor switchgear installations, earthing switches are required not only directly adjacent to the disconnectors but also at other positions in the installation, e.g. for earthing individual busbar sections. Single-column earthing switches are used for this purpose, and they can be simultaneously used as supports for tubular busbars.

The components of the earthing switches are the same for mounting on disconnectors or separate single-column configuration. The only exceptions are the frame and support for the earthing contact.

The insulator is supported by a base frame with the operating mechanism (Fig. 10-7). It supports the contact holder with the earthing contact.

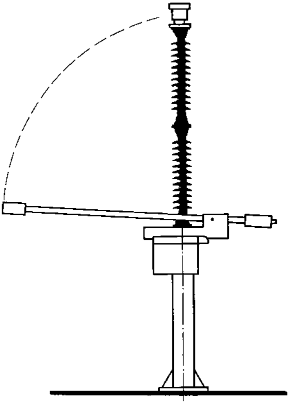


Fig.10-7

Single-column earthing *switch, type TEB, 420 kV*

Two designs are available for the different requirements: a) Vertical-reach earthing switches for low rated voltages and rated currents, b) rotary-linear earthing switches for higher rated voltages and currents. They differ in the design of the earthing mechanism and hence in the switching movement of the contact arm.

On the vertical-reach earthing switch, the contact arm swivels on the shaft and only rotates around a switching angle of about 90 degrees. In the closed position, the earthing contact is situated between the contact fingers and these are against a spring stop. On the other hand, the rotary-linear earthing switch has a more complex mechanism. The contact arm first executes a rotary movement similar to that of the vertical-reach earthing switch and towards the end of the rotary movement moves on a straight line into the earthing contact. The contact blade on the contact arm is fixed in the earthing contact so the connection can withstand even high peak currents.

10.2.5 Operating mechanisms for disconnectors and earthing switches

Disconnectors are almost entirely actuated by motor-driven operating mechanisms, but manual mechanisms are also used for earthing switches. The operating mechanism is either mounted directly on the base frame of the disconnector or earthing switch or placed at operator level (1.20 m above ground level). Motor-operated mechanisms may also have an emergency manual actuator in case of failure of auxiliary power or for adjustments.

The operating mechanism housing has the position indicator switches for showing the switching position and for control and interlocking, and the motor-operated mechanisms also have contactors, etc. for controlling the actuators. The controllers are designed so that only one switching impulse is necessary to start the mechanism. They shut down automatically when the end position is reached. In the event of an emergency manual operation, the control circuit of the motor-operated mechanism is interrupted by a safety contact, making a simultaneous actuation from the control room impossible. The motor-operated mechanisms can also be fitted with pushbuttons for local control.

The mechanisms of the disconnectors and earthing switches can be interlocked relative to each other and to the associated circuit-breakers to prevent maloperation. Motor-operated mechanisms have an indicator switch contact for the relevant device incorporated into the control circuit of the mechanism. Manual and motor-operated mechanisms can also be fitted with a locking solenoid, which prevents manual switching when there is no power and also breaks the control circuit of the motor mechanism with a separate auxiliary contact. Mechanical interlocking between disconnectors and earthing switches is also possible with directly mounted earthing switches.

The mechanical actuation energy is transmitted from the motor to the actuation shaft by a spindle gear, which has an increased torque on closing and opening the main contact point to break ice loads.

Disconnectors and earthing switches have an operating mechanism with centre-point interlocking, which prevents any spontaneous changes of position under extreme external influences, such as short circuits, earthquakes or hurricanes.

Future generations of mechanisms will be motor-operated mechanisms with semiconductor controls and electronic indication of switch position.

10.3 Switch disconnectors

High-voltage switch disconnectors are switching devices that make, carry and break operating currents and also carry and in part also make short-circuit currents. In their open position, they also form an isolating distance.

The relevant standards are the following:

- DIN EN 60 265-1 (VDE 0670 Part 301) for rated voltages of 1 kV to 52 kV
- DIN EN 60 265-2 (VDE 0670 Part 302) for rated voltages of 52 kV and above

  Note: the standards also cover switches, i.e. devices whose open switching gap does not meet the special requirements of an isolating distance. In practice, equipment of this type is no longer used in central Europe.

The two above standards classify the switch disconnectors into the following by their usage:

- general-purpose switch disconnectors,
- switch disconnectors for limited applications and
- switch disconnectors for special applications.

General-purpose switch disconnectors must be capable of making and breaking the load current for which their current path is designed (rated current) and of carrying and making (at the same level) short-circuit currents for a specified time (1s, 3s). These devices have a very wide application. They are encountered with rated voltages of 12 kV, 24 kV and 36 kV in varying designs, primarily for operating currents to 630 A, but also for 1250 A (Section 8.1.2). Switch disconnectors with this versatility are found in the area of transmission voltages only as integrated devices in SF_6-insulated switchgears.

Switch disconnectors are available for special applications in the area of air-insulated switchgear technology in the range up to 245 kV. They are capable of carrying high operating currents (up to 2000 A) and short-circuit currents, but can only make and break much lower currents.

These devices are used as follows:

- Transformer switches for smaller power supplies in the distribution network for switching magnetizing currents and commutation currents (e.g. 100 A at up to 2.5 kV voltage difference) when changing transformers or the power supply,
- Line switches at one end of an overhead line
- Busbar section switches
- Switches for short cable length (I_c < 3A).

While the switch disconnector is the most common switching device in many distribution networks, it is much less common in transmission networks, in spite of its much lower costs compared to circuit-breakers.

10.4 Circuit-breakers

10.4.1 Function, selection

High-voltage circuit-breakers are mechanical switching devices capable of making, carrying continuously and breaking electrical currents, both under normal circuit conditions and, for a limited period, abnormal circuit conditions, such as in the event of a short circuit. Circuit-breakers are used for switching overhead lines, cable feeders, transformers, reactor coils and capacitors. They are also used in bus ties in installations with multiple busbars to allow power to be transmitted from one busbar to another.

Specially designed breakers are used for specific duties such as railways, where they have to extinguish longer-burning arcs (longer half-wave) in 16 $^{2}/_{3}$-Hz networks. Breakers used with smelting furnaces frequently operate with reduced actuating force and lower breaking capacity. This leads to less wear in spite of the high switching frequency and to long service intervals.

The following points are important when selecting circuit-breakers:

– maximum operating voltage on location
– installation height above sea-level
– maximum load current occurring on location
– maximum short-circuit current occurring on location
– network frequency
– duration of short-circuit current
– switching cycle
– special operational and climatic conditions

Important national and international standards:

IEC	DIN VDE		
60056	DIN VDE 0670 – 101	(0670 Part 101)	General and definitions
	DIN VDE 0670 – 102	(0670 Part 102)	Classification
	DIN VDE 0670 – 103	(0670 Part 103)	Design and construction
	DIN VDE 0670 – 104	(0670 Part 104)	Type and routine testing
	DIN VDE 0670 – 105	(0670 Part 105)	Selection of circuit-breakers for service
	DIN VDE 0670 – 106	(0670 Part 106)	Information in enquiries, tenders and orders
60427	DIN EN 60 427	(0670 Part 108)	Synthetic testing
60694	DIN EN 60 694	(0670 Part 1000)	Common specifications for high voltage switchgear and controlgear standards

ANSI (**A**merican **N**ational **S**tandards **I**nstitution)

C 37 04	–1979	Rating structure
C 37 06	–1979	Preferred ratings
C 37 09	–1979	Test procedure
C 37 010	–1979	Application guide
C 37 011	–1979	Application guide for transient recovery voltage
C 37 012	–1979	Capacitance current switching

10.4.2 Design of circuit-breakers for high-voltage (> 52 kV)

Fig. 10-8 shows the basic design of HV outdoor circuit-breakers with the following components: operating mechanism, insulators, interrupting chamber and grading capacitor. HV circuit-breakers have a modular design. Higher voltages and higher capacities are dealt with by increasing the number of interrupting chambers. Self-blast interrupting chambers with low operating energy requirements are used for voltages of up to 170 kV and breaking currents of up to 40 kA (see Section 10.4.4). Single-chamber breakers are used for voltages of up to 300 kV and breaking currents of 50 kA. Multiple-chamber breakers are used for higher currents of up to 80 kA in this voltage range. Multiple-chamber breakers are used for voltages > 300 kV. Two-chamber breakers are used up to 550 kV and a breaking current of 63 kA.

In the lower voltage range and for three-phase autoreclosure, it is best to mount the three poles on a common base frame. Single-pole mounting and a separate mechanism for each pole are standard for voltages above 245 kV. HV circuit-breakers can also be mounted on trolleys with sprocket or plain rollers. Fig. 10-8 shows examples from the ABB outdoor breaker range.

The outdoor circuit-breaker design shown in Fig. 10-8 is the current type preferred in Europe. In America, the “dead tank” design is also common. This design, which is based on the earlier oil tank breaker, has the interrupting unit in an earthed metal tank filled with SF_6. The terminals of the interrupting unit are connected on both sides to SF_6-air bushings.

The same interrupting chambers and mechanisms as in outdoor circuit-breakers are also used with the integrated circuit-breakers of gas-insulated switchgear installations (GIS). An example of such breakers is shown in Fig. 10-9 with the section through the circuit-breaker of the SF_6-insulated switchgear installation EXK-01 for 123 kV and 40 kA. The self-blast interrupting chamber is identical to that of the outdoor circuit-breaker type LTB-D1; the three-pole circuit-breaker is operated by the HMB-1 mechanism.

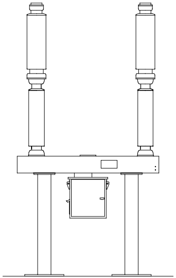
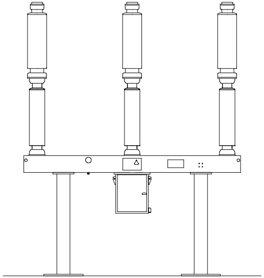
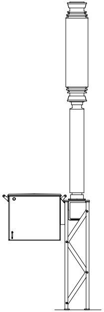
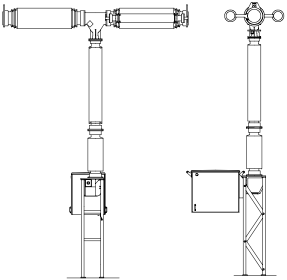
Rated voltage kV	123	123-170	245-300	420-(550)
Rated short-circuit breaking current kA	40	40	50	63
Breaker arrangement				
Breaker type	ELF-SD3-1 16 ⅔ Hz	LTB-D1	HPL-B1	HPL-B2
Mechanism type	HMB-1	HMB-1/HMB-1S	HMB-4	HMB-8

Fig.10-8

ABB SF$_6$ outdoor circuit-breaker, standard types for the central European region

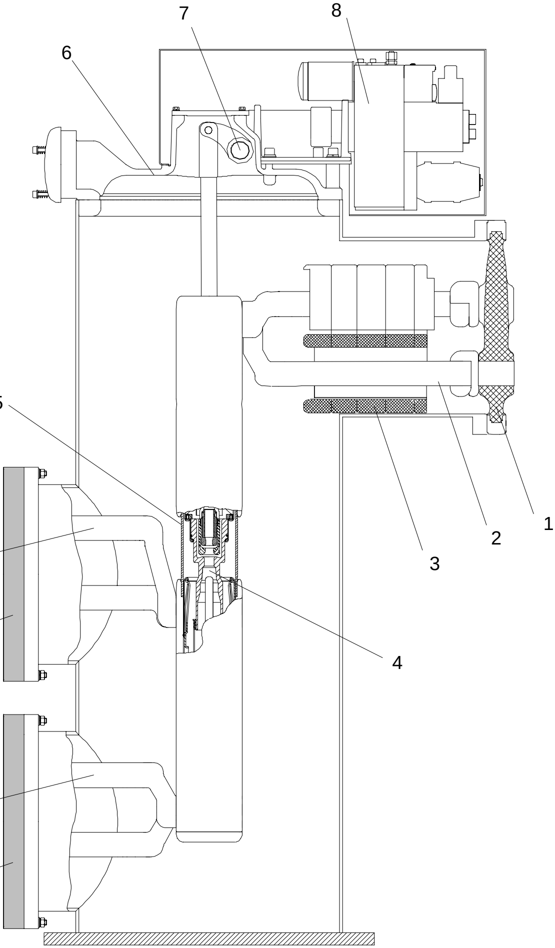


Fig.10-9

GIS circuit-breaker EXK-01 with SF_6 self-blast interrupting chamber and hydraulic spring mechanism HMB-1

1 Barrier insulator	*4 Interrupting chamber*	*7 Rotary feed*
2 Feed conductor	*5 Chamber insulator*	*8 Mechanism*
3 Current transformer	*6 Cover*	

10.4.3 Interrupting principle and important switching cases

There are two basic arc-extinction processes.

Direct current extinction, Fig. 10-10

A d.c. arc can only be extinguished by forcing a current zero. This means that the arc voltage U_s must be higher than the voltage at the breaker LS. A sufficiently high arc voltage can be built up – by reasonable means – only in low and medium voltage d.c. circuits (magnetic blow-out breakers). In high-voltage d.c. circuits, the voltage must be lowered appropriately to extinguish the d.c. arc and/or artificial current zeros must be created by inserting a resonant circuit (see Fig. 11-39).

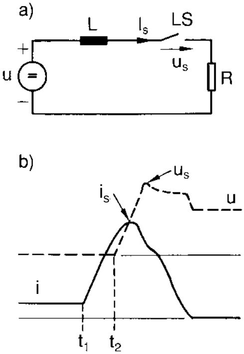


Fig.10-10

Direct current extinction a) simplified equivalent circuit, b) curves of current i_s and arc voltage u_s, t_1 initiation of short circuit, t_2 contact separation

Alternating current extinction, Fig. 10-11

A.C. arcs may extinguish at every current zero. In high-voltage circuits and without special measures, the arc re-ignites immediately after passing zero crossing, so that the arc continues to burn. The arc plasma is intensively cooled in the interrupting chambers of HV circuit-breakers with the result that it loses its electrical conductivity at current zero and the recovery voltage is not sufficient for re-ignition.

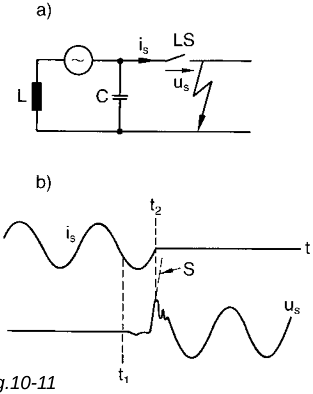


Fig.10-11

Alternating current extinction,
a) simplified equivalent circuit, b) curves of short-circuit current i_s and recovery voltage u_s, t_1 contact separation, t_2 arc extinction, S rate of rise of recovery voltage

Voltage stress of the breaker, Fig. 10-12

When interrupting an inductive load (Fig. 10-12a), the breaker voltage oscillates to the peak value of the recovery voltage. The breaker must be able to withstand the rate of rise of the recovery voltage and its peak value. Once the arc is quenched, the dielectric strength between the contacts must build up more quickly than the recovery voltage to prevent re-ignition.

When interrupting a purely resistive load (Fig. 10-12b), current zero and voltage zero coincide. The recovery voltage at the breaker rises sinusoidally with the operating frequency. The breaker gap has sufficient time to recover dielectric strength.

When switching a capacitive load (Fig. 10-12c), the supply-side voltage (infeed breaker terminal) oscillates at system frequency after current interruption between ± û, while the capacitor-side terminal remains charged at + û.

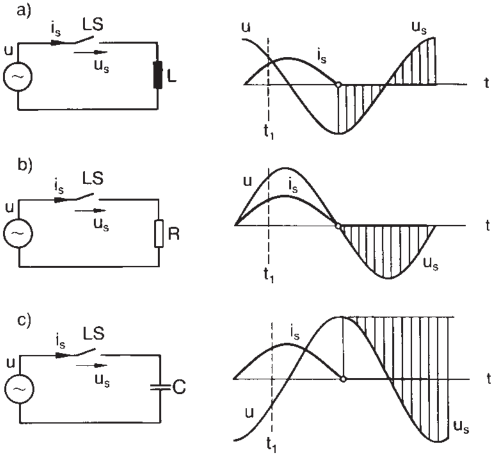


Fig.10-12

Recovery voltage u_S when breaking a) inductive load, b) resistive load, c) capacitive load

Various switching cases

Circuit-breakers must handle various switching cases that place different requirements on the breaker depending on their location.

Terminal fault (symmetrical short-circuit current), Fig. 10-13

The terminal fault is a short circuit on the load side of a breaker in the immediate vicinity of the breaker terminals. The short-circuit current is symmetrical if the fault begins at the voltage maximum. The recovery voltage oscillates to the value of the driving voltage. Rate of rise and amplitude of the transient voltage are determined by the network parameters. The values to be used in testing are defined in the relevant standards (Section 10.4.1).

Terminal fault (asymmetrical short-circuit current), Fig. 10-13

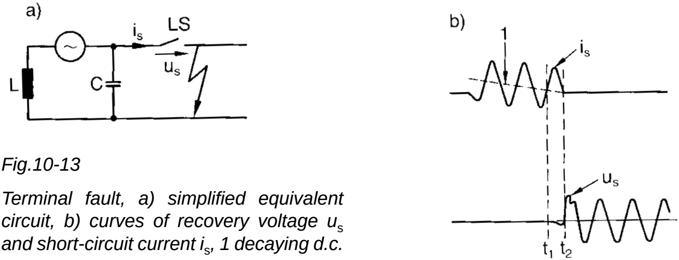


Fig.10-13

Terminal fault, a) simplified equivalent circuit, b) curves of recovery voltage u_s and short-circuit current i_s, 1 decaying d.c. current component

A more or less high d.c. current component must be switched in addition to the symmetrical short-circuit current depending on the opening time of the breaker. The d.c. current component of the short-circuit current depends on the moment of short-circuit initiation (max. at voltage zero) and on the time constants of the network supply-side components, such as generators, transformers, cables and HV lines. In accordance with IEC and DIN VDE, a time constant of 45 ms is set as standard. This means a d.c. current component of about 40% to 50% with the usual opening times of modern SF_6 outdoor breakers.

Short-line fault, Fig. 10-14

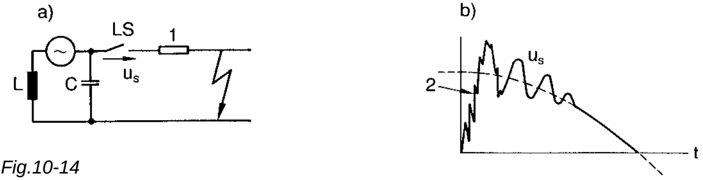


Fig.10-14

Short-line fault, a) simplified equivalent circuit, b) recovery voltage u_s across the breaker, 1 Line, 2 Sawtooth shape of u_s

Short line faults are short circuits on overhead lines at a short distance (up to a few kilometres) from the breaker. They impose a particularly severe stress on the breaker because two transient voltages are superimposed: the transient voltage of the supply network and the transient voltage on the line side. The superimposition results in a particularly high rate of rise of the voltage with only a minor reduction of the short-circuit current. The critical distance of the short circuit depends on the current, voltage and arc-quenching medium.

Switching under out-of-phase conditions (phase opposition), Fig. 10-15

The (power-frequency) voltage stress is severe if the phase angle of the systems on either side of the breaker are different (system components fall out of step because of overload or incorrect synchronization of generator circuit-breakers).

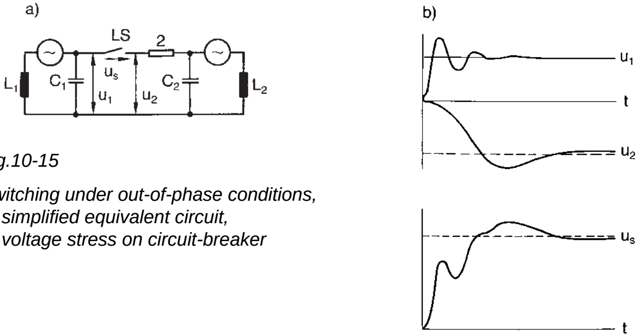


Fig.10-15

Switching under out-of-phase conditions,
a) simplified equivalent circuit,
b) voltage stress on circuit-breaker

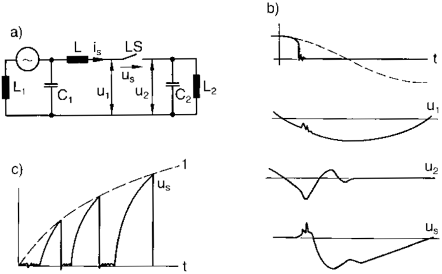
Interruption of small inductive currents, Fig. 10-16

Depending on the network configuration, interruption of small inductive currents, such as reactor coils or magnetizing currents from transformers, causes a rapid rise of the recovery voltage and under some circumstances high overvoltage resulting from current chopping before the natural zero crossing.

The overvoltages are also heavily dependent on the individual properties of the load circuit (inductance L_2 and capacitance C_2). There is no generally applicable test circuit that covers all load cases occurring in the network. However, in transmission networks an overvoltage of 2.5 pu is normally not exceeded.

Fig.10-16

Interruption of small inductive currents,
a) simplified equivalent circuit, b) curve of current and voltages with current chopping without restriking,
c) voltage curve when restriking occurs



Switching of capacitive currents, Fig. 10-17

Since breakers that prevent restriking are generally available, this switching case does not cause extreme stress (see Fig. 10-12c). However, theoretically, repeated restriking can increase the voltage load to several times the peak value of the driving voltage.

Switching of unloaded lines and cables:

The capacitance per unit length of line or cable imposes a similar situation as with the switching of capacitors

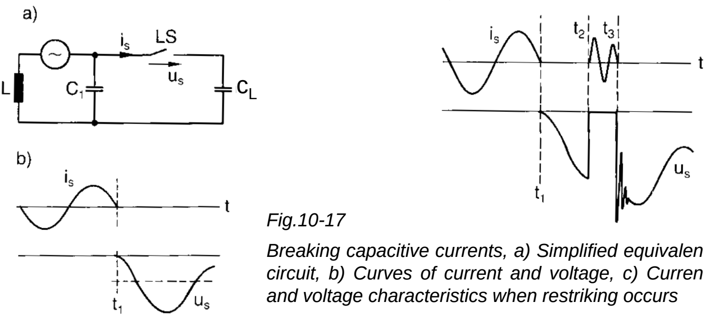


Fig.10-17

Breaking capacitive currents, a) Simplified equivalent circuit, b) Curves of current and voltage, c) Current and voltage characteristics when restriking occurs

Closing of inductive currents, Fig. 10-18

The most important switching case of this type for switchgear technology is the closing on short circuit. The timing of the contact making with reference to the driving voltage determines the effects on the contact system. Fig. 10-18a shows the closing operation with pre-arcing on contact proximity in the area of the peak value of the persistent voltage and the associated symmetrical fault current curve. Fig. 10-18b shows the curve on contact making in the area of the zero crossing of the persistent voltage with the peak value increased to almost double the value (1.8 times) by a transient direct current component in the current path.

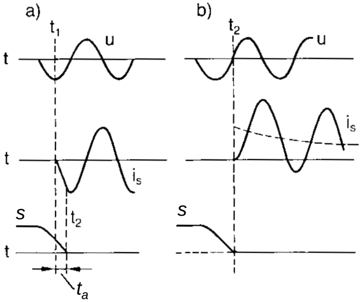
One breaker pole nearly always reaches this curve during three-pole switching with simultaneous closing time of the three breaker poles.

Fig.10-18

Making inductive currents:
t_1 = instant of pre-arcing
t_2 = instant of contact touch
S = contact path

a) symmetrical current with pre-arcing
t_a = pre-arcing duration

b) asymmetrical current with maximum peak current



Closing of unloaded overhead lines

Overhead lines can be shown in the electrical equivalent circuit diagram as combinations of series-connected inductances and capacitances to earth. During closing of long overhead lines, due to reflections of the voltage at the open end of the line, voltage increase of about 100% can occur. For this reason, at high transmission voltages and very long lines (> 300 km) circuit-breakers are fitted with closing resistors or closing is single-phase synchronized at the instant of zero crossing of the persistent voltage.

Short-circuit making and breaking tests

Making and breaking tests of circuit-breakers are performed in high-power test laboratories. The short-circuit current for the test is supplied by specially designed generators. The single-phase breaking power of a 420 kV circuit-breaker with a rated short-circuit current of 63 kA is approximately 15 000 MVA, which cannot be performed in a direct test circuit even by the most powerful test laboratory. Therefore, as early as the 1940s synthetic test circuits were developed for testing breakers with high short-circuit switching capability.

The basic reasoning behind a synthetic breaking test is that in the event of a short circuit, the short-circuit current and the recovery voltage do not occur simultaneously. This allows current and voltage to be supplied from two different sources. Fig. 10-19a shows the simplified test circuit for a synthetic test with current injection.

When test- and auxiliary-breakers are closed, the short circuit is initiated by closing the making switch. Auxiliary-breaker and test-breaker open at approximately the same time. Shortly before current zero of the current that is to be interrupted, the spark gap is ignited and an oscillating current of high frequency with an amplitude of some kA is superimposed on the short-circuit current in the test-breaker (Fig. 10-19b). The test-circuit elements must be selected so that the rate of current rise of the oscillating current at zero crossing coincides with the rate of rise of the high current.

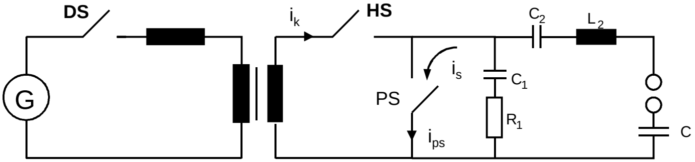


Fig.10-19a:

Synthetic test circuit with current injection
G: short-circuit generator, DS: making switch, HS: auxiliary breaker, PS: test breaker, i_k: short-circuit current, i_s: injection current, $i_{ps} = (i_k + i_s)$: test current through the test breaker, C, C_1, C_2, R_1, L_2: element of the synthetic circuit

An oscillogram of a make (c)/break (o) operation in a synthetic test circuit is shown in Fig. 10-19c.

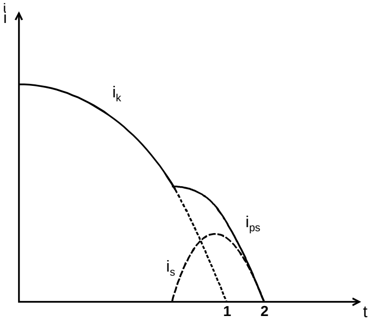


Fig.10-19b:

Current versus time in the synthetic test circuit

The auxiliary breaker interrupts the short-circuit current i_k at zero crossing 1, the test breaker interrupts the test current i_{ps} at zero crossing 2, i_s is the injection current.

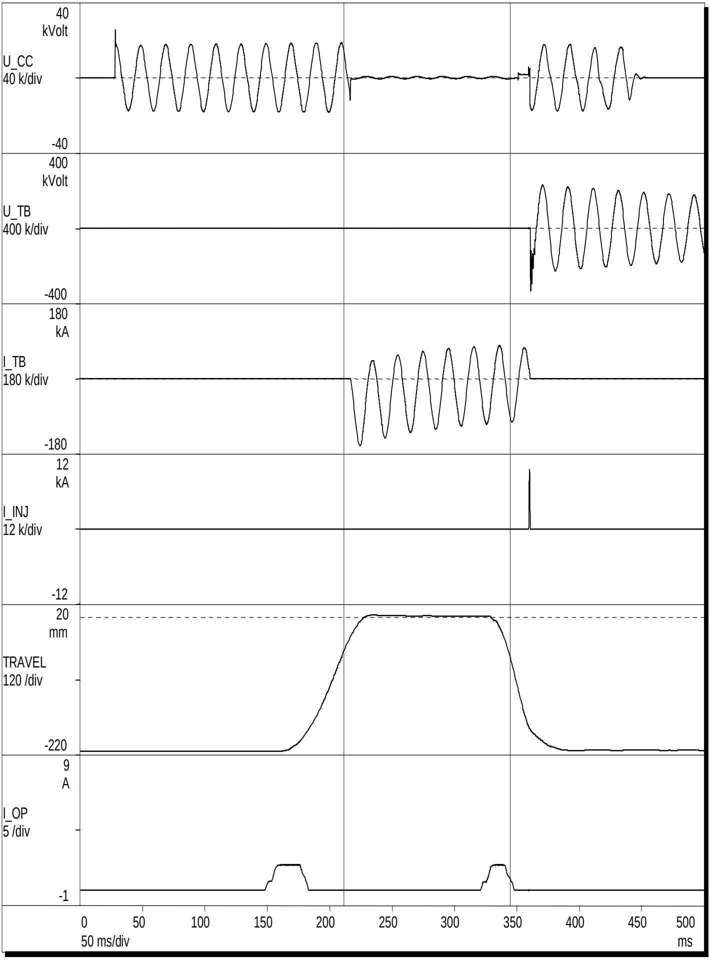


Fig.10-19c:

Oscillogram of a CO operation in the synthetic test circuit (half-pole test)

U_{CC}	*Generator voltage*	I_{INJ} (= i_S)	*injected oscillating current*
U_{TB}	*recovery voltage across the breaker gap*	*Travel*	*contact travel of breaker contacts*
I_{TB} (= i_{ps})	*current through the test object*	I_{OP}	*closing command and opening command*

10.4.4 Quenching media and operating principle

SF_6 gas

High-voltage circuit-breakers with SF_6 gas as the insulation and quenching medium have been in use throughout the world for more than 30 years. This gas is particularly suitable as a quenching medium because of its high dielectric strength and thermal conductivity (see also Section 11.2.2). Puffer-type breakers are used for high breaking capacity, while the self-blast technique is used for medium breaking capacity.

Puffer (piston) principle

Fig. 10-20 shows the design and operation of the interrupting chamber of the puffer principle. The extinction unit consists of the fixed contact and the moving contact with the blast cylinder. During the opening movement, the volume of the blast cylinder is steadily reduced and thereby increases the pressure of the enclosed gas until the fixed contact and the movable contact separate. The contact separation causes an arc to be drawn, which further increases the pressure of the SF_6 gas in the blast cylinder. At sufficiently high pressure, the compressed gas is released and blows the arc, depleting its energy and causing it to be extinguished. The nozzle shape of the two contacts provides optimum flow and quenching properties.

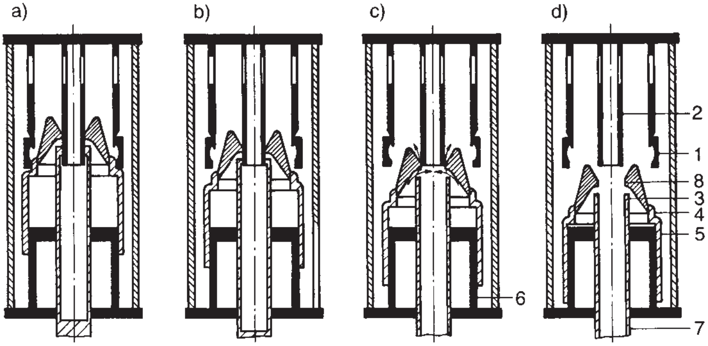


Fig.10-20

Puffer (piston) method showing the 4 stages of the opening process, a) closed position, b) beginning of the opening movement, c) arcing contacts separate, d) open position, 1 fixed continuous current contact, 2 fixed arcing contact, 3 movable arcing contact, 4 movable continuous current contact, 5 compression cylinder, 6 compression piston, 7 actuating rod, 8 quenching nozzle

Self-blast principle

In 1985, ABB introduced the self-blast quenching principle, which has been in use with SF_6 medium-voltage breakers for many years (see Fig. 8-15), in a modified form for HV circuit-breakers, without any need for a magnetic coil to rotate the arc. Fig. 10-21 shows the design and operation of the self-blast interrupting chamber up to 170 kV, 40 kA.

For small currents, the required extinction pressure is generated by compressing the gas in volume 5 as with a puffer-type breaker during the opening movement (Fig. 10-21 c). In contrast, for short-circuit currents the energy of the high-amp arc heats the quenching gas and increases its pressure in the heating volume 6 (Fig. 10-21 d). This overpressure does not affect the mechanism in any way. Its energy only needs to be dimensioned for switching normal operating currents.

Compared to the puffer principle, the self-blast principle only requires about 20% of the actuating energy for the same circuit-breaker performance data. The operational advantages are the compact mechanisms, low mechanical stresses on the overall system, low dynamic foundation loads, low noise level and generally improved reliability.

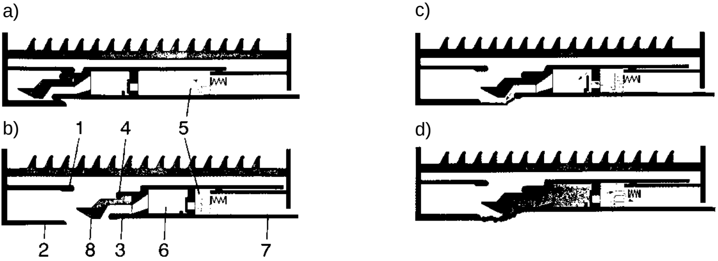


Fig.10-21

Self-blast principle for high-voltage circuit-breakers, a) closed position, b) open position, c) interruption of small currents (by the puffer method), d) interruption of short-circuit currents (by the self-blast method)
1 fixed continuous current contact, 2 fixed arcing contact, 3 movable arcing contact, 4 movable continuous current contact, 5 compression volume, 6 heating volume, 7 actuating rod, 8 quenching nozzle

The dielectric behaviour of the insulating media SF_6 gas, transformer oil, compressed air and air at atmospheric pressure is shown in Fig. 10-22.

The external dielectric strength of the interrupting chamber depends on the pressure of the ambient air, but not on the SF_6 gas pressure inside the chamber. The SF_6 gas pressure and the contact distance determine the dielectric strength inside the chamber.

Fig. 10-23 shows the current status of interrupting chamber breaking capacity of the ABB outdoor circuit-breakers

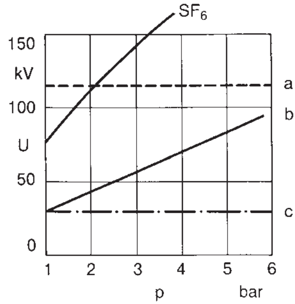


Fig.10-22

General dielectric behaviour of various insulation materials; breakdown strength U (a.c. voltage) with electrode distance 38 mm in function of the pressure p, a transformer oil, b compressed air, c reference line of air at atmospheric pressure

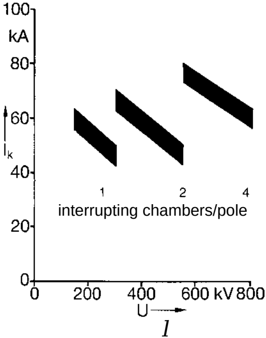


Fig.10-23

Interrupting chamber switching capacity U = rated voltage I_k = rated short-circuit breaking current

Oil

Up to about 1930, HV circuit-breakers were exclusively of the bulk-oil circuit-breaker type. The oil was used for insulation and arc extinction. The breaking arc heats the oil in its vicinity, induces an oil flow and causes the arc extinction. The minimum-oil breakers with a small volume of oil in the quenching chamber provided great advantages compared with the bulk-oil circuit-breakers with their large volume of oil. The arc also heats the oil in this type of breaker and extinguishes the arc in this way. When breaking small currents, the arc extinction is supported by pump action.

Compressed air

Until the end of the 1970s, air-blast breakers using compressed air as a quenching, insulation and actuating medium were widely used. They contain the quenching medium at a pressure of up to around 30 bar in the breaker tank and inside the breaker. At the instant of contact separation, compressed air is forced through the nozzle-shaped contacts thereby extinguishing the arc and establishing the insulating distance. Compressors, storage and distribution systems supply the air-blast breaker with clean and dry compressed air, see Section 15.5.

10.4.5 Operating mechanism and control

Operating mechanisms for circuit-breakers consist of energy storage unit, controller unit and power-transmitter unit. The energy-storage unit must be suited for storing energy for an autoreclosure cycle (OCO). This can be performed with different actuating systems.

Spring-operated mechanism

The spring-operated mechanism is a mechanical actuating system using a powerful spring as energy storage. The spring is tensioned with an electric motor and held by a latch system. When the breaker trips, the latch is released by magnetic force, and the spring energy moves the contacts by mechanical power transmission.

Pneumatic operating mechanism

The pneumatic operating mechanism operates by compressed air, which is fed directly to the breaker from a compressed air tank used as energy storage. Solenoid valves allow the compressed air into the actuating cylinder (for closing) or into the atmosphere (for opening). The compressed-air tank is replenished by a compressor unit. Compressed-air mechanisms have not been used for ABB circuit-breakers for many years.

Hydraulic operating mechanism

The hydraulic operating mechanism has a nitrogen accumulator for storing the actuation energy. The hydraulic fluid is pressurized by a compressed cushion of nitrogen. A hydraulic piston transmits the power to actuate the breaker contacts.

The mechanism operates on the differential piston principle. The piston rod side is permanently under system pressure. The piston face side is subject to system pressure for closing and pressure is released for opening. The system is recharged by a motor-driven hydraulic pump, which pumps oil from the low-pressure chamber to the nitrogen storage chamber. The hydraulic mechanisms from ABB were replaced by the hydraulic spring-operated mechanism in 1986.

Hydraulic spring -operated mechanism

The hydraulic spring-operated mechanism is an operating mechanism combining hydraulics and springs. Energy is stored in a spring set which is tensioned hydraulically. Power is transmitted hydraulically with the actuating forces for the circuit-breaker contacts being generated as with a hydraulic mechanism by a differential piston integrated into the actuation unit. As an example, Fig. 10-24 shows a section through the hydraulic spring operating mechanism type HMB-1.

The ABB hydraulic spring-operated mechanism is available in several different sizes (Fig. 10-25). Circuit-breakers with common base frames, i.e. outdoor breakers up to 170 kV, GIS circuit-breakers and dead-tank breakers, have a common mechanism for all three poles. All mechanisms are designed to eliminate external pipe joints.

The hydraulic spring operating mechanism offers the following advantages:

- temperature-independent disc-spring set, allowing the lowest possible oil volume (example: < 1.5 litres for the HMB-1)
- compact
- high repeat accuracy of operating times
- integrated hydraulic damping
- high mechanical endurance
- easily adaptable to different breaker types.

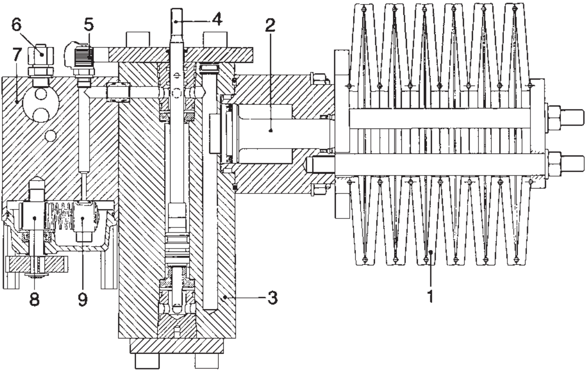


Fig.10-24

Section through the hydraulic spring operating mechanism for SF_6 *self-blast breakers, 1 Springs, 2 Spring piston, 3 Actuating cylinder, 4 Piston rod, 5 Measuring connection, 6 Oil filler connection, 7 Pump block, 8 Pump drive shaft, 9 Pump unit*

Modern ABB HV circuit-breakers are operated exclusively with the hydraulic spring mechanism or the mechanical spring mechanism.

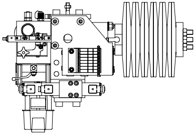
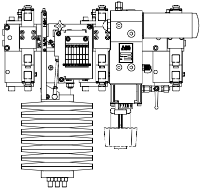
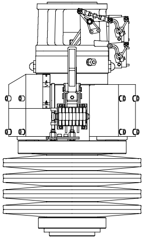
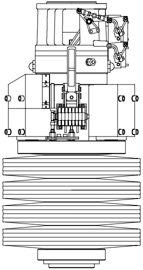
Design				
Type Used for	HMB-1	HMB-1 S	HMB-4	HMB-8
Outdoor circuit-breaker type	LTB-D1	LTB-D1	HPL-B1	HPL-B2
GIS circuit-breaker type	ELK	ELK	ELK	ELK
Generator circuit-breaker type	HG	–	HE	HE
Dead-tank circuit-breaker type	PM, PASS	PM	PM, PASS	PM, PASS

Fig.10-25

Sizes of hydraulic spring operating mechanisms for high-voltage circuit-breakers

Requirements for electrical control of circuit-breakers

Phase-discrepancy monitoring

Breakers with a single-phase mechanism are fitted with phase-discrepancy monitoring.

If the three breaker poles are in different positions during a three-pole closing, the phase-discrepancy monitoring detects the differential position. All three breaker poles are tripped together after a preset waiting time of 2 seconds.

Anti-pumping control

The anti-pumping control prevents repeated, undesired operation of one or more breaker poles if an existing OFF command is followed by several ON commands. The breaker must then close only once followed by a lockout, i.e. it must remain in the OFF position regardless of whether and how long control commands are applied.

Non-stop motor operation

Depending on the design and the type of switching cycle performed, the pump or the compressor requires a specific period to restore the consumed energy. If there is a leak in the pressure system, the motor will run more often or will run continuously. Continuous running is detected and reported as a fault.

SF_6 gas monitoring

The breaking capacity of a circuit-breaker is dependent on the gas density in the breaker chamber. This is measured by a temperature-compensated pressure gauge. If the gas pressure falls to a specified value, an alarm is triggered, and if it falls further to a lower limit value, the breaker is blocked.

Local/remote control

To allow work on the breaker, it can generally be controlled from the local control cubicle; control can be switched from remote to local by a selector switch.

Energy monitoring

The air or oil pressure is monitored and controlled in pneumatic and hydraulic mechanisms by a multiphase pressure switch. The pressure switch has the following functions:

- control of compressor or pump motor
- OFF blocking, ON blocking, autoreclosure blocking, dependent on available pressure

A pressure control is not required for hydraulic spring mechanisms. Instead of that they have a gate control, which monitors and controls the tension of the spring (spring travel) as a measure of the available energy.

Autoreclosure

A single- or three-pole autoreclosure is selected depending on the type of system earthing, the degree of interconnection, the length of the lines and the amount of infeed from large power plants. The trip commands of the network protection (overcurrent and line protection, Section 14.2) are accordingly evaluated differently for the tripping action of the circuit-breaker.

Circuit-breakers for three-pole autoreclosure only require one hydraulic spring mechanism with one actuation cylinder, allowing *one* tripping initiates the closing and opening of all poles.

For single-pole autoreclosure, these breakers have a hydraulic spring mechanism with three actuation cylinders, which are controlled separately. This allows any pole to be tripped independently. Power is fed to the three poles from one power unit. Single-phase autoreclosure is intended to trip short-time faults and restrict them in time and place without allowing larger system units to fail for any length of time. Single-pole tripping improves network stability and prevents the network from going out of phase. At the same time, breakers with single-pole autoreclosure can be operated as three-pole autoreclosure by opening and closing the three poles together.

Circuit-breakers with separate poles and single-pole actuation are equally suited for both single-pole and three-pole autoreclosure.

Synchronized switching

Synchronized switching of circuit-breakers in which every breaker pole is synchronously actuated by a suitable control unit at the instantaneous value of the current or the phase-to-earth voltage are becoming increasingly important. Examples of applications of synchronized switching include closing overhead lines under no load without closing resistors and switching capacitor banks in transmission networks.

The operating mechanisms of the HMB series have already proven very suitable for this because of their very constant operating times.

Cable units within an overhead line should be protected immediately adjacent to the two end seals with arresters.

Surge counters may be used to monitor surge arresters. They are installed in the ground conductor of the arrester that is to be monitored; the arresters must be installed insulated against ground.

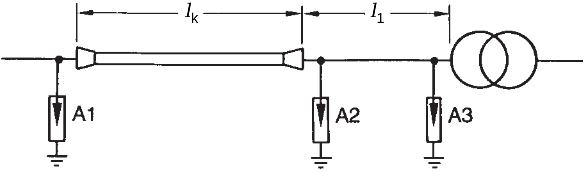


Fig.10-37

Overvoltage protection of the cable link of overhead lines, l_K*: length of cable unit,* l_1*: distance cable / transformer, A1 & A2 arresters for protection of the cable, A3 arrester for protection of the transformer*

10.5 Instrument transformers for switchgear installations

Instrument transformers are used to transform high voltages and currents to values that can be unified or measured safely with low internal losses. With current transformers, the primary winding carries the load current, while with voltage transformers, the primary winding is connected to the service voltage. The voltage or the current of the secondary winding is identical to the value on the primary side in phase and ratio except for the transformer error. Current transformers operate almost under short-circuit conditions while voltage transformers operate at no-load. Primary and secondary sides are nearly always electrically independent and insulated from one another as required by the service voltage. Above a service voltage of 110 kV, instrument transformers are frequently manufactured as combined current and voltage transformers.

In modern substation and bay control systems, current and voltage transformers can be replaced by sensors. They offer the same accuracy as conventional instrument transformers. The output signal, A/D-converted, is processed by the digital bay control unit.

10.5.1 Definitions and electrical quantities

A distinction is made between transformers for measurement purposes used to connect instruments, meters and similar devices and transformers for protection needs for connection of protection devices.

Instrument transformers are classified according to their measurement precision and identified accordingly. They are used as shown in Table 10-2.

Table 10-2

Selection of instrument transformers by application

Application	VDE class	IEC class	ANSI class
Precision measurements and calibration	0.1	0.1	0.3
Accurate power measurement and tariff metering	0.2	0.2	0.3
Tariff metering and accurate measuring instruments	0.5	0.5	0.6
Industrial meters: voltage, current, power, meters	1	1	1.2
Ammeters or voltmeters, overcurrent or voltage relays	3	3	1.2
Current transformer protective cores	5P, 10P	5P, 10P	C, T

Current transformer – DIN VDE 0414-1 (VDE 0414 Part 1) –

- Primary rated current: the value of the primary current that identifies the current transformer and for which it is rated.
- Secondary rated current: the value of the secondary current that identifies the current transformer and for which it is rated.
- Burden: impedance of the secondary circuit expressed in ohms with the power factor. The burden is usually given as apparent power in volt amperes, which is assumed at a specified power factor and secondary rated current intensity.
- Rated burden: the value of the burden on which the accuracy requirements of this standard are based.
- Rated output: the value of the apparent power (in volt amperes at a specified power factor), which the current transformer yields at secondary rated current intensity and rated burden.
- Current error (transformation ratio error): the deviation of a current transformer when measuring a current intensity and derived from the deviation of the actual transformation from the rated transformation. The current error is given by the equation below and expressed as a percentage.

$$\text{Current error in \%} = \frac{(K_n \cdot I_s - I_p) \cdot 100}{I_p}$$

Here:

K_n rated error
I_s actual primary current intensity
I_p actual secondary current intensity, if flowing I_p under measuring conditions

- Phase displacement: the angular difference between the primary and secondary current vectors. The direction of the meter is specified so that on an ideal current transformer the phase displacement is equal to zero. The phase displacement is considered positive when the secondary current meter is ahead of the primary current meter. It is usually expressed in minutes or in centiradians.

  Note: the definition is strictly speaking only applicable to sinusoidal currents.

- Composite error: in its stationary state, the composite error ε_c based on the rms value of the primary current is the difference between
  a) the instantaneous values of the primary current intensity
  b) the instantaneous values of the secondary current intensities multiplied by the rated transformation.

The positive signs of the primary and secondary current must be specified in accordance with the agreement on connection labels.

The composite error in general is expressed as a percentage of the rms values of the primary current intensity as given by the following equation.

$$\varepsilon_c = \frac{100}{I_p} \sqrt{\frac{1}{T} \int_0^T (K_N \cdot i_s - i_p)^2 \, d\, t}$$

Here:

K_n	Rated transformation ratio of the current transformer
I_p	Rms value of the primary current
i_p	Instantaneous value of the primary current
i_s	Instantaneous value of the secondary current
T	Period duration

– Rated limiting current (IPL): the value of the lowest primary current at which the composite error of the current transformer at the secondary rated burden for measurements is equal to or greater than 10 %.

Note: the composite error should exceed 10 % to protect the device fed from the current transformer against the high current values occurring if there is a fault in the network.

– Overcurrent limit factor (FS): the ratio of the rated limiting current to the primary rated current.

Note: if a short-circuit current flows through the primary winding of the current transformer, the load on the instruments connected to the current transformer is smaller in proportion to smallness of the overcurrent limit factor.

– Rated accuracy limit current: the value of the primary current up to which the current transformer for protection needs meets the requirements for the composite error.

– Accuracy limit factor: the ratio of the primary rated accuracy limit current to the primary rated current.

– Thermal rated continuous current: unless otherwise specified, the thermal rated continuous current intensity is equal to the primary rated current.

– Current transformer with extended current measuring range: the thermal rated continuous current must be equal to the extended primary rated current. Standard values: 120 %, 150 % and 200 %.

– Rated short-time thermal current: the rated short-time thermal current (I_{th}) must be given for every current transformer. (see definition in Section 3.25 in DIN VDE 0414-1).

Note: if a current transformer is a component of another device (e.g. switchgear installation), a time different from one second may be given.

– Rated peak short-circuit current: the value of the rated peak short-circuit current (I_{dyn}) must in general be 2.5 I_{th}. Only in the event of deviation from this value must I_{dyn} be given on the nameplate. (see definition in Section 3.26 in DIN VDE 0414-1).

Voltage transformer – DIN VDE 0414-2 (VDE 0414 Part 2) –

- Primary rated voltage: the value of the primary voltage that identifies the voltage transformer and for which it is rated.
- Secondary rated voltage: the value of the secondary voltage that identifies the voltage transformer and for which it is rated.
- Rated transformation ratio: the ratio of the primary rated voltage to the secondary rated voltage.
- Burden: the admittance of the secondary circuit given in Siemens with indication of the power factor (inductive or capacitive).

  Note: The burden is usually given as apparent power in volt amperes, which is assumed at a specified power factor and secondary rated voltage.

- Rated burden: the value of the burden on which the accuracy requirements of this standard are based.
- Rated output: the value of the apparent power (in volt amperes at a specified power factor), which the voltage transformer yields at secondary rated voltage and rated burden.
- Thermal limiting output: the value of the apparent power – based on the rated voltage – that can be drawn at a secondary winding at primary rated voltage without exceeding the limit values for overtemperature (dependent on the rated voltage factor).

  Note 1: the limit values for measurement deviations may be exceeded here.

  Note 2: if there is more than one secondary winding, the thermal limiting output must be given for each winding.

  Note 3: the simultaneous load of more than one secondary winding is not approved without special consultation between manufacturer and purchaser.

- Rated thermal limiting output of windings for ground fault detection: the rated thermal limiting output of the winding for ground fault detection must be given in volt-amperes; the values must be 15, 25, 50, 70, 100 VA and their decimal multiples, based on the secondary rated voltage and a power factor of 1.

  Note: because the windings for ground fault detection are connected in the open delta, they are subject to load only in the event of malfunction.

The thermal rated burden rating of the winding for ground fault detection should be based on a load duration of 8 h.

- Rated voltage factor: the multiple of the primary rated voltage at which a voltage transformer must respond to the thermal requirements for a specified load duration and its accuracy class.

– Voltage error (transformation ratio error): the deviation of a voltage transformer when measuring a voltage resulting from the deviation of the actual transformation from the rated transformation. The voltage error is given by the equation below and expressed as a percentage.

$$\text{Voltage error in \%} = \frac{(K_n \cdot U_s - U_p) \cdot 100}{U_p}$$

Here:

K_n rated transformation ratio
U_p actual primary voltage
U_s actual secondary voltage when U_p is subject to measuring conditions.

– Phase displacement: the angular difference between the primary and secondary voltage vectors. The direction of the vector is specified so on an ideal voltage transformer the phase displacement is equal to zero. The phase displacement is considered positive when the secondary vector is ahead of the primary vector. It is usually expressed in minutes or in centiradians.

Note: the definition is strictly speaking only applicable to sinusoidal voltage

10.5.2 Current transformer

The primary winding is incorporated in the line and carries the current flowing in the network. It has various secondary cores. The current transformers are designed to carry the primary current with respect to magnitude and phase angle within preset error limits. The main source of transmission errors is the magnetizing current. To ensure that this and the resulting transmission errors remain small, the current transformers without exception are fitted with high-grade core magnets. The core material are made of silicon-iron or high-alloy nickel-iron. Fig. 10-26 shows the magnetizing curves of different core materials. In special cases, cores with an air gap are used to influence the behaviour of a transformer core in the event of transient processes.

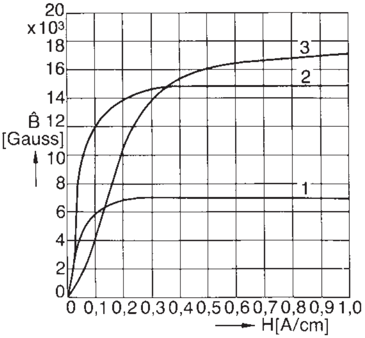


Fig.10-26

Magnetizing curves of various core materials. Measuring cores use core material 1 and protective cores core material 3.

H = field intensity (A/cm), B = peak value of the induction (Gauss),
1 = nickel-iron with approx. 75 % Ni,
2 = nickel-iron with approx. 50% Ni,
3 = cold-rolled silicon-iron with mill pattern

Depending on the design of the primary winding, current transformers are divided into single-turn transformers and wound-type transformers. Single-turn transformers are designed as outdoor inverted-type transformers, straight-through transformers, slipover and bar transformers. Wound-type transformers are bushing transformers, post-type transformers and miniature transformers and also outdoor post-type and tank transformers with oil-paper insulation. Fig. 10-27 shows the structural design of an top-core type transformer (Fig. 10-27a) and a tank transformer (Fig. 10-27b).

The various designs of current transformers classified by the insulating medium are shown in Table 10-3.

Table 10-3

Designs of current transformers

Insulation	Type	Voltage range	Application
Dry	Slipover, wound and cable current transformer	Low voltage	Indoor switchgear
Cast resin	Post-type and bushing transformer	Medium voltage	Indoor and SF_6 installations
Oil-paper/ porcelain	Tank and top-core type transformers	High and highest voltage	Outdoor installations
SF_6/compound*)	top-core type transformer	High and highest voltage	Outdoor installations

*) Compound material of fibre glass and silicone rubber

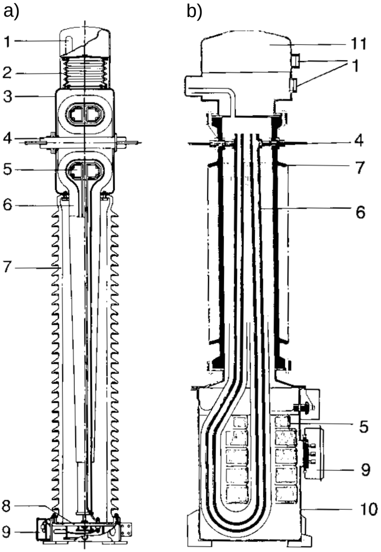


Fig. 10-27

a) Top-Core-type transformer type AOK for 145 ... 525 kV, 40 ... 6000 A, b) Hairpin-type transformer type IMBD for 36 ... 300 kV, 50 ... 2000 A

1 Oil-level indicator, 2 Bellows, 3 Terminal, 4 Primary connections, 5 Cores with secondary winding, 6 Core and coil assembly with main insulation, 7 Insulator, 8 Base plate, 9 Terminal box, 10 Tank, 11 Nitrogen cushion

If desired, current transformers can be provided with switching facilities for two or more primary currents.

The following designs are possible.

Primary reconnection

The reconnection takes the form of series/series-parallel or parallel switching of two or more partial primary windings. The rated output and rated overcurrent factor remain unchanged.

Secondary tappings

The changeover takes the form of tappings at the secondary winding.

When the primary rated current intensity is reduced in this way, the rated output in classes 0.1 . . . 3 decreases approximately as the square of the reduction in primary current and in safety classes 5 P and 10 P approximately proportional to the reduction of the primary current.

The absolute values of the rated short-time thermal current and the rated peak short-circuit current remain unchanged for all ratios.

Selection of current transformers

The choice of a current transformer is based on the values of the primary and secondary rated current, the rated output of the transformer cores at a given accuracy class rating and the overcurrent limit factor. The overcurrent limit factor must be adjusted to the load current of the consumer.

Determining the secondary output of a current transformer

The secondary output of a current transformer depends on the number of ampere turns, the core material and the core design. The output varies approximately as the square of the number of ampere turns (approximately linear with protective cores). However, it also decreases roughly as the square (approximately linear with protective cores) of the difference between the load current and the rated current of the current transformer. So with a transformer with 30 VA rated power with a load of half the rated current, the output is reduced by a quarter, about 7.5 VA.

The rated output of a current transformer is the product of the rated burden Z and the square of the secondary rated current I_{2n}^2, i.e.: $S_n = Z \cdot I_{2n}^2$ in VA. A current transformer with secondary $I_{2n} = 5$ A and a connected burden of 1.2 Ω has a rated output of $1.2\ \Omega \cdot 5^2 A^2 = 30$ VA. The transformer may be loaded with the rated output on the nameplate without exceeding the error limits. All current paths of the instruments, meters, protection relays and the resistance of the associated connecting lines connected in series in the secondary current circuit must not reach more than the resistance value of this rated burden as a maximum (Table 10-4).

Table 10-4

Rated output and rated burden of current transformers (at 50 Hz)

Rated output in VA	5	10	15	30	60
Rated burden at 5 A in Ω	0.2	0.4	0.6	1.2	2.4
Rated burden at 1 A in Ω	5	10	15	30	60

The transformer output at 16⅔ Hz must be multiplied with the factor 0.33 and at 60 Hz by 1.2.

When selecting the current transformers, not only the output but also the overcurrent limit factor of the transformer must be considered. The overcurrent limit factor is given on the nameplate.

In the case of *measuring and metering cores,* the overcurrent limit factor should be as small as possible, e. g. 5 or 10, to protect the connected instrumentation against excessive overcurrents or short-circuit currents. Because the overcurrent limit factor only applies for the rated burden but actually rises with a smaller burden or smaller transformer load in approximately an inverse ratio, the operating burden of the connected instrumentation including the required connection lines must be equal to the rated burden of the transformer so far as possible to protect the measuring mechanisms from destruction. Otherwise, the secondary circuit should include an additional burden.

For additional details on selecting classes, error limits, rated outputs and designations, see DIN VDE 0414-1.

Example:

Current transformer for 100/5 A, 30 VA 0.5 FS 5

Power requirement:	1 ammeter	2.5 VA
	1 wattmeter	3 VA
	25 m of lines of 2.5 mm^2	4.5 VA
Total power requirement	....	10 VA

Since the product of the rated output of the core and overcurrent limit factor is approximately constant, the example gives 30 VA • 5 = 150 VA. Then for a burden of only 10 VA, an overcurrent factor of 150 : 10 = 15 is reached. Instrument protection is therefore not sufficient. If a transformer of only 15 VA is selected, the overcurrent factor is 7.5. The transformer output could therefore be even smaller, or an additional burden would have to be included.

Protective cores for connection of protection relays, in contrast to the measuring cores, must be selected so that their total error even with short-circuit currents in the range in which the protection relays should function accurately according to their settings, e.g. 6 to 8 times rated current, is not too large. Therefore, the protective core must be designed so the product of the rated output and the overcurrent limit factor is at least equal to the product of the power requirement of the secondary transformer circuit at rated current and the required overcurrent limit factor. This is particularly important when verifying the thermal short-circuit stress indicates a large primary conductor cross-section. In this case, a current transformer for higher rated current can be selected, where the primary winding number and also the output will be lower because the load current is less than the rated current, or a special transformer can be used.

Example:

Transformer for 400/5 A, 15 VA 5 P 10

Power requirement:	Overcurrent relay	8 VA
	Differential relay	1 VA
	Lines	3 VA
Total power requirement		12 VA

The overcurrent factor is then $\frac{15\text{ VA} \cdot 10}{12\text{ VA}} = 12.5$

i.e. the transformer is correctly selected.

An overcurrent relay set to 8 I_n will trip, because the current in the above case to 12.5 x rated current increases in proportion to the primary current.

The direct current component occurring at the beginning of a short circuit results in transmission errors by core saturation with fully displaced short-circuit current. Specially dimensioned cores with a high overcurrent limit factor (e.g. 200) or the selection of a high transformation ratio for the protective core can remedy this.

The above selection criteria also apply for current transformers in enclosed switchgear installations.

Current transformers according to international standards (e.g. ANSI) are in principle selected under similar criteria. Transformer dimensioning is made easier under the above provisions by using the following short overview with Tables 10-5 to 10-9.

Definition and standardized values as per IEC 60185 and DIN VDE 0414-1

Measuring core rated output: 2.5 – 5.0 – 10 – 15 – 30 VA;
burden output factor cos β = 0.8

Classes: 0.1 – 0.2 – 0.5 – 1: valid in the range of 25 % and 100 % of the rated burden.

0.2 s and 0.5 s: For special applications (electrical meters that measure correctly between 50 mA and 6 A, i.e. between 1% and 120% of the rated current of 5A)

3 – 5: valid in the range 50% to 100% of the rated burden

Label: measuring cores are identified by a combination of the rated output with the overcurrent limit factor and with the class, e.g.

15 VA class 0.5 FS 10
15 VA class 0.5 ext. 150%
(extended current measuring range)

Protective cores Rated output: preferably 10 – 15 – 30 VA

Classes: 5 P and 10 P: the numbers identify the maximum permissible total error with limit error current; the letter P stands for “protection”.

Accuracy limit factors: 5 – 10 – 15 – 20 – 30

Table 10-5

Error limits for measuring cores as per DIN VDE 0414-1

Accuracy class	Current error in % at rated current percentage value						± phase displacement at rated current percentage value									
							in minutes					in centiradians				
	1	5	20	50	100	120%	1	5	20	100	120%	1	5	20	100	120%
0.1	–	0.4	0.2	–	0.1	0.1	–	15	8	5	5	–	0.45	0.24	0.15	0,15
0.2	–	0.75	0.35	–	0.2	0.2	–	30	15	10	10	–	0.9	0.45	0.3	0,3
0.5	–	1.5	0.75	–	0.5	0.5	–	90	45	30	30	–	2.7	1.35	0.9	0,9
1	–	3	1.5	–	1.0	1.0	–	180	90	60	60	–	5.4	2.7	1.8	1,8
3	–	–	–	3	–	3	–	–	–	–	–	–	–	–	–	–
5	–	–	–	5	–	5	–	–	–	–	–	–	–	–	–	–
0.2S	0.75	0.35	0.2	–	0.2	0.2	30	15	10	10	10	0.9	0.45	0.3	0.3	0,3
0.5S	1.5	0.75	0.5	–	0.5	0.5	90	45	30	30	30	2.7	1.35	0.9	0.9	0,9

NOTE: the limit values given for current error and phase displacement are generally applicable for any position of an outside conductor with a distance no less than the insulation distance in air for the maximum voltage for equipment (U_m).

Special application conditions, enclosed low service voltages in connection with high current values should be subject to separate agreement between manufacturer and purchaser.

Table 10-6

Error limits for protective cores as per DIN VDE 0414-1

Accuracy class	Current error in % at primary	Phase displacement at primary rated current		Composite error in % at
	Rated current	in minutes	in centiradians	Rated accuracy limits
5 P	± 1	± 60	± 1.8	5
10 P	± 3	–	–	10

Definition and standardized values as per ANSI/IEEE – Standard C57.13-1978
(based on rated frequency 60 Hz)

Measuring cores Classes: 0.3 – 0.6 – 1.2

Designation: measuring cores are identified by a combination of the class with the burden identification, e.g.

0.3 B-0.1 or 0.6 B-0.5

Table 10-7

Normal burdens (for 5 A – secondary current)

Des. of burden	resistance (Ω)	inductance (mH)	impedance (Ω)	rated power (VA)	cos β
B-0.1	0.09	0.116	0.1	2.5	0.9
B-0.2	0.18	0.232	0.2	5.0	0.9
B-0.5	0.45	0.580	0.5	12.5	0.9
B-0.9	0.81	1.04	0.9	22.5	0.9
B-1.8	1.62	2.08	1.8	45.0	0.9

Table 10-8

Error limits in the range cos β = 0.6 – 1.0

Class	Ratio error (factor) at rated current 100 %		10 %		± Phase displacement at rated current 100 %	10 %	corresp. IEC class
	min.	max.	min.	max.	minutes1)	minutes1)	
0.3	0.997	1.003	0.994	1.006	16	33	0.2
0.6	0.994	1.006	0.988	1.012	33	65	0.5
1.2	0.968	1.012	0.976	1.024	65	130	1

1) approximate values derived from diagram

Protective cores

Table 10-9

Normal burdens: (for 5 A secondary current)[1)]

Designation of burden	Resistance Ω	Inductance (mH)	Impedance Ω	Rated power (VA)	cos β
B-1	0.5	2.3	1.0	25	0.5
B-2	1.0	4.6	2.0	50	0.5
B-4	2.0	9.2	4.0	100	0.5
B-8	4.0	18.4	8.0	200	0.5

[1)] In the case of other secondary currents, the burden values are converted at unchanged rated power and cos ß

Classes/Error limits

“C” and “T” at max. total error ≦ 10% in the range 1–20 x primary rated current (corresponding to IEC Class 10 P 20).

With “C” transformers, the magnetic flux in the transformer core does not influence the transformation ratio. With “T” transformers, magnetic flux influence at a limited level is permissible, but must be verified by testing.

Secondary terminal voltage

The transformer must supply this voltage at the rated burden at 20 times the secondary rated current without exceeding the max. ratio error of 10%.

Sec. terminal voltage (V)	Rated burden
100	B-1
200	B-2
400	B-4
800	B-8

Label

Protective cores are identified by class and secondary terminal voltage, e.g. C 100, a C-transformer with secondary terminal voltage 100 V for rated burden B-1.

Testing (100%) of current transformers

The transformers are subjected to the testing (100%) required under the standards before delivery. Table 10-10 shows an overview of the tests according to DIN VDE, IEC and ANSI.

Table 10-10

Testing (100%) of current transformers

Test	DIN VDE*) 0414-1	IEC 60185 (1987)	ANSI C 57.13 (1978)
1. connection labels	×	×	×
2. insulating capacity/alternating voltage test of the primary winding against ground	×	×	×
3. insulating capacity/alternating voltage test of the secondary windings against one another and against ground	×	×	×
4. winding test	×	×	
5. verification/accuracy measurement, current error and phase displacement	×	×	×
6. verification/accuracy measurement, total error with protective cores	×	×	
7. measurement of the magnetizing current with protective cores			×
8. partial-discharge measurement	× VDE 0414 Part10	× IEC 60044-4	
9. polarity measurement			×

*) largely identical to IEC 60185

10.5.3 Inductive voltage transformers

Inductive voltage transformers are transformers of low output with which the secondary voltage is practically proportional to and in phase with the primary voltage. Voltage transformers are used to transform the system voltage to be measured to a secondary voltage to be fed to measuring and protection devices. The primary and secondary windings are galvanically separated from each other.

Inductive voltage transformers are supplied in the following designs:

1. Two-phase isolated voltage transformers

   for connection between two phases, ratio 6000/100 V, for example. Two voltage transformers in V connection are normally used for measuring power in three-phase networks.

2. Single-phase isolated voltage transformers

   for connection between one phase and ground, ratio
   110 000 / $\sqrt{3}$ // 100 / $\sqrt{3}$ V.
   Three voltage transformers connected in star are required for measuring power in three-phase networks. If single-phase isolated voltage transformers have an auxiliary winding for ground-fault monitoring, in three-phase networks, this must be measured for the ratio of 100/3 V. The “open delta” in the three-phase set can also have a fixed resistance for damping relaxation oscillations (resulting from ferroresonances in insulated networks with small capacitances).

3. Three-phase voltage transformers

   with the measuring windings connected in star and an auxiliary winding on the 4th and 5th limb for ground-fault detection. The auxiliary winding has a voltage of 100 V in the event of a ground fault.

Inductive voltage transformers are selected by the primary and secondary rated voltage and the accuracy class and rated output of the secondary windings in accordance with the requirements of the devices to which they are to be connected.

If there is a winding for ground fault detection, its rated thermal limit output must be given. For the short-time withstand, the rated voltage factor and the specified load duration at increased voltage are required.

10.5.4 Capacitive voltage transformers

Voltage transformers at higher system voltages to 765 kV that operate under the principle of the capacitive voltage divider can also be used. The capacitive voltage transformers are designed for connection of all standard operational instrumentation and network protection relays; they are also approved for tariff metering.

Fig. 10-28 shows the line diagram of a capacitive voltage transformer. Network protection relays with transistorized circuits for the shortest closing times are also securely fed from capacitive transformers, particularly if the transformers have a sampling device that damps all transient oscillations of the transformer in the shortest time.

Capacitive voltage transformers also have the advantage of being usable for coupling high-frequency power-line carrier systems, e.g. for telecommunications, remote-control installations and similar purposes. The required supplementary elements (choke, surge arrester) can be installed in terminal boxes.

When selecting capacitive voltage transformers, primary and secondary rated voltage, rated frequency, rated output and class are the essential features. In addition, the rated thermal limiting output of a ground-fault detector winding, rated voltage factor and the specified load duration at increased voltage must be considered.

Capacitive voltage transformers are selected similarly to the inductive transformers, but the capacitances of the high-voltage capacitors (C_1), of the intermediate-voltage capacitor (C_2) and the rated capacity (C_n) must also be given. A dimensioning example for a capacitive voltage transformer is shown below:

Primary rated voltage	$\frac{110\,000}{\sqrt{3}}$V
Secondary rated voltage of the measuring effect	$\frac{110}{\sqrt{3}}$V
of the winding for the ground fault detection	$\frac{100}{3}$V
Rated output	75 VA, Cl. 0.5
Rated voltage factor	1.9 U_n, 4h
Thermal rated burden rating	120 VA, 8h
Rated capacity	4.400 pF ± 10 %
Rated frequency	50 Hz

The properties with transient processes are also important with capacitive transformers (interaction with network protection).

SF_6-insulated switchgear installations also include inductive and capacitive voltage transformers, see Section 11.2.

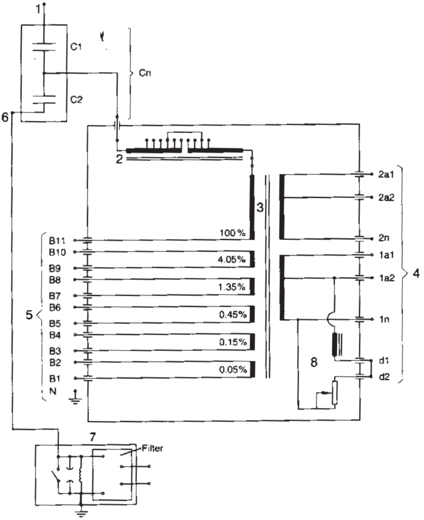


Fig.10-28

Basic diagram of a capacitive voltage transformer

1 High-voltage terminal,
2 Medium-voltage choke coil,
3 Transformer, 4 Secondary terminals, 5 Terminal box trimming winding, 6 TFH terminal, 7 TFH coupling,
8 Damping device, C_n C_1 C_2 capacitive voltage divider

10.5.5 Non-conventional transformers

In contrast to conventional transformers, non-conventional current and voltage transformers are distinguished by compact size and low weight. They are generally not saturable and have high transmission bandwidths. The measured values are best transmitted by fibre-optic cables, which are practically immune to electromagnetic fields (EMC). The non-conventional type of measured value acquisition and transmission requires only limited output in the area of 0.1 ... 5 VA on the secondary side.

Non-conventional transformers consist of a measurement recorder, a measured value transmission line bridging the potential difference between high voltage and ground potential and an electronic interface at ground potential for measured-value processing and connections to protection devices in the station control system.

Measurement recorders can be divided into active and passive systems depending on the method used.

Active non-conventional transformers

Hall-effect elements, Rogowski coils or specially designed bar-type current transformers with linear characteristics are used for current detection. Voltage acquisition is generally done using resistive or capacitive voltage dividers. In substation technology for rated voltages below 52 kV and also for GIS installations for higher voltages, active non-conventional transformers offer very attractive solutions.

However, in outdoor substation technology for transmission networks, the electrical measured quantities must still be converted to a digital or analogue optical signal at high-voltage potential. This requires devices for providing the required auxiliary energy at high-voltage potential. This energy requirement may be taken from the high-voltage system that is being monitored and also provided by optical means, whether by solar cell or by energy transmission via fibre-optic lines.

Passive non-conventional transformers

Passive measurement recorders do not require auxiliary energy at high-voltage potential. They are normally completely constructed of dielectric materials.

Passive optical voltage transformers

Linear electro-optic effects (Pockel effect) linked to specific classes of crystals are used for voltage measurement with optical voltage transformers. The physical principle of the Pockel effect is a change of the polarization state of light that is sent within an electrical field through a transparent material. The change in polarization is linearly proportional to the applied electrical field.

In the ABB-developed EOVT (electro optical voltage transducer) the Pockel cell, a BGO crystal ($Bi_{12}GeO_{20}$) is installed directly between the high voltage electrode and ground with the light path parallel to the electrical field (Fig. 10-29).

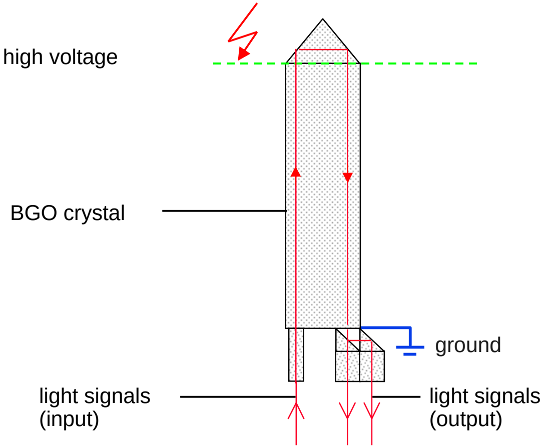


Fig.10-29

Principle of the light circuit in a crystal (BGO) for passive optical voltage measurement using the Pockel effect

The monochromatic polarized light beam entering at ground potential in the end face of the crystal is reflected at the prismatic end of the crystal at high-voltage potential so the dielectrically stressed range is run through twice by light. This doubles the polarity change caused by the electrical field. The light beam exiting the end face is split into two directional components by an optical system. These are transmitted to the photodiodes by fibre-optic cables. They indicate the phase difference (polarization change) arising in the dielectric field from the intensities of the two components and therefore a scale for the applied voltage. The use of two light signals at the output has the advantage of providing an accurate measurement result in spite of relatively small output signals and parasitic effects (phase change by temperature influence and natural double refraction properties of the crystal) are eliminated.

The EOVT was designed from the outset for voltage levels to at least 420 kV. Therefore, the BGO crystal is basically surrounded by an SF_6 atmosphere. Fig. 10-30 shows the EOVT in an enclosed SF_6-insulated switchgear installation for 123 kV. The BGO crystal is surrounded by a glass tube between two field-control electrodes, the lower at high-voltage potential and the upper at ground potential. The monochromatic light feed and the return line of the subcomponents after the polarization change is through fibre-optic cables, which feed through the grounded installation enclosure to the processing device.

For applications in outdoor installations, the active component of the EOVT, as shown in Fig. 10-33 as a combination solution with a current transformer, is installed inside an appropriate SF_6-filled composite insulator. The technical data of the EOVT optical voltage transformer is shown in Table 10-11.

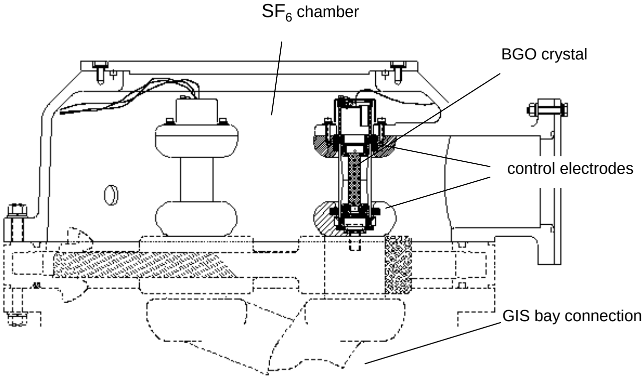


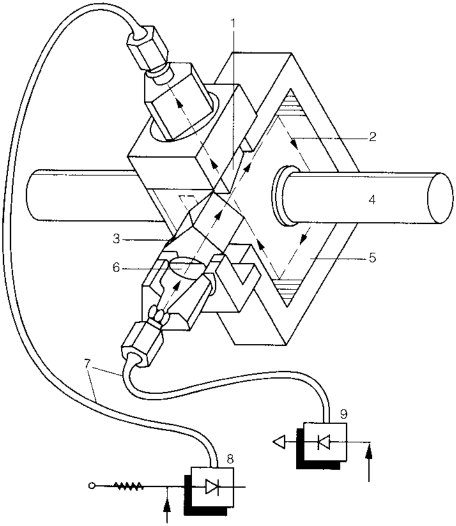
Fig.10-30

View of a voltage transformer (EOVT) for a gas-insulated switchgear installation (GIS). The transformers for two phases of a GIS bay.

Passive optical current transformer

An optical current transformer like the ABB-developed MOCT (magneto optical current transducer) uses the Faraday effect in crystalline structures for passive measurement of currents. Again monochromatic light is sent polarized into a solid body of glass, which surrounds the current carrying conductor. Reflection from the bevelled corners of the glass container directs the light beam around the conducting line before it exits again on one side (Fig. 10-31).

The magnetic field around the conductor rotates the polarization plane of the light, whose phase difference is proportional to the magnetic field intensity H. Because the light in the glass body completely surrounds the current path as a line integral along a closed curve, the phase difference at the end of the path in the glass body is directly proportional to the current. A polarization filter at the exit point of the light from the glass body only allows one subcomponent of the light generated by the rotation to pass. It is fed to the processing unit through fibre-optic cables. The intensity of this subcomponent is the scale for the polarization change and so for the magnitude of the current.



Legend

1 Analyzer
2 Light path in sensor
3 Polarizer
4 Primary conductor
5 Faraday sensor
6 Lens
7 fibre-optic cable
8 Detector
9 Light source

Fig.10-31

Passive non-conventional current transformer (MOCT). The Faraday sensor around the conductor line is structured as a glass block.

The technical data of the MOCT optical current transformer are summarized in Table 10-12. Its low space requirements and low weight (Fig. 10-32) provide new options in the design of outdoor switchgear installations, such as by a (already implemented) combination of circuit-breaker and MOCT. In addition, the combined solution of EOVT and MOCT shown in Fig. 10-33 is distinguished on one hand by the environmental aspect – no danger of contamination by leaking oil – and on the other hand by a substantial reduction in weight compared to conventional solutions.

Connection to protection technology

Devices and systems in conventional secondary technology are generally directly linked to the primary quantity with standardized current and voltage ports (typically 100 V or 1 A). The former specification of these ports is based on the requirements of analogue secondary devices with high power requirements and the attempt to attain security with reference to electromagnetic influence by relatively high signal levels.

However, modern secondary devices, in general digital, only require a small part of the input power that was formerly required (typically 0.1 VA to 1 VA).

In non-conventional metering transformers, the processing device sends a small signal that is generally suitable for digital secondary devices. However, if necessary, supplementary amplifier inserts can generate current and voltage signals suitable for the interfaces of conventional secondary technology.

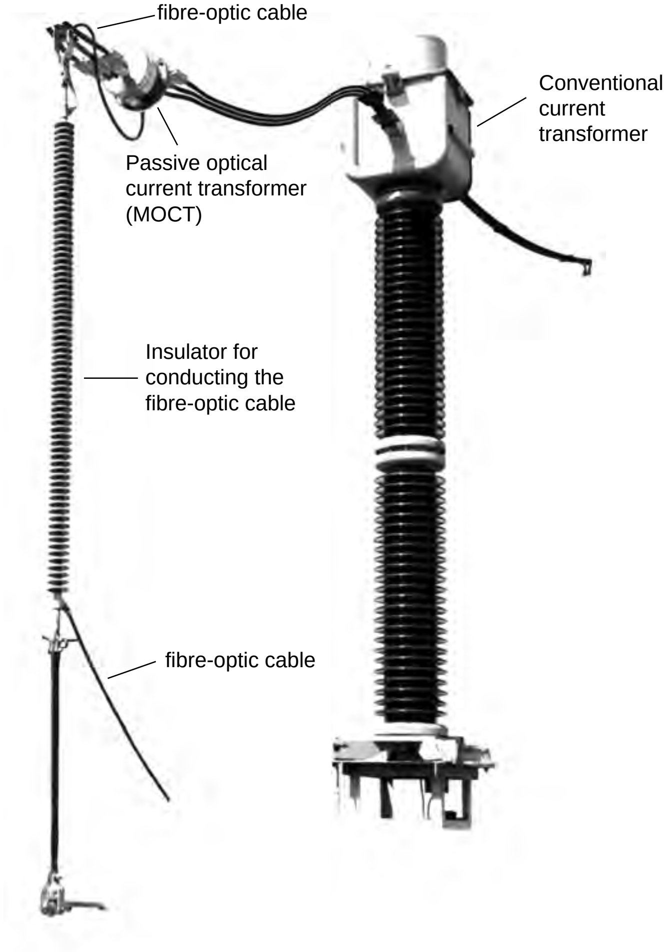


Fig.10-32

Comparison of a non-conventional current transformer (left in the picture) with a conventional outdoor transformer with paper-oil insulation

Table 10-11

Technical data of the non-conventional passive voltage transformer (EOVT)

Voltage level outdoor transformer	420 kV
Voltage level GIS transformer	66 to 170 kV
Accuracy class rating	0.2
Frequency range	> 5 kHz
Output signal (secondary electronics)	4.8 V AC at U_{rated} (100 V interface for conventional connection also available)
Operating temperature range	– 25 °C to + 70 °C

Table 10-12

Technical data of the non-conventional passive current transformer (MOCT)

Measurement range	0 to 32 kA_{eff}
Rated current	2 000 A
Rated short-time current	50 kA (1 s)
Voltage level	420 kV
Accuracy class rating	0.2 in the range 4 .... 4 000 A
Frequency range	> 5 kHz
Output signal measurement (secondary electronics)	2.0 V AC (at I_{rated})
Output signal protection (secondary electronics)	2.0 V AC (at 10 x I_{rated}) (1 A interface for conventional connection also available)
Operating temperature range	– 50 °C to + 70 °C
Max. transmission length	800 m
Weight of measurement recorder	approx. 18 kg

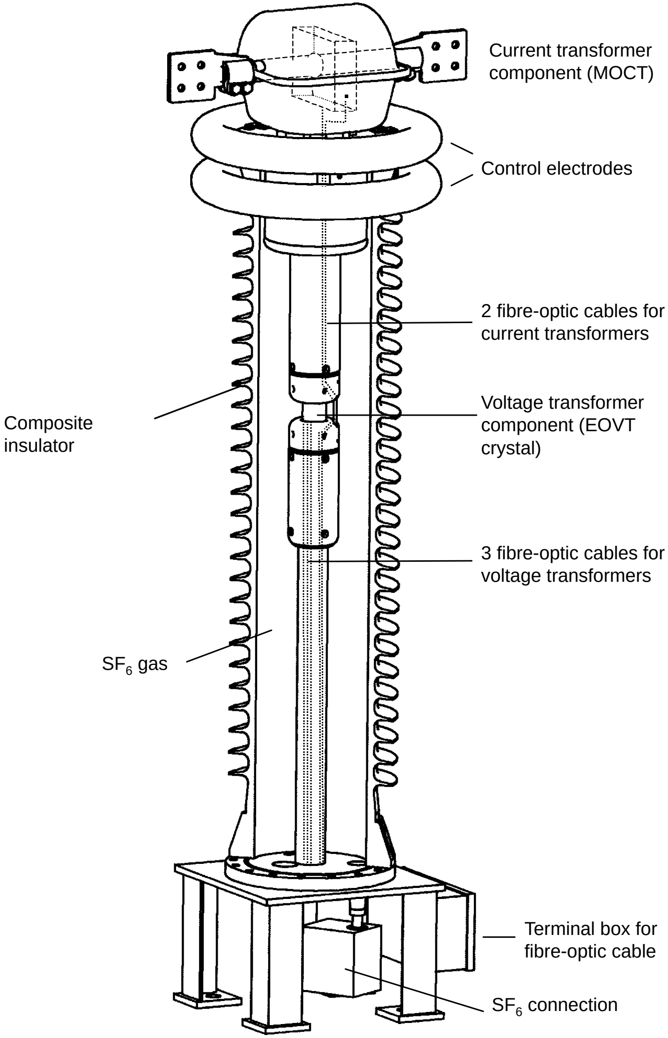


Fig. 10-33

Outdoor design of a combined non-conventional current/voltage transformer in passive optical technology

10.6 Surge arresters

10.6.1 Design, operating principle

The operation and design of the surge arrester has radically changed over the last twenty years.

Arresters with spark gap with series-connected silicon carbide (SiC) resistors have been replaced by surge arrester technology without spark gap and with metal-oxide resistors. The former porcelain housing is also being replaced more and more by polymer insulation. DIN EN 60 099-4 (VDE 0675 Part 4) contains detailed information on the new arrester technology.

The gapless arresters are based on metal oxide (MO) resistors, which have an extremely non-linear U/I characteristic and a high energy-absorption capability. They are known as metal oxide surge arresters, MO arresters for short.

The MO arrester is characterized electrically by a current/voltage curve (Fig. 10-34). The current range is specified from the continuous operating range (range A of the curve, order of magnitude 10^{-3} A) to a minimum of the double value of the rated discharge current (order of magnitude 10^3 A). The MO arrester corresponding to the characteristic is transferred from the high-resistance to the low-resistance range at rising voltage without delay. When the voltage returns to the continuous operating voltage U_c or below, the arrester again becomes high-ohmic.

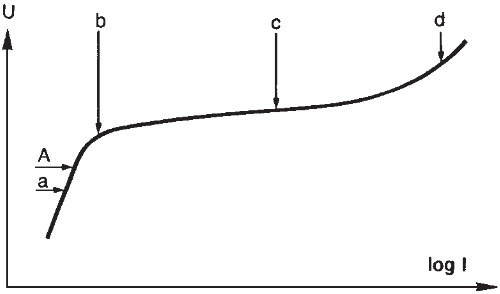


Fig. 10-34

Current-voltage characteristic of a metal oxide resistor; a Lower linear part, b Knee point, c Strongly non-linear part, d Upper linear part (“turn up” area), A Operating point (continuous persistent voltage)

The protective level of the MO arrester is set by its residual voltage U_P. The residual voltage is defined as the peak value of the voltage at the terminals of the arrester when a surge current flows. A surge current with a front time of about 1 µs, a time to half-value of up to 10 µs and a current of up to 10 kA represents very steep overvoltage waves, and the associated residual voltage is comparable to the front sparkover voltage of spark-gapped arresters.

A surge current with a front time of about 8 µs and a current intensity of up to 10 kA yields a residual voltage that is approximately equal to the protection level with lightning surge voltage. The current wave with a front time between 30 µs and 100 µs corresponds to a switching voltage pulse. The residual voltage with this wave form at 1 kA yields the protection level for switching voltages.

Surge arresters are protective devices that may be overloaded under extreme fault conditions. In such cases, e.g. when voltage leaks from one network level to the other, a single-phase earth fault occurs in the resistor assembly of the arrester. The pressure relief ensures that porcelain housings do not explode. The earth-fault current of the network at the arrester site must be less than the guaranteed current for the pressure relief of the relevant arrester. Fig. 10-35 shows the structural design of an MO arrester with a polymer housing.

Today, MO arresters for protection of medium-voltage equipment almost always have composite housings of silicon polymer. This insulation material allows the metal oxide resistors to be directly surrounded without gas inclusions. This type, in contrast to arresters with porcelain or other tube material, does not require a pressure-relief device for a possible overload. Because the polymeric arresters are substantially lighter, have a better response under contamination layer conditions and the arrester cannot fall apart in the event of an overload, this new technology is becoming more and more common even for arresters for high voltage.

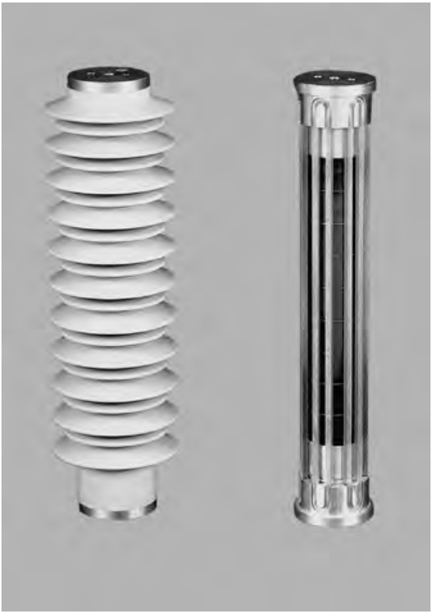


Fig.10-35

Cutaway view (principle design) of a metal oxide surge arrester, type POLIM-H

10.6.2 Application and selection of MO surge arresters

Surge arresters are used for protection of important equipment, particularly transformers, from atmospheric overvoltages and switching overvoltages. MO arresters are primarily selected on the basis of two basic requirements:

- the arrester must be designed for stable continuous operation,
- it must provide sufficient protection for the protected equipment.

Stable continuous operation means that the arrester is electrically and mechanically designed for all load cases that occur under standard operation and when system faults occur. This requires that the electrical and mechanical requirements are known as precisely as possible. The magnitude of the maximum power-frequency voltage, magnitude and duration of the temporary overvoltages and the anticipated stresses caused by switching and lightning overvoltages must all be known. In addition, the stress caused by short-circuit current forces and special environmental conditions, e.g. pollution, ambient temperatures over 45 °C, installation in earthquake regions etc., are very important.

When selecting the arrester by its electrical data, there must be an appropriate margin between the protection level of the arrester and the insulation levels standardized for the applicable operating voltage to meet the requirements of the insulation coordination as per DIN EN 60 071-1 (VDE 0111 Part 1) (Fig. 10-36).

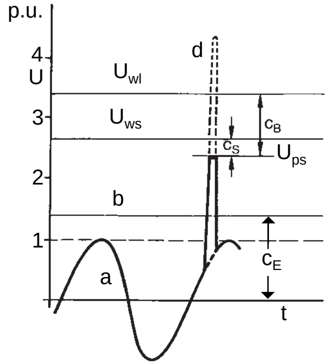
Parallel connecting of MO resistor columns allows every technically necessary dimension of the energy-absorption capability to be implemented at equivalent protection levels. Doubling the number of columns can reduce the protection level and almost double the energy-absorption capability.

DIN EN 60099-5 (VDE 0675 Part 5) outlines the correct selection of MO arresters.

Fig.10-36

Arrester selection for a low-resistance earthed network ($c_E = 1,4$) in range II ($U_m \geq 245$ kV) as per DIN EN 600099-5 (VDE 0675 Part 5)

a	*maximum power frequency conductor-ground voltage in the normally operating network (1 p.u. = peak value)*
b	*peak value of the maximum temporary power frequency conductor-ground voltage at earth fault in an adjacent phase*
c_E	*earth fault factor (= 1.4)*
d	*switching impulse overvoltage (limited by arrester to U_{ps})*
U_{ps}	*switching impulse protection level of the arrester*
U_{wL}	*rated lightning impulse voltage for equipment-standardized values*
U_{wS}	*rated switching impulse voltage for equipment-standardized values*



C_B, C_S *safety margins*

For MO arresters, the *continuous operating voltage* U_c is defined as the maximum power frequency voltage that the arrester can withstand continuously. The peak value of the continuous operating voltage of the arrester must be higher than the peak value of the operating voltage. On one hand, it is determined by the power-frequency voltage that corresponds to the maximum voltage in the network; but on the other hand, possible harmonics of the voltage must be considered. In normal networks, a safety margin of 5% over the power frequency system voltage is sufficient.

The *rated voltage* U_r of an MO arrester is the reference value to the power frequency voltage versus time characteristic and is decisive for the selection of the arrester with reference to temporary overvoltages. During the operating duty test of an MO arrester type, a test voltage of U_r is applied immediately following the surge current for a period of 10 s to the test object.

U_r is the 10 s value in the power frequency voltage versus time characteristic of the arrester. Peak values of the permissible power-frequency alternating voltage for other periods (U_t , T_t) are taken from the characteristic submitted by the manufacturer or derived approximately for period T_t in s between 0.1 s and 100 s by calculation as in the following equation:

$$U_t = \sqrt{2}\, U_r \left(\frac{10}{T_t}\right)^m$$

m = arrester-specific exponent, average value 0.02
Possible causes of the occurrence of temporary overvoltages include

- Earth fault
- Load shedding
- Resonance phenomena and
- Voltage increases over long lines

The following selection recommendations can be formulated based on the neutral treatment in networks:

Arresters between line and earth

- In networks with automatic earth-fault interruption, the continuous operating voltage U_c of the arrester should be equal to or greater than the peak value of the maximum operating voltage of the network against ground divided by $\sqrt{2}$
- In networks with earth-fault neutralizing or isolated neutral point without automatic fault disconnection, the continuous operating voltage should be greater than or at least equal to the maximum operating voltage of the network.

Arresters between phases

- The continuous operating voltage must be at least 1.05 times the maximum service voltage.

Neutral-point arresters

- For networks with low-resistance neutral-point configuration, the continuous operating voltage U_c of the arresters is derived from the dielectric strength specified for the neutral point of the equipment.
- For networks with earth-fault compensation or with insulated neutral point, the continuous operating voltage should be at least equal to the maximum service voltage divided by $\sqrt{3}$

Table 10-13 shows recommended standard values for selecting MO arresters (under the asumption that no additional temporary overvoltages occur) for some current nominal system voltages and the earth-fault factors appearing there.

Table 10-13

Recommended values for MO arresters according to the continuous operating voltage U_c and the associated rated voltage U_r

Nominal system voltage kV	Phase arrester				Neutral-point arrester			
	at $C_E = 1.4$		at $C_E = \sqrt{3}$		at $C_E = 1.4$		at $C_E = \sqrt{3}$	
	U_c kV	U_r kV	U_c kV	U_r kV	U_c kV	U_r kV	U_c kV	U_r kV
6	–	–	7,2	9	–	–	> 4,7	> 5,9
10	–	–	12	15	–	–	> 7,8	> 9,75
20	–	–	24	30	–	–	> 15,6	> 12,5
30	–	–	36	45	–	–	> 23,4	> 29,3
110	75	126	123 1)	144 1)	50	78	72	84
220	160	216 2)	–	–	60	108	–	–
380	260	360 2)	–	–	110	168	–	–

1) Lower values are possible if the duration of the earth fault is accurately known.

2) Higher values are set for generator transformers.

After specifying the continuous operating voltage and the rated voltage of the arrester that is to be used, selection is based on the energy-absorption capability required by the system conditions (rated discharge current and line discharge class). The following selection recommendation for rated discharge current can be set as a general guideline:

Distribution networks of up to 52 kV	
– sufficient under standard conditions	5 kA
– at higher lightning intensity, cable units, capacitors, specially important analogues	10 kA
– specially high lightning loads	20 kA
Transmission networks of up to 420 kV	10 kA
Transmission networks over 420 kV	20 kA

In specially supported cases, it may be necessary to determine the required energy-absorption capability more accurately, e.g. as follows

- Closing or reclosing long lines,
- Switching capacitors or cables with non-restrike-free switching devices,
- Lightning strikes in overhead lines with high insulation level or back flashovers near the installation site.

If the calculated energy content exceeds the energy quantity absorbed at the duty test of the arresters, an arrester with higher rated discharge current or parallel connected arresters must be selected.

Surge arresters are preferably installed parallel to the object to be protected between phase and earth. Because of the limited protection distance with steep lightning impulse voltages, the arresters must be installed immediately adjacent to the equipment that is to be protected (e.g. transformer) as much as possible. The size of the protection distance of an arrester is dependent on a whole series of influencing parameters. It increases as follows:

- the difference between rated lightning impulse voltage of the equipment and the protection level (U_{pl}) of the arrester,
- the limitation of the peak value of the incoming lightning surge voltage wave by the mast type of the overhead line before the substation (e.g. grounded cross-arms or timber masts),

but also from the point of view of the insulation coordination with

- the decrease of the lightning strike rate of the overhead line (e.g. shielding by overhead ground wire) and with
- the increase of the fault rate that is still considered acceptable for the equipment that must be estimated.

Examples for the size of protection ranges in outdoor switchgear installations for various rated system voltages under practice-relevant conditions are shown in Table 10-14. Permissible fault rates of 0.25% per year for the equipment and lightning strike rates of 6 per 100 km x year for the 24 kV overhead lines and of 2 per 100 km x year for the high-voltage lines are assumed.

Table 10-14

Guidance values for the protection range of MO arresters

Network nominal voltage kV	Arrester protection level kV	Rated lightning impulse withstand voltage kV	Protection distance m
24	80	125	3[1)]/15[2)]
123	350	550	24
420	900	1425	32

[1)] Overhead line with timber masts (without grounding)

[2)] Overhead line with grounded cross-arms

The ABB travelling wave program for testing larger switchgear installations can be used to calculate the temporal course of the voltage at all interesting points of the installation.

In overhead lines with cable feed, the travelling wave through the cable with overvoltages must be calculated by reflection in spite of the depression. Arrester A1 is to be provided for protection of the cable in short cable units ($l_k \leq 5$ m) and arrester A3 for protection of the transformer, see fig. 10-37. however, if $l_k > 5$ m, the cable must be protected on both sides with arresters A1 and A2. In this case, arrester A3 can only be omitted with the transformer if the protection range of arrester A2 is greater thanl_1.

Cable units within an overhead line should be protected immediately adjacent to the two end seals with arresters.

Surge counters may be used to monitor surge arresters. They are installed in the ground conductor of the arrester that is to be monitored; the arresters must be installed insulated against ground.

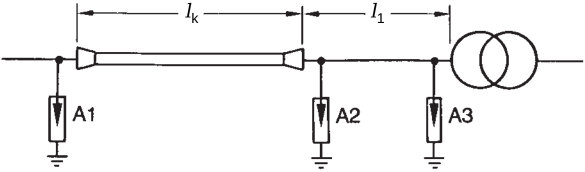


Fig.10-37

Overvoltage protection of the cable link of overhead lines, l_K*: length of cable unit,* l_1*: distance cable / transformer, A1 & A2 arresters for protection of the cable, A3 arrester for protection of the transformer*

11 High-Voltage Switchgear Installations

11.1 Summary and circuit configuration

11.1.1 Summary

A switchgear installation contains all the apparatus and auxiliary equipment necessary to ensure reliable operation of the installation and a secure supply of electricity. Three-phase a.c. high-voltage switchgear installations with operating voltages of up to 800 kV are used for distributing electricity in towns and cities, regions and industrial centres, and also for power transmission. The voltage level employed is determined by the transmission capacity and the short-circuit capacity of the power system.

Distribution networks are operated predominantly up to 123 kV. Power transmission systems and ring mains round urban areas operate with 123, 245 or 420 kV, depending on local conditions. Over very large distances, extra high powers are also transmitted at 765 kV or by high-voltage direct-current systems.

Switchgear installations can be placed indoors or outdoors. SF_6 gas-insulated switching stations have the important advantage of taking up little space and being unaffected by pollution and environmental factors.

Indoor installations are built both with SF_6 gas-insulated equipment for all voltage ratings above 36 kV and also with conventional, open equipment up to 123 kV. SF_6 technology, requiring very little floor area and building volume, is particularly suitable for supplying load centres for cities and industrial complexes. This kind of equipment is also applied in underground installations.

Outdoor switching stations are used for all voltage levels from 52 to 765 kV. They are built outside cities, usually at points along the cross-country lines of bulk transmission systems. Switchgear for HVDC applications is also predominantly of the outdoor type.

Transformer stations comprise not only the h.v. equipment and power transformers but also medium- and low-voltage switchgear and a variety of auxiliary services. These must additionally be accounted for in the station layout.

Depending on the intended plant site, the construction of a switchgear installation must conform to IEC requirements, VDE specifications (DIN VDE 0101) or particular national codes.

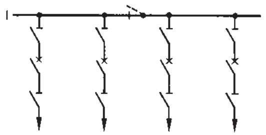
The starting point for planning a switchgear installation is its single-line diagram. This indicates the extent of the installation, such as the number of busbars and branches, and also their associated apparatus. The most common circuit configurations of high and medium-voltage switchgear installations are shown in the form of single-line diagrams in Section 11.12.

11.1.2 Circuit configurations for high- and medium-voltage switchgear installations

The circuit configurations for high- and medium-voltage switchgear installations are governed by operational considerations. Whether single or multiple busbars are necessary will depend mainly on how the system is operated and on the need for sectionalizing, to avoid excessive breaking capacities. Account is taken of the need to isolate parts of the installations for purposes of cleaning and maintenance, and also of future extensions.

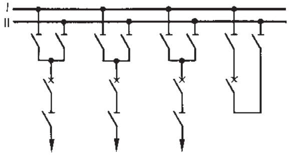
When drawing up a single line-diagram, a great number of possible combinations of incoming and outgoing connections have to be considered. The most common ones are shown in the following diagrams.

Common circuit configurations



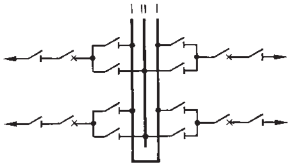
Single busbars

Suitable for smaller installations. A sectionalizer allows the station to be split into two separate parts and the parts to be disconnected for maintenance purposes.



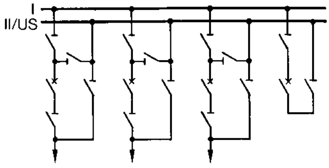
Double busbars

Preferred for larger installations. Advantages: cleaning and maintenance without interrupting supply. Separate operation of station sections possible from bus I and bus II. Busbar sectionalizing increases operational flexibility.



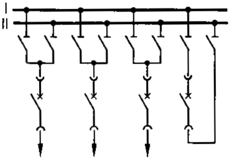
Double busbars in U connection

Low-cost, space-saving arrangement for installations with double busbars and branches to both sides.



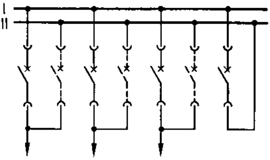
Composite double bus/bypass bus

This arrangement can be adapted to operational requirements. The station can be operated with a double bus, or with a single bus plus bypass bus.



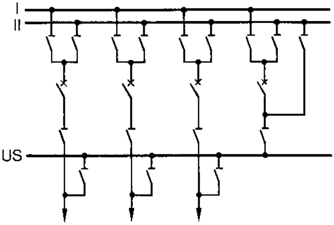
Double busbars with draw-out circuit-breaker

In medium-voltage stations, draw-out breakers reduce downtime when servicing the switchgear; also, a feeder isolator is eliminated.



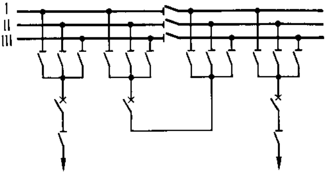
Two-breaker method with draw-out circuit-breakers

Draw-out circuit-breakers result in economical medium-voltage stations. There are no busbar isolators or feeder isolators. For station operation, the draw-out breaker can be inserted in a cubicle for either bus I or bus II.



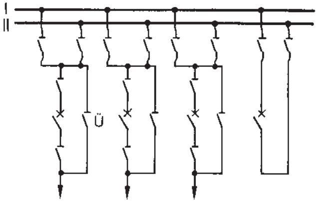
Double busbars with bypass busbar (US)

The bypass bus is an additional busbar connected via the bypass branch. Advantage: each branch of the installation can be isolated for maintenance without interrupting supply.



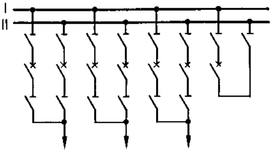
Triple (multiple) busbars

For vital installations feeding electrically separate networks or if rapid sectionalizing is required in the event of a fault to limit the short-circuit power. This layout is frequently provided with a bypass bus.



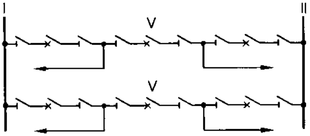
Double busbars with shunt disconnector

Shunt disconnector “U” can disconnect each branch without supply interruption. In shunt operation, the tie breaker acts as the branch circuit-breaker.



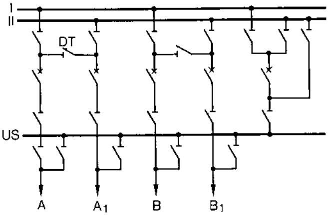
Two-breaker method with fixed switchgear

Circuit-breaker, branch disconnector and instrument transformers are duplicated in each branch. Busbar interchange and isolation of one bus is possible, one branch breaker can be taken out for maintenance at any time without interrupting operation.



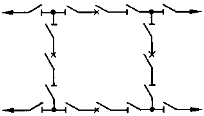
1 ½-breaker method

Fewer circuit-breakers are needed for the same flexibility as above. Isolation without interruption. All breakers are normally closed. Uninterrupted supply is thus maintained even if one busbar fails. The branches can be through-connected by means of linking breaker V.



Cross-tie method

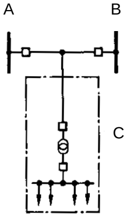
With cross-tie disconnector “DT”, the power of line A can be switched to branch A_1, bypassing the busbar. The busbars are then accessible for maintenance.



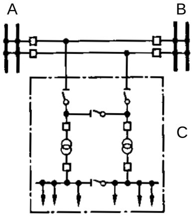
Ring busbars

Each branch requires only one circuit-breaker, and yet each breaker can be isolated without interrupting the power supply in the outgoing feeders. The ring busbar layout is often used as the first stage of 1 ½-breaker configurations.

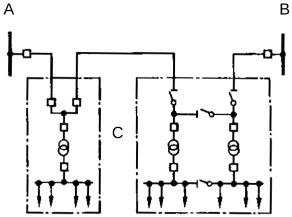
Configurations for load-centre substations



Single-feed station



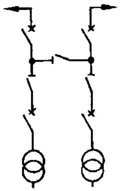
Double-feed station



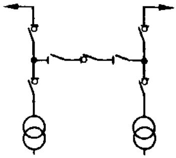
Ring stations

A and B = Main transformer station, C = Load-centre substation with circuit-breaker or switch disconnector. The use of switch-disconnectors instead of circuit-breakers imposes operational restrictions.

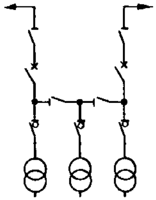
Switch-disconnectors are frequently used in load-centre substations for the feeders to overhead lines, cables or transformers. Their use is determined by the operating conditions and economic considerations.



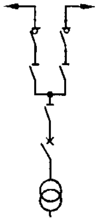
H connection with circuit-breakers



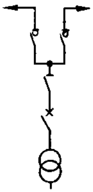
H connection with switch-disconnectors



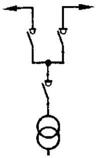
H connection with 3 transformers



Ring main cable connection allowing isolation in all directions

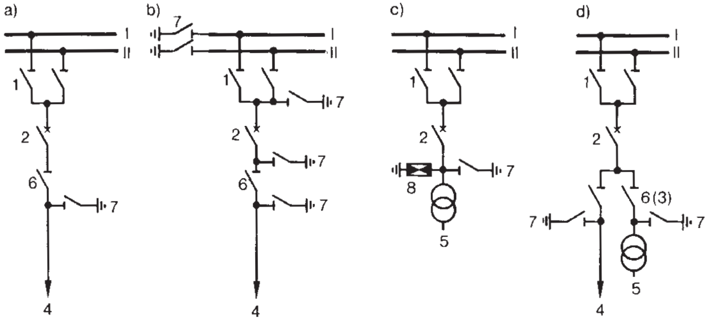


Simple ring main cable connection



Cable loop

Branch connections, variations a) to d)



1 Busbar disconnector, 2 Circuit-breaker, 3 Switch-disconnector, 4 Overhead-line or cable branch, 5 Transformer branch, 6 Branch disconnector, 7 Earthing switch, 8 Surge arrester

a) Overhead-line and cable branches

Earthing switch 7 eliminates capacitive charges and provides protection against atmospheric charges on the overhead line.

b) Branch with unit earthing

Stationary earthing switches 7 are made necessary by the increase in short-circuit powers and (in impedance-earthed systems) earth-fault currents.

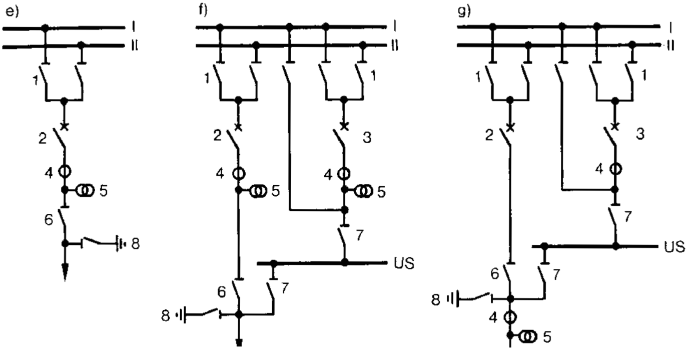
c) Transformer branches

Feeder disconnectors can usually be dispensed with in transformer branches because the transformer is disconnected on both h.v. and l.v. sides. For maintenance work, an earthing switch 7 is recommended.

d) Double branches

Double branches for two parallel feeders are generally fitted with branch disconnectors 6. In load-centre substations, by installing switch-disconnectors 3, it is possible to connect and disconnect, and also through-connect, branches 4 and 5.

Connections of instrument transformers, variations e) to g)



1 Busbar disconnectors, 2 Branch circuit-breaker, 3 Bypass circuit-breaker, 4 Current transformers, 5 Voltage transformers, 6 Branch disconnector, 7 Bypass disconnectors, 8 Earthing switch

e) Normal branches

The instrument transformers are usually placed beyond the circuit-breaker 2, with voltage transformer 5 after current transformer 4. This is the correct arrangement for synchronizing purposes. Some kinds of operation require the voltage transformer beyond the branch disconnectors, direct on the cable or overhead line.

f) Station with bypass busbar

Instrument transformers within branch.

The instrument transformers cease to function when the bypass is in operation. Line protection of the branch must be provided by the instrument transformers and protection relays of the bypass. This is possible only if the ratios of all transformers in all branches are approximately equal. The protection relays of the bypass must also be set for the appropriate values. Maintenance of the branch transformers is easier and can be done during bypass operation. If capacitive voltage transformers are used which also act as coupling capacitors for a high-frequency telephone link, this link is similarly inoperative in the bypass mode.

g) Station with bypass busbar

Instrument transformers outside branch.

In bypass operation, the branch protection relays continue to function, as does the telephone link if capacitive voltage transformers are used. It is only necessary to switch the relay tripping circuit to the bypass circuit-breaker 3. Servicing the transformers is more difficult since the branch must then be out of operation.

The decision as to whether the instrument transformers should be inside or outside the branch depends on the branch currents, the protection relays, the possibility of maintenance and, in the case of capacitive voltage transformers, on the h.f. telephone link.

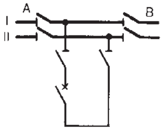
Busbar coupling connections

A and B = Busbar sections, LTr = Busbar sectioning disconnector

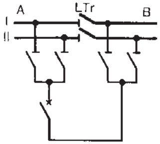
In the configurations earlier in this chapter, the tie-breaker branches are shown in a simple form. Experience shows, however, that more complex coupling arrangements are usually needed in order to meet practical requirements concerning security of supply and the necessary flexibility when switching over or disconnecting. This greater complexity is evident in the layouts for medium- and high-voltage installations.

Division into two bays is generally required in order to accommodate the equipment for these tie-breaker branches.

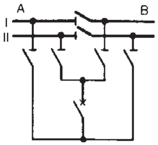
Double busbars



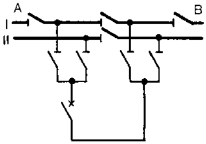
Bus coupling SSI/II
for A or B



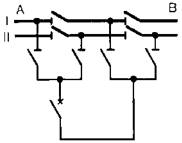
Section coupling for A-B
Bus coupling SSI/ll via
disconnector LTr



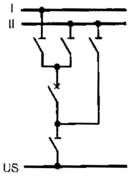
6-tie coupling
Section coupling for
A-B Bus
coupling SSI/II for A or B



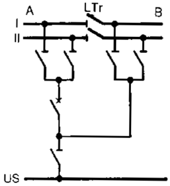
Section coupling for A-B
Bus coupling SSI/ll for
A or B via tie-breaker
bus ll



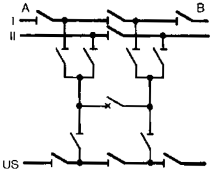
8-tie coupling
Section coupling for
A-B Bus coupling SSI/II
for A or B



Bus coupling SSI/ll
Bypass (US) coupling
SSI or II to bypass

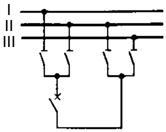


Section coupling for A-B
Bus coupling SSI/ll via
LTr Bypass coupling A
direct, B via LTr to
bypass

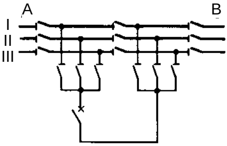


13-tie coupling
Most flexible method of
section, bus and bypass
coupling

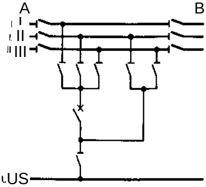
Triple busbars



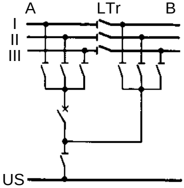
Bus coupling SSI/II/III



Section- and bus coupling for all possible ties between the 6 sections A-B



Bus coupling SSI/II/III for A or B
Bypass coupling SSI/II/III
to bypass (US) for A or B



Section coupling for A-B,
Bus coupling SSI/II/III via LTr,
Bypass coupling A SSI/II/III
to bypass,
Bypass coupling B/ bypass via LTr

11.2 SF_6 gas-insulated switchgear (GIS)

11.2.1 General

The range of application of SF_6 gas-insulated switchgear extends from voltage ratings of 72.5 up to 800 kV with breaking currents of up to 63 kA, and in special cases up to 80 kA. Both small transformer substations and large load-centre substations can be designed with GIS technology.

The distinctive advantages of SF_6 gas-insulated switchgear are: compact, low weight, high reliability, safety against touch contact, low maintenance and long life. Extensive in-plant preassembly and testing of large units and complete bays reduces assembly and commissioning time on the construction site.

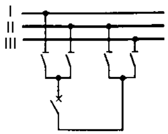
GIS equipment is usually of modular construction. All components such as busbars, disconnectors, circuit-breakers, instrument transformers, cable terminations and joints are contained in earthed enclosures filled with sulphur hexafluoride gas (SF_6).

The "User Guide for the application of GIS" issued by CIGRÈ WG 23-10 includes comprehensive application information.

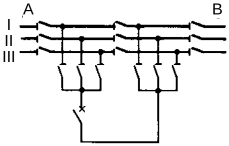
Up to ratings of 170 kV, the three phases of GIS are generally in a common enclosure, at higher voltages the phases are segregated. The encapsulation consists of non-magnetic and corrosion-resistant cast aluminium or welded aluminium sheet.

Table 11-1 shows an overview of the various sizes.

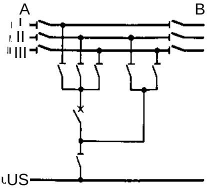
Triple busbars



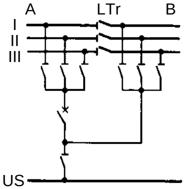
Bus coupling SSI/II/III



Section- and bus coupling for all possible ties between the 6 sections A-B



Bus coupling SSI/II/III for A or B
Bypass coupling SSI/II/III
to bypass (US) for A or B



Section coupling for A-B,
Bus coupling SSI/II/III via LTr,
Bypass coupling A SSI/II/III
to bypass,
Bypass coupling B/ bypass via LTr

11.2 SF_6 gas-insulated switchgear (GIS)

11.2.1 General

The range of application of SF_6 gas-insulated switchgear extends from voltage ratings of 72.5 up to 800 kV with breaking currents of up to 63 kA, and in special cases up to 80 kA. Both small transformer substations and large load-centre substations can be designed with GIS technology.

The distinctive advantages of SF_6 gas-insulated switchgear are: compact, low weight, high reliability, safety against touch contact, low maintenance and long life. Extensive in-plant preassembly and testing of large units and complete bays reduces assembly and commissioning time on the construction site.

GIS equipment is usually of modular construction. All components such as busbars, disconnectors, circuit-breakers, instrument transformers, cable terminations and joints are contained in earthed enclosures filled with sulphur hexafluoride gas (SF_6).

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Up to ratings of 170 kV, the three phases of GIS are generally in a common enclosure, at higher voltages the phases are segregated. The encapsulation consists of non-magnetic and corrosion-resistant cast aluminium or welded aluminium sheet.

Table 11-1 shows an overview of the various sizes.

Table 11-1

Rating data and dimensions of the GIS range from 72.5 to 800 kV

Range	EXK-01	ELK-04	ELK-14	ELK-34	ELK-4
Service voltage in kV	72.5 – 123	145 – 170	245 – 300	362 – 550	800
Lightning impulse voltage	550	750	1050	1550	2000
Breaking current in kA	40	40 – 50	40 – 63	40– 63	40 – 50
Load current in A	2 500	3150	4000	6300	6300
Bay width in m	0.8/1.0	1.2	1.7	2.7	4.5
Bay height in m	2.3	3.0	3.5	4.8	7.5
Bay depth in m	3.2	4.6	5.1	6.0	8.0
Bay weight in t	2.5	3.7	7.0	11.0	14.0

11.2.2 SF_6 gas as insulating and arc-quenching medium

Sulphur hexafluoride gas (SF_6) is employed as insulation in all parts of the installation, and in the circuit-breaker also for arc-quenching. SF_6 is an electronegative gas, its dielectric strength at atmospheric pressure is approximately three times that of air. It is incombustible, non-toxic, odourless, chemically inert with arc-quenching properties 3 to 4 times better than air at the same pressure, see also Section 10.4.4.

Commercially available SF_6 is not dangerous, and so is not subject to the Hazardous Substances Order or Technical Regulations on Hazardous Substances (TRGS). New SF_6 gas must comply with IEC 60376 (VDE 0373 Part 1). Gas returned from SF_6 installations and apparatus is dealt with in IEC 60480 (VDE 0373 Part 2). SF_6 released into the atmosphere is considered a greenhouse gas. With its contribution to the greenhouse effect below 0.1%, the proportion of SF_6 is low compared to that of the better known greenhouse gases (carbon dioxide, methane, nitrous oxide etc.). To prevent any increase of SF_6 in the atmosphere, its use should in future be confined to closed systems. Devices suitable for processing and storing SF_6 gas are available for this purpose. The gas pressure is monitored in the individually sealed gas compartments and in the circuit-breaker housing. The low gas losses (below 1 % per year) are taken into account with the first gas filling. Automatic make-up facilities are not necessary.

The isolating gas pressure is generally 350 to 450 kPa at 20 °C. In some cases this can be up to 600 kPa. The quenching gas pressure is 600 to 700 kPa. Outdoor apparatus exposed to arctic conditions contains a mixture of SF_6 and N_2, to prevent the gas from liquefying. The pressure-temperature relationship of pure SF_6 gas is shown in Fig. 11-1.

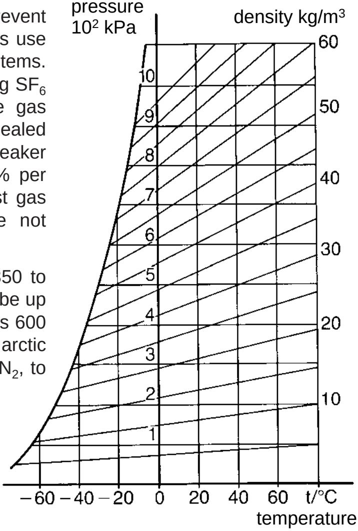


Fig. 11-1

p/t diagram of pure SF_6 gas

Arcing causes the decomposition of very small amounts of SF_6 gas. The decomposition products react with water, therefore the gas's moisture content, particularly in the circuit-breaker, is controlled by drying (molecular) filters. Careful evacuation before first gas filling greatly reduces the initial moisture content. Fig. 11-2 illustrates the conversion of water vapour content into dewpoint, see also Section 15.5.2.

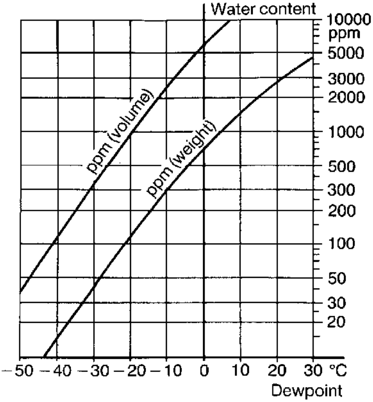


Fig. 11-2

Conversion of water vapour content into dewpoint

11.2.3 GIS for 72.5 to 800 kV

SF_6 switchgear type EXK/ELK

For voltages from 72.5 to 800 kV ABB has five graduated module sizes of the same basic design available. The modular construction offers the advantages of quantity production, standard components, simple stocking of spares and uniform performance. By combining the various components of a module size, it is possible to assemble switching installations for all the basic circuit configurations in Section 11.1.2.They are thus able to meet every layout requirement.

As a general recommendation, the intended location for totally enclosed equipment should comply with the requirements of DIN VDE 0101 for indoor switchgear installations. The buildings can be of lightweight construction, affording some protection against the outdoor elements. With minor modifications, GIS apparatus can also be installed outdoors.

Components

The *busbars* are segregated by barrier insulators at each bay and form a unit with the busbar disconnectors and the maintenance earthing switches.

The *circuit-breaker* operates on the self-blast principle. Conventional puffer-type breakers use the mechanical energy of the actuator to generate the breaker gas stream while the self-blast breaker uses the thermal energy of the short-circuit arc for this purpose. This saves up to 80% of the actuation energy. Depending on their size, the breakers have one to four breaker gaps per pole. They have single- or triple-pole actuation with hydraulic spring mechanisms, see also Section 10.4.4 and 10.4.5.

Switch-disconnectors are used in smaller distribution substations. These are able to switch load currents and connect and disconnect transformers as well as unloaded lines and cables. They are able to close onto short-circuit currents and carry them for a short time. They also work on the single-pressure puffer principle and have a motor-driven spring operating mechanism.

The *current transformers* for measuring and protection purposes are of the toroidal-core type and can be arranged before or after the circuit-breaker, depending on the protection concept. Primary insulation is provided by SF_6 gas, so it is resistant to ageing. Iron-free current transformers using the Rogowski coil principle are used with SMART-GIS. They allow quantized evaluation of short-circuit currents and so make it possible to create a contact erosion image of the circuit-breaker.

Voltage transformers for measurement and protection can be equipped on the secondary side with two measuring windings and an open delta winding for detecting earth faults.

Inductive voltage transformers are contained in a housing filled with SF_6 gas. Foil-insulated voltage transformers are used, with SF_6 as the main insulation.

Capacitive voltage transformers can also be employed, usually for voltages above 300 kV. The high-voltage capacitor is oil-insulated and contained in a housing filled with SF_6 gas. The low-voltage capacitors and the inductive matching devices are placed in a separate container on earth potential. Capacitive tappings in conjunction with electronic measuring amplifiers are also available.

Electro-optical voltage transformers using the Pockels principle are also used with SMART-GIS.

The *cable sealing end* can accommodate any kind of high voltage cable with conductor cross-sections up to 2000 mm^2. Isolating contacts and connection facilities are provided for testing the cables with d.c. voltage. If there is a branch disconnector, it is sufficient to open this during testing.

Plug-in cable sealing ends for cross-linked polyethylene cables are available for voltages of up to 170 kV. They consist of gas-tight plug-in sockets, which are installed in the switchgear installation, and prefabricated plugs with grading elements of silicone rubber. Plug-in cable sealing ends do not have insulating compound. They are half as long as the standard end seal.

The make-proof *earthing switch* can safely break the full short-circuit current. A stored-energy mechanism with a motorized winding mechanism gives it a high closing speed. It may also be manually actuated.

Maintenance earthing switches, which may be required during servicing, are usually placed before and after the circuit-breaker. Normally mounted on or integrated in the isolator housing, they are operated by hand or motor only when the high-voltage part is dead. The maintenance earthing switch after the circuit-breaker may be omitted if there is a high-speed earthing switch on the line side.

SF_6 outdoor bushings allow the enclosed switchgear to be connected to overhead lines or the bare terminals of transformers. To obtain the necessary air clearances at the outdoor terminals, the bushings are splayed using suitably shaped enclosure sections.

SF_6 oil bushings enable transformers to be connected directly to the switchgear, without outdoor link. The bushing is bolted straight to the transformer tank. A flexible bellows takes up thermal expansion and erection tolerances and prevents vibration of the tank due to the power frequency from being transmitted to the switchgear enclosure.

SF_6 busbar connections are chiefly suitable for transmitting high powers and currents. They can be used for large distances, e.g. from an underground power plant or transformer station to the distant overhead line terminal, also refer to Section 11.2.7.

The *surge arresters* are generally of the gap-less type and contain metal oxide resistors. If the installation is bigger than the protected zone of the line-side arrester, arresters can also be arranged inside the installation. It is generally advisable to study and optimize the overvoltage protection system, particularly with distances of more than 50 m.

Each bay has a control cubicle containing all the equipment needed for control, signalling, supervision and auxiliary power supply.

The gastight enclosure of high-grade aluminium is of low weight so that only light foundations are required. The enclosure surrounds all the live parts, which are supported on moulded-resin insulators and insulated from the enclosure by SF_6 gas at a pressure of 350 to 450 kPa.

Barrier insulators divide the bay into separate gas compartments sealed off from each other. This minimizes the effects on other components during plant extensions, for example, or in case of faults, and also simplifies inspection and maintenance. The flanged joints contain non-ageing gaskets. Any slight leakage of gas can pass only to the outside, but not between the compartments.

The circuit-breaker in Fig. 11-3 has one extinction chamber per phase, that in Fig. 11-6 has three. Depending on the breaking capacity, a pole can have up to four extinction chambers connected in series. As shown in Table 11-1, the breakers can handle breaking currents of up to 63 kA.

In branches where only load currents have to be switched, up to a rated voltage of 362 kV switch-disconnectors can be used instead of circuit-breakers for economic reasons.

Each switching device is provided with an easily accessible operating mechanism (arranged outside the enclosure) with manual emergency operation. The contact position can be seen from reliable mechanical position indicators.

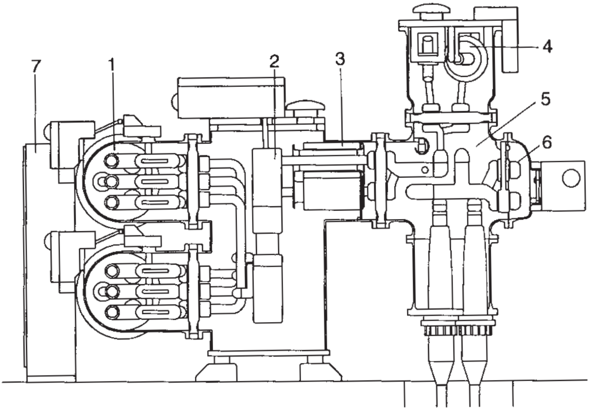


Fig. 11-3

SF_6 GIS for 123 to 170 kV, section through a bay, double busbar and cable branch
1 Busbar with combined disconnector / maintenance earthing switch, 2 Circuit-breaker, 3 Current transformer, 4 Voltage transformer, 5 Combined disconnector / maintenance earthing switch with cable sealing end, 6 High-speed earthing switch, 7 Control cubicle

11.2.4 SMART-GIS

A characteristic of SMART-GIS is replacement of conventional secondary technology, such as transformers, contactors and auxiliary switches with modern sensor technology and actuators. Inductive proximity switches and rotary transducers detect the position of the switching devices; the SF_6 gas density is calculated from the gas pressure and temperature. Actuators control the trip solenoids and the electric motors of the mechanisms. Specially designed sensors detect current and voltage. Rogowski coils and electro-optical voltage transformers without ferromagnetic components are generally used for this purpose. To ensure secure transmission of signals, fibre-optic cables instead of the conventional hard-wired connections are used within the bay and for connection to the station control system.

The process is controlled and monitored by decentralized distributed computer-supported modules (PISA = Process Interface for Sensors and Actuators), which communicate with one another and with higher-order control components via a process bus.

All sensors and the entire electronics for data processing and communications are self-monitoring and software routines continuously check the hardware in use.

Timer controls can be set for important data. Critical states can be avoided before they affect operation and maintenance. This results in a reduced reserve and redundancy requirement in the system and improved economy of operation.

11.2.5 Station arrangement

Gas supply

All enclosed compartments are filled with gas once at the time of commissioning. This includes allowance for any leakage during operation (less than 1 % per year). All the gas compartments have vacuum couplings, making gas maintenance very easy, most of which can be done while the station remains in operation. The gas is monitored by density relays mounted directly on the components.

Electrical protection system

A reliable protection system and electrical or mechanical interlocks provide protection for service staff when carrying out inspections and maintenance or during station extension, and safeguard the equipment against failure and serious damage.

The fast-response busbar protection system is recommended for protecting the equipment internally.

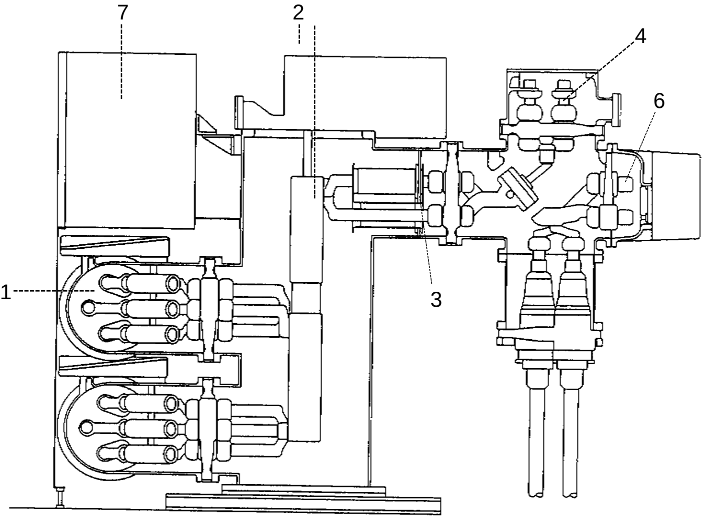


Fig. 11-4

SMART-GIS Type EXK-01 for 72.5 to 123 kV, section through a switchbay with double busbar and cable feeder, 1 Busbar with combined disconnector and earthing switch, 2 Circuit-breaker, 3 Current sensor (Rogowski coil), 4 Electro-optical voltage transformer, 6 Make-proof earthing switch, 7 Control cubicle

Earthing

Being electrically connected throughout, the switchgear enclosure acts as an earth bus. It is connected at various points to the station earthing system. For inspection or during station extension, parts of the installation can be earthed with suitably positioned maintenance earthing switches. Protective earthing for disconnected cables, overhead lines or transformers is provided by short-circuit make-proof earthing switches located at the outgoing feeders.

By short-circuiting the insulation between earthing switch and metal enclosure during operation, it is possible to use the earthing switch to supply low-voltage power or to measure switching times and resistances. Thus there is no need to intervene inside the enclosure.

Erection and commissioning

Only lightweight cranes and scaffolding are required. Cranes of 5000 kg capacity are recommended for complete bays, lifting gear of 2000 to 4000 kg capacity is sufficient for assembling prefabricated units.

Cleanliness on site is very important, particularly when erecting outdoors, in order to avoid dirt on the exposed parts of joints.

The completely installed substation undergoes a voltage test before entering operation. This is done with eighty per cent of the rated power-frequency test voltage or impulse withstand voltage. If a test transformer of suitable size is available, testing is done with a.c. voltage. Resonance test equipment or generators for oscillating switching surges are commonly used with rated voltages above 245 kV.

11.2.6 Station layouts

The modular construction of SF_6 switchgear means that station layouts of all the basic circuit configurations shown in Section 11.1 are possible.

For layout engineering, attention must be paid to DIN VDE 0101. Sufficiently dimensioned gangways must allow unhindered access to the components for erection and maintenance. Minimum gangway distances must be observed even when the cubicle doors are open. A somewhat larger floor area, if necessary at the end of the installation, facilitates erection and later extensions or inspection.

A separate cable basement simplifies cable installation and distribution. Where outdoor lines terminate only at one side of the building, the required clearances between bushings determine the position of the SF_6-switchgear bay. These are usually at intervals of three to four bays. If overhead line connections are brought out on both sides of the building or are taken some distance by means of SF_6 tube connections, the respective feeder bays can be next to each other.

Installations of the model ranges EXK-01 for 72.5/123 kV and ELK-0 for 145/170 kV as shown in Fig. 11-5 are extremely compact because of the three-phase encapsulation of all components. Combining busbar, disconnector and earthing switch into one assembly reduces the depth of the building.

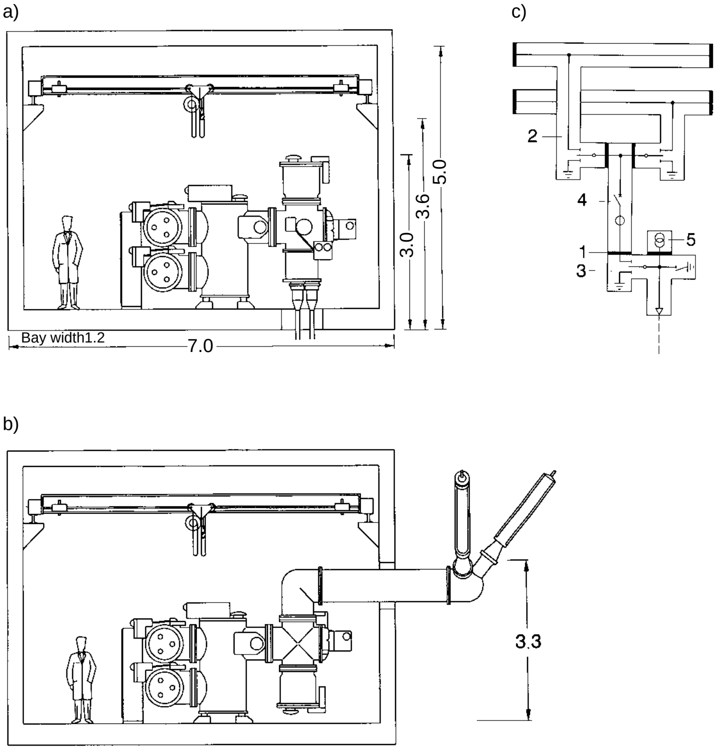


Fig. 11-5

SF_6 switchgear type ELK-04 for 123 to 170 kV with double busbar (dimensions in m)
a) Section at cable bay, b) Section at overhead line bay, c) Circuit and gas diagram at a)
1 Barrier insulator, 2 Busbar gas compartment, 3 Feeder gas compartment, 4 Circuit-breaker gas compartment, 5 Voltage transformer

Installations for rated voltages of 245 kV or more are single-phase encapsulated. This makes the components smaller and easier to handle. Busbar and busbar disconnector are combined in one assembly. The busbars are partitioned at each bay so that if access to the busbar compartment is necessary (e.g. for station extension) only small amounts of gas have to be stored. Partitioning each bay avoids damage to adjacent bays in the event of a fault.

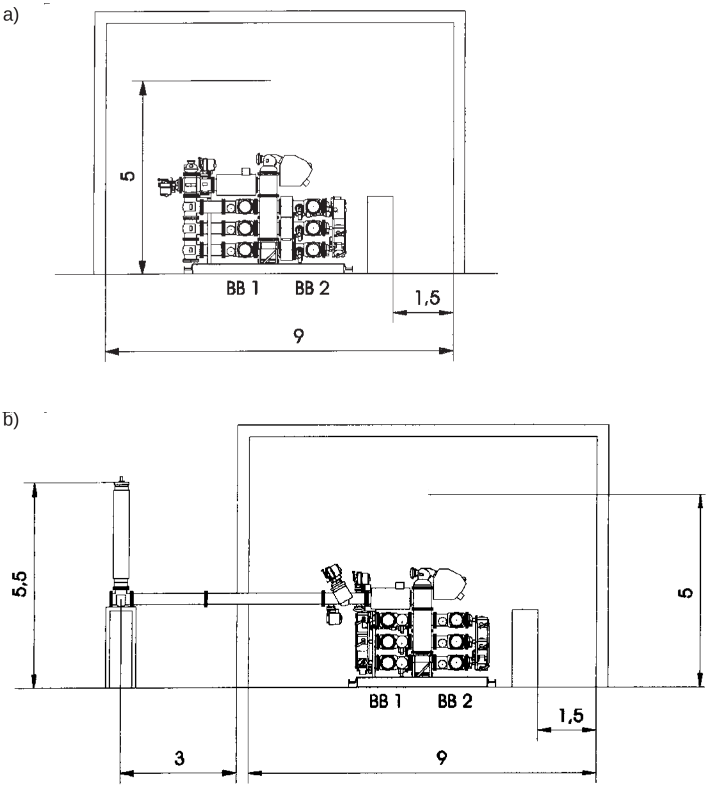


Fig. 11-6

SF_6 switchgear installation type ELK-14 for rated voltage 245 to 300 kV (dimensions in m) a) Cable feeder, b) Overhead Line branch

The structural type with standing breaker is preferred in all installation layouts. This allows the interrupter chambers to be easily removed from the circuit-breakers with a crane or lifting gear.

Single busbars, formerly used only for small installations, have become more important owing to the high reliability of the apparatus and its outstanding availability. Plant operation has become less complicated by dividing the station into sections by means of bus-ties.

Bypass buses with their disconnectors add another busbar system to stations with single or double busbars. The bypass bus enables any circuit-breaker to be isolated without interrupting the feeders.

A special form of the single busbar is the H connection or double H connection. It is employed chiefly for load centres in urban and industrial areas. These stations often have switch-disconnectors instead of circuit-breakers.

Combined busbars: In GIS stations with double busbars the second busbar is increasingly used as a bypass bus with the aid of an additional disconnector, resulting in a so-called combined busbar. This greatly improves the station availability at little extra cost.

11.2.7 SF_6-insulated busbar links

SF_6-insulated busbar links are particularly suitable for transmitting high power. They complement the usual cables and overhead lines for voltages above 72.5 kV, see Table 11-2.

They have the following advantages over cable links: greater transmission capacity with smaller losses, low charging power, non-ageing oil-free insulation, earthed enclosure with full earth-fault current carrying capacity. Large differences in height are easily overcome. Bridging considerable distances is possible without shunt reactors.

SF_6-insulated tie links are often left exposed, particularly for shorter distances or in walkable, covered ducts. Owing to the low ohmic losses, extra cooling is generally unnecessary.

Table 11-2

Rating data and dimensions of the SF_6 insulated busbar connections type CGI (typical values)

Service voltage	kV	72.5	123	145	245	420	550	800
Transmission output								
above ground	MVA	175	450	525	1200	3250	4800	7400
underground	MVA	125	250	300	650	1600	2200	3300
Rated current, underground	A	1000	1200	1200	1500	2100	2300	2400
Losses at rated current, 3ph	W/m	115	105	105	120	148	154	180
Weight with SF_6 gas, 1ph	kg/m	13.2	14.5	14.5	30.9	44.7	50.3	59.3
Gas pressure at 20 °C	kPa	420	420	420	420	420	420	420
External diameter	mm	165	240	240	310	470	510	620
Centre-to-centre distance of phases	mm	305	370	370	460	660	710	810
Right-of-way width	mm	1200	1300	1300	1500	2100	2300	2600

11.3 Outdoor switchgear installations

11.3.1 Requirements, clearances

The minimum clearances in air and gangway widths for outdoor switching stations are as stated in DIN VDE 0101 or specified by IEC. They are listed in the rated insulation levels as per DIN EN 60071-1 (VDE 0111 Part 1) (see Table 4-10 in Section 4.6.1). Where installation conditions are different from the standardized atmospheric conditions, e.g. installations at high altitudes, they must be taken into account by the atmospheric correction factor by determining the required withstand voltage in the course of the insulation coordination (compare Section 4.1).

Where phase opposition cannot be ruled out between components having the same operating voltage, the clearances must be at least 1.2 times the minimum values. The minimum distance between parts at different voltage levels must be at least the value for the higher voltage level.

When wire conductors are used, the phase-to-phase and phase-to-earth clearances during swaying caused by wind and short-circuit forces are allowed to decrease below the minimum values. The values by which the clearances are permitted to extend below the minima in this case are stated in DIN VDE 0101, Para. 4.4.

Equipment for outdoor switching stations is selected according to the maximum operating voltage on site and the local environmental conditions. The amount of air pollution must be taken into account, as on outdoor insulators, it can lead to flashovers. The hazard these represent can be influenced by the shape of the insulator, by extending the creepage distance, by siliconizing and by cleaning. IEC 60815 defines various degrees of contamination and specifies minimum creepage distances in relation to the equipment's maximum voltage U_m (see Table 11-3).

Table 11-3

Degree of contamination		Examples	Minimum creepage distance mm/kV
I	slight	Predominantly rural areas without industry and far from sea air	16
II	moderate	Areas in which little severe pollution is expected	20
III	severe	Industrial areas with relatively severe pollution, sea air, etc.	25
IV	very severe	Areas with heavy industry and much dust, fog, sea air	31

Lengthening the creepage distance with the same insulator height is not an effective method of preventing flashovers due to pollution deposits.

11.3.2 Arrangement and components

Surge arresters

Surge arresters for limiting atmospheric and switching overvoltages are described in Section 10.6. The protection zone of an arrester is limited. For rated voltages of 123 kV, the arrester should therefore not be further than approx. 24 m distant from the protected object, and for 245 to 525 kV, not further than approx. 32 m. The minimum distances from neighbouring apparatus must conform to the arrester manufacturer’s specific instructions.

PLC communication

The power line carrier (PLC) system is a means of communicating over high-voltage lines. A PLC link requires a line trap and capacitor or capacitive voltage transformer in one or two phases of the incoming lines, positioned as shown in Fig. 11-14.

Control cubicles and relay kiosks

In outdoor switchyards, the branch control cubicles are of steel or aluminium sheet or of plastic (GFR polyester-reinforced resin). The cubicles contain the controls for local operation, auxiliary equipment and a terminal block for connecting the control, measuring and auxiliary cables. The size depends on how much equipment they have to contain. In large switchyards, the cubicles are replaced by relay kiosks containing all the equipment for controlling and protecting two or more high-voltage branches.

Busbars and connections

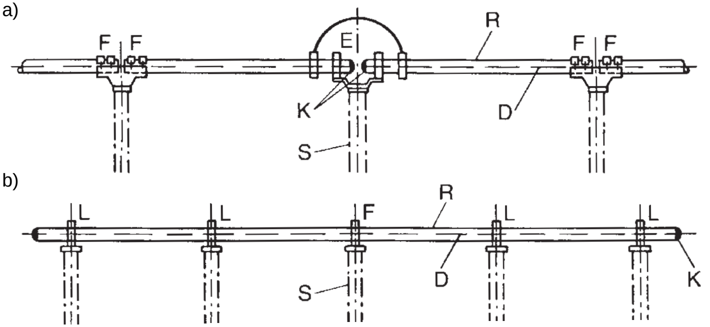
Busbars and the necessary connections to the equipment can be of wire or tube. Busbars are usually of aluminium/steel wire strung between double dead-end strings of cap-&-pin type or long-rod insulators with means of arc protection. Bundle conductors are employed for high voltages and high currents, and when single-column disconnectors are used. The tension of the wires is selected to be as small as possible to reduce stresses on the gantries. The choice of tension is further governed by the variation in sag.

In the case of spans carrying the stirrup contacts of single-column disconnectors, account must be taken of the difference in sag at temperatures of –5 °C plus additional load and +80 °C. The change in sag can be reduced by means of springs located at one end of the span between the dead-end string and the portal structure.

Wires with cross sections of at least 95 mm^2 are used for installations with a rated voltage of 123 kV. At higher operating voltages, wires of not less than 300 mm^2 or two parallel wires forming a bundle-conductor are employed in view of the maximum permissible surface voltage gradients (see Section 4.3.3). Tensioned conductors are usually of aluminium/steel and rarely of aluminium. Aluminium wire is used for connections to HV equipment where the conductors are not tensioned, but only strung loosely. Wires are selected on the basis of mechanical and thermal considerations, see Sections 4.2.2, 4.2.3, 4.3.1 and 13.1.4.

Tubes are more economical than wires with busbar currents of more than 3000 A. Suitable diameters of the aluminium tubes are 100 mm to 250 mm, with wall thicknesses from 6 to 12 mm. For the same conductor cross-section area, a tube of larger diameter has greater dynamic strength than one of smaller diameter. Tubular conductors can be mounted on post insulators in spans of up to 20 m or more. To avoid costly joints, the tubes are welded in lengths of up to 120 m. Aluminium wires are inserted loosely into the tubes to absorb oscillation. Dampers of various makes are another method of suppressing tube oscillations. Tubular conductors for busbars and equipment interconnections are sized according to both thermal and dynamic considerations, see Sections 4.2.1, 4.3.2, 4.4.6 and 13.1.2.

Common tubular conductor arrangements for busbars and equipment links are shown in Fig. 11-7.



c)

Tube dia. mm	Max. span without damping wire m	Aluminium wire mm^2
100	4.5	240
120	5.5	300
160	7.5	500
200	9.5	625
250	12.0	625

Fig. 11-7

Use of tubular conductors for busbars and equipment interconnections
a) Tubes and damping wires cut at each support, b) Tubes welded across several supports, damping wire continuous, c) Recommended damping wires
L = Sliding tube support, F = Fixed tube support, E = Expansion joint, D = Damping wire, K = End cap, S = Support insulator, R = Tube

High-voltage terminals (connectors, clamps)

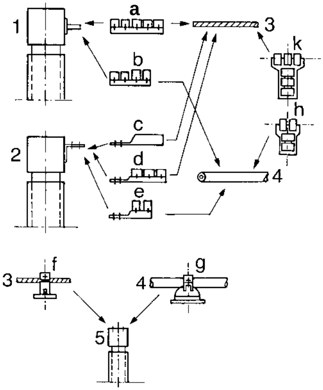
High-voltage HV terminals connect high-voltage apparatus to electrical conductors.

Their purpose is to provide a permanent, corona-free connection of sufficient thermal/ mechanical strength for continuous and short-circuit currents at the maximum operating voltage.

Unless specified otherwise, HV terminals conform to DIN VDE 48084, 46203 and 46206 Parts 2 and 3.

Besides current conducting terminals, the conductors require purely mechanical supports attaching them to the insulators, see Fig. 11-7.

The principal kinds of terminal connection are shown in Fig. 11-8.



1 HV apparatus with connection bolt
2 HV apparatus with flat pad
3 Stranded wire conductor
4 Tubular conductor
5 Support insulator
a Screw type terminal, bolt/wire
b Screw type terminal, bolt/tube
c Compression terminal with flat pad
d Screw type terminal flat pad / wire
e Screw type terminal flat pad / tube
f Conductor support for wire
g Conductor support for tube
h Tube connector
k Wire connector

Fig. 11-8

High-voltage terminals, alternative connections for outdoor switchgear installations

Depending on the installation site, straight, 45° angle or 90° angle HV terminals are used. With stranded wire connections, terminals are used for both a single stranded wire and for bundled wires.

HV terminals have to satisfy a number of technical requirements. To select the correct terminal, the following points need to be considered:

- design, e.g. screw type flat terminal
- material of body, screws
- conductor type, e.g. stranded wire Al 400 mm^2 to DIN 48201, dia. 26.0 mm
- contact area or surface of pin, e.g. flat terminal to DIN 46206 Part 3
- rated voltage, e.g. 380 kV
- surface voltage gradient
- rated current, e.g. 2000 A
- peak short-circuit current, e.g. $I_s = 80$ kA
- total opening time or short-circuit duration
- ambient temperatures
- ultimate temperatures terminal/conductor
- mechanical stress
- specific environmental factors

When connecting different materials, e.g. terminal bolt of Cu to stranded wire conductor of Al, a cover or plate of Cupal (a Cu/AI bimetal) is usually inserted between terminal and apparatus connector. Two-metal (Al/Cu) terminals are used where the local climate is unfavourable. The two different materials of these terminals are factory-bonded to prevent corrosion.

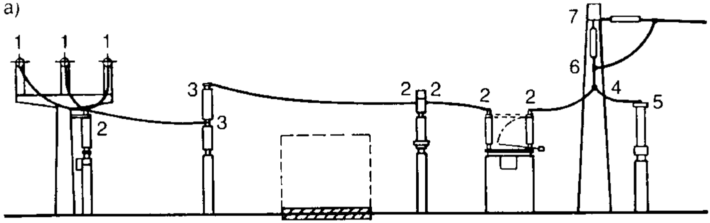
Special care is called for when selecting and using terminals and conductor supports for aluminium tubes $\geqq$ 100 mm diameter. The following additional criteria must be considered:

- elongation in the case of lengthy tubes
- tube supports, fixed or sliding
- tube oscillation induced by wind
- connection to apparatus, fixed or flexible (expansion joint)

see also Fig. 11-7.

Fig. 11-9 shows the terminal arrangement and a terminal listing for 110 kV outdoor branches.

a)



b)

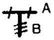
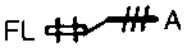
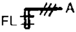
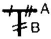
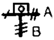
Pos.	Symbol	Mat.	Rated current (A)	Description	Total Qty.	Location	Bay 1 2 3
1		Al	850	T–terminal A = Al tube 63 dia., 2 caps B = Al wire 400 mm^2 (26.0 dia.) 3 caps	9	BB feeder	3 3 3
2		Al	850	Straight flat terminal, A = Al wire 400 mm^2 (26.0 dia.) 3 caps FL = flat term. to DIN 46206 P3	54	BB disconnector, Current transformer, Feeder disconnector	6 6 6 6 6 6 6 6 6
3		Al	850	90° flat terminal A = Al wire 400 mm^2 (26.0 dia.) 3 caps, FL = flat term. to DIN 46206 P3	18	Circuit-breaker	6 6 6
4		Al	850	Parallel connector A & B = Al wire 400 mm^2 (26.0 dia.), 3 screws	9	Voltage transformer drop off	3 3 3
5		Al with Cupal.	850	T–terminal A = Al wire 400 mm^2 (26.0 dia.) 3 caps B = Cu bolt 30 dia., 2 caps with Cupal cover	9	Voltage transformer connection	3 3 3
6		Al	680	T-terminal with hanger 19 dia. A = Al/St 265/35 mm^2 (22.4 dia.) 3 caps B = Al wire 400 mm^2 (26.0 dia.) 3 caps	9	Line connection	3 3 3
7		I_s =	31.5 kA/1s	110 kV V-suspension to GSHP 130212 Sh. 4	9	Line connection	3 3 3

Fig. 11-9

Example of a) terminal arrangement and b) terminal listing for three 110 kV outdoor branches

Support structures

The steel supporting structures for outdoor switchgear are made in the form of wide-flange, frame or lattice constructions (Fig. 11-10). A conductor pull of 10 to 40 N/mm^2 max. is specified for busbar supporting structures.

The strength of supporting structures, portals and foundations is calculated in accordance with DIN VDE 0210 for overhead line construction. The structures should be fitted with a ladder so that the span fixings can be cleaned and repaired. In 525 kV installations, handrails have proved an additional safeguard for personnel.

The supporting structures for switchgear, instrument transformers and arresters are of wide-flange, frame or lattice construction, sometimes precast concrete components are used. The choice depends on economic considerations, but also appearance.

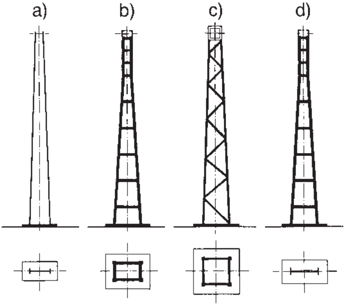


Fig 11-10

Examples of steel supporting structures for outdoor switchgear:
a) Wide-flange construction, b) Frame construction,
c) Lattice construction, d) A-tower construction

Foundations

The foundations for portals, HV switchgear and transformers are in the form of concrete blocks or rafts according to the soil's load-bearing capacity. The bottom of the foundation must be unaffected by frost, i.e. at a depth of some 0.8 to 1.2 m. The foundations must be provided with penetrations and entries for the earth wires and, where appropriate, for cables.

Access roads

Access roads in the usual sense are only rarely laid in 123 kV switchyards. The various items of switchgear, being built on the modular principle, can be brought by light means of transport to their intended position in the compound. The cable trench running in front of the apparatus serves as a footpath. It is usual to provide an equipment access route in large installations with relatively high voltages. A road or railway branch line is provided for moving the transformers.

Cable trenches, see Fig. 11-11

In outdoor installations, the cables are laid in covered trenches. Large switchyards lacking modern control facilities may require a tunnel with walking access and racks on one or both sides to accommodate the large number of control cables.

The main trenches follow the access road, the branch control cubicles being so placed that their foundations adjoin the trench. In view of the size of the covering slabs or plates, these cable trenches should not be more than 100 cm wide. Their depth depends on the number of cables. Cable supports are arranged along the sides. A descent in the lengthwise direction and drain holes ensure reliable drainage. In each branch, ducts are teed off from the control cubicle to the circuit-breaker, the instrument transformers and the isolator groups. The top of the main and branch ducts is slightly above ground level so that the trench remains dry even in heavy rain. Cable connections to individual items of equipment can also be laid in preformed troughing blocks or direct in the ground and covered with tiles.

See also civil construction requirements, Section 4.7.2.

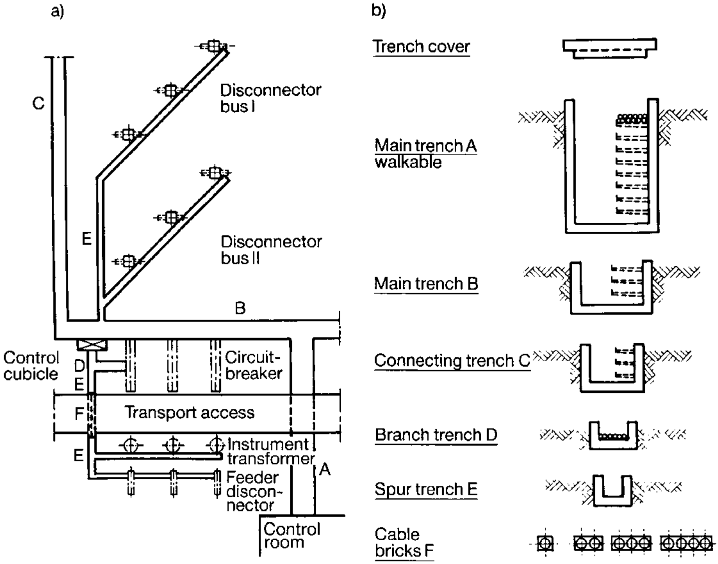


Fig. 11-11

a) Plan view of cable trench arrangement for a feeder, diagonal layout, b) Sizes of cable trenches

Protective screens, see Fig. 11-12

Equipment which stands low, e.g. circuit-breakers and instrument transformers on rails at 600 to 800 mm above ground level, must be provided with wire-mesh screens at least 1800 mm high, or railings at least 1100 mm high. The prescribed protective barrier distances must be observed (see Section 4.6.1).

Protective screens, railings and the like are not necessary within a switchyard if the minimum height to the top edge of the earthed insulator pedestal is 2250 mm, as specified in DIN VDE 0101, with account taken of local snow depths.

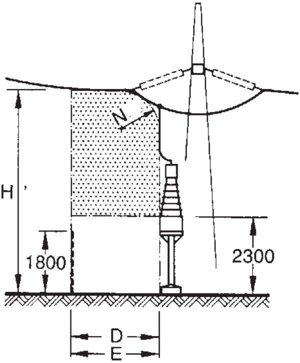


Fig. 11-12

Protective barrier clearances and minimum height H' at the perimeter fence. Distances as Table 4-11, C Solid wall, E wire-mesh screen

Perimeter fencing, see Fig. 11-12

The perimeter fence of an outdoor switching station must be at least 1800 mm high. The minimum clearance (between perimeter fence and live parts) must be observed. The perimeter fence is generally not connected to the station earth, owing to the danger of touch voltages, unless continuous separation is not possible (distance ≦ 2 m).

Station perimeter fences of conducting material must be earthed at intervals of no more than 50 m by means of driven earthrods or earthing strips at least 1 m in length, unless bonding is provided by means of a surface earth connection approximately 1 m outside the fence and about 0.5 m deep.

No special measures are required in the case of perimeter fences of plastic-coated wire mesh with plastic-coated or concrete posts.

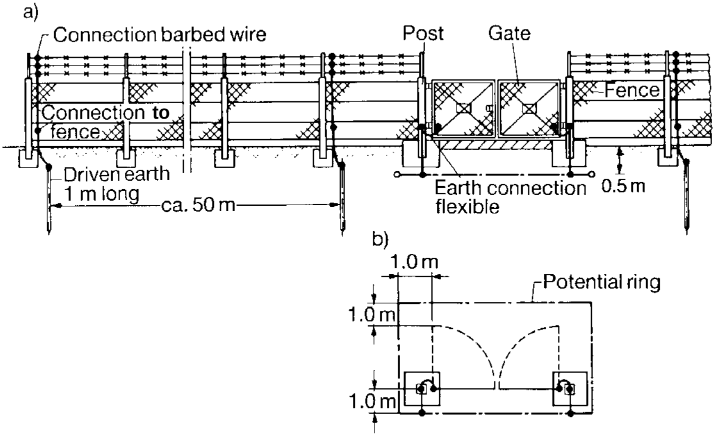


Fig. 11-13

Principle of fence earthing if distance from earth network to fence ⩾ 2 m a) Elevation, b) Plan view at gate

11.3.3 Switchyard layouts

General

The arrangement of outdoor switchgear installations is influenced by economic considerations, in particular adaptation to the space available and the operational requirements of reliability and ease of supervision. To meet these conditions, various layouts (see Table 11-4) have evolved for the circuit configurations in Section 11.1.2. Many electric utilities have a preference for certain arrangements which they have adopted as standard.

The spacing of the branches is determined by the switchyard configuration.

A span length of 50 m is economical for guyed wire (strain) busbars. The number and design of portal structures is governed by the overall length of the installation. The larger bay width T_1 and T_2 of the busbar step-down bays (starting bay, end bay) must be taken into account when planning the layout.

For stations with busbar current ratings above about 3000 A, tubular busbars offer a more economical solution than tensioned wires. In 123 kV stations, the tubular busbars are supported at each alternate bay, but at each bay with higher voltages.

The overhead lines leading from the transformer stations are generally also used for power-line carrier telephony. The necessary equipment (line trap, capacitor) is incorporated in the outgoing overhead lines as shown in Fig. 11-14.

Points in favour of rotary and vertical-break disconnectors are their mechanical simplicity and the fact that they are easier to position as feeder disconnectors. The single-column disconnector makes for a simple station layout owing to its isolating distance between the two line levels; it saves some 20% of the ground area needed for two-column disconnectors.

Table 11-4

Outdoor switchyard configurations, preferred application

Layout	≦ 145 kV	245 kV	420 kV	≧ 525 kV
Low rise (classical) layout	×	×		
In-line layout	×			
Transverse layout	×	×		
High-rise layout	×			
Diagonal layout		×	×	
1½-breaker layout		×	×	×

Each branch (bay) consists of the circuit-breaker with its disconnectors, instrument transformers and control cubicle. The apparatus is best placed at a height such that no fencing is needed. Here, it must be noted that according to DIN VDE 0101 (Fig. 4-37, Section 4.6.1), the height to the top edge of the earthed insulator base must be at least 2250 mm. The high-voltage apparatus is generally mounted directly on equipment support structures.

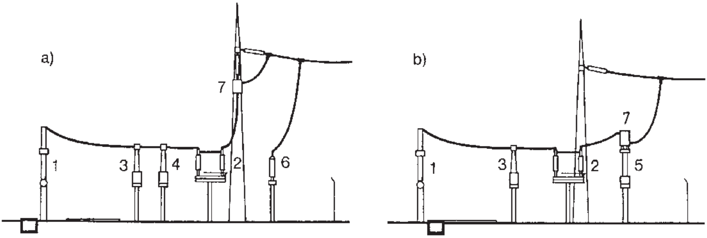


Fig. 11-14

Arrangement of overhead line bays for power-line carrier telephony:

a) Line trap suspended, capacitor standing,
b) Line trap mounted on capacitive voltage transformer,
1 Circuit-breaker, 2 Feeder disconnector, 3 Current transformer, 4 Inductive voltage transformer, 5 Capacitive voltage transformer, 6 Capacitor, 7 Line trap

Selected examples of switchyard layouts

With the *low-rise* (classical) layout (Fig. 11-15), the busbar disconnectors are arranged side by side in line with the feeder. The busbars are strung above these in a second level, and in a third plane are the branch lines, with connections to the circuit-breaker. A great advantage of this layout is that the breaker and transformer can be bypassed by reconnecting this line to the feeder disconnector. Features of this configuration are the narrow spacing between bays, but higher costs for portal structures and for means of tensioning the wires.

The classical layout is also used for stations employing the 2-breaker method.

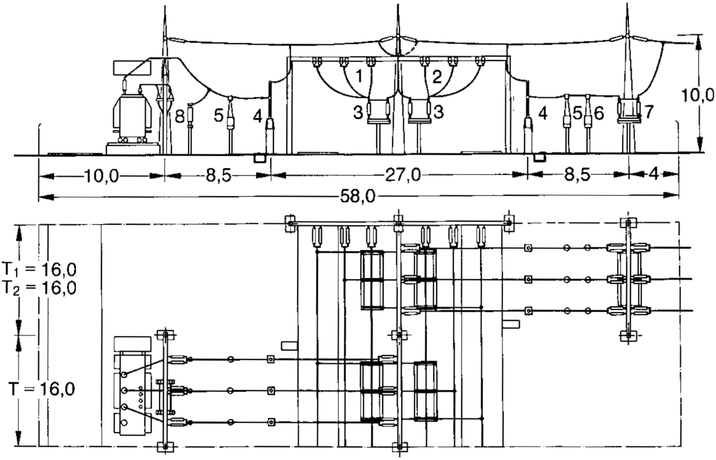


Fig. 11-15

245 kV outdoor switchyard with double busbars, low-rise (classical) layout:
1 Busbar system I, 2 Busbar system II, 3 Busbar disconnector, 4 Circuit-breaker, 5 Current transformer, 6 Voltage transformer, 7 Feeder disconnector, 8 Surge arrester; T Bay width, T_1 Width initial bay, T_2 Width final bay at busbar dead-end

An *in-line* layout with tubular busbars is shown in Fig. 11-16. It is employed with busbar current ratings of more than 3000 A. The poles of the busbar disconnectors stand in line with the busbars. Portals are needed only for the outgoing overhead lines. This arrangement incurs the lower costs for supporting steelwork and results in an extremely clear station layout.

In stations including a bypass bus, the layout chosen for the bypass bus and its disconnectors is the same as for the busbars. In stations with feeders going out on both sides, the bypass bus must be U-shaped so that all branches can be connected to it.

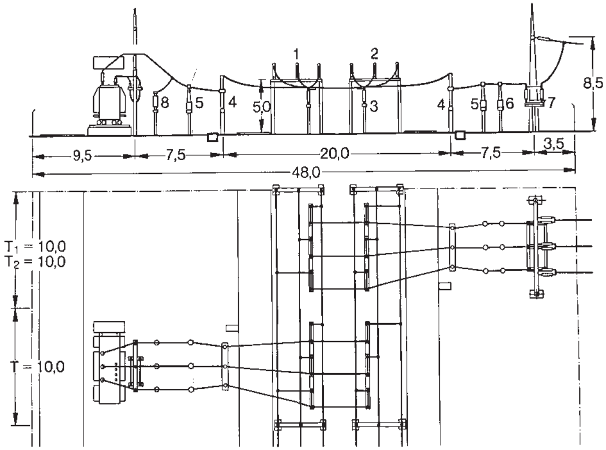


Fig. 11-16

123 kV outdoor switchyard with double busbars, in-line layout:
1 Busbar system I, 2 Busbar system II, 3 Busbar disconnector, 4 Circuit-breaker, 5 Current transformer, 6 Voltage transformer, 7 Feeder disconnector, 8 Surge arrester; T Bay width, T_1 Width initial bay, T_2 Width final bay. The busbars are tubular.

With the *transverse* layout, the poles of the busbar disconnectors are in a row at right angles to the busbar, see Fig. 11-17. With this arrangement too, the busbars can be of wire or tube. The outgoing lines are strung over the top and fixed to strain portals. Though the bay width is small, this arrangement results in a large depth of installation.

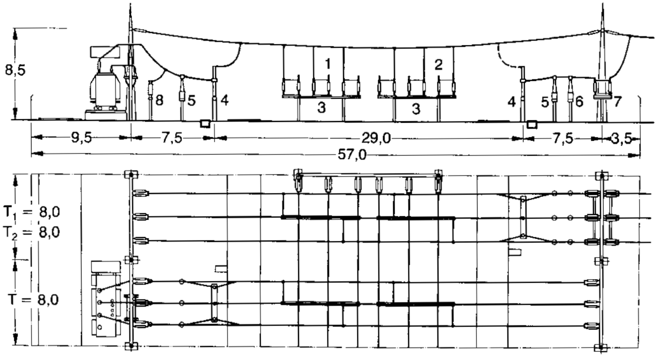


Fig. 11-17

123 kV outdoor switchyard with double busbars, transverse layout:
1 Busbar system I, 2 Busbar system II, 3 Busbar disconnector, 4 Circuit-breaker, 5 Current transformer, 6 Voltage transformer, 7 Feeder disconnector, 8 Surge arrester; T Bay width, T_1 Width initial bay, T_2 Width final bay.

Special layouts

Arrangements with draw-out breakers save a great deal of space, as the draw-out circuit-breaker does away with the need for disconnectors. The outgoing line simply includes an earthing switch. This configuration is used for stations with single busbars. The costs are low. The circuit-breaker is fitted with suitable plug-in contacts and a hydraulically operated truck.

Load-centre substations with one or two power transformers are usually in the form of simplified transformer stations. In Fig. 11-18, two incoming overhead lines connect to two transformers (H-connection). This gives rise to two busbar sections joined via two sectionalizers (two disconnectors in series). In this way, each part of the installation can be isolated for maintenance purposes. The bus sections can be operated separately or crosswise, ensuring great reliability and security of supply.

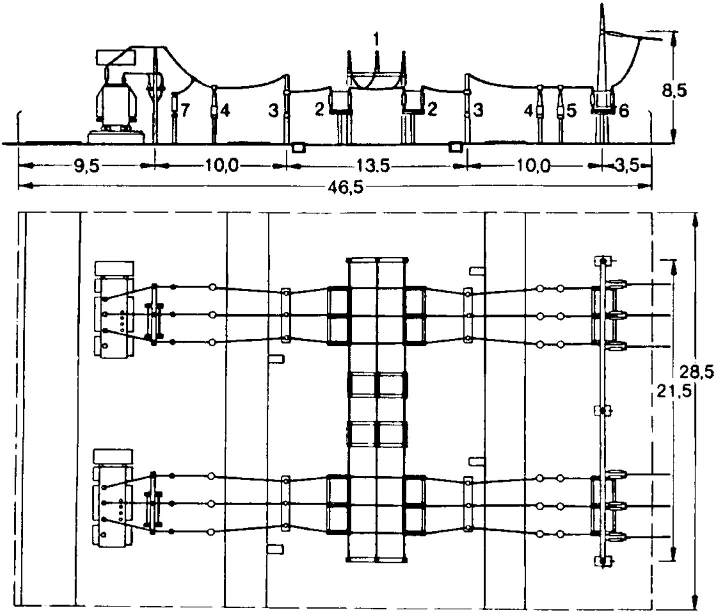


Fig. 11-18

123 kV load-centre station (H-connection): 1 Busbars, 2 Busbar disconnector, 3 Circuit-breaker, 4 Current transformer, 5 Voltage transformer, 6 Feeder disconnector, 7 Surge arrester.

Table 11-5 compares different layouts of 123-kV outdoor switchyards as regards area, foundations (volume) and steelwork (weight) for one line branch and one transformer branch with double busbar, assuming a total size of the substation of 5 bays.

Table 11-5

Comparison of different layouts for 123 kV

Type of branch (bay)	Overhead line			Transformer		
Type of layout	Area	Foundations (volume)	Steelwork	Area	Foundations (volume)	Steelwork except cable gantry on LV side
In-line (tubular busbars)	225 m^2	23.3 m^3	6.6 t	193 m^2	52.3 m^3	4.3 t
	100 %	100 %	100 %	100 %	100 %	100 %
Transverse (tubular busbars)	282 m^2	27.2 m^3	7.8 t	302 m^2	78.4 m^3	9.6 t
	125 %	117 %	118 %	156 %	150 %	223 %
Low-rise (classical, wire busbars)	192 m^2	33.9 m^3	8.4 t	201 m^2	81.3 m^3	8.8 t
	86 %	145 %	127 %	104 %	155 %	205 %

Table 11-6 compares different layouts of 245-kV outdoor switchyards as regards area, foundations (volume) and steelwork (weight) for one line branch and one transformer branch with double busbar and bypass bus or 1½-breaker layout.

Table 11-6

Comparison of different layouts for 245 kV

Type of branch (bay)	Overhead line			Transformer		
Type of layout	Area	Foundations (volume)	Steelwork	Area	Foundations (volume)	Steelwork except cable gantry on LV side
In-line (tubular busbars)	323 m^2	28.0 m^3	7.9 t	344 m^2	63.2 m^3	7.0 t
	100 %	100 %	100 %	100 %	100 %	100 %
Transverse (tubular busbars)	413 m^2	31.9 m^3	9.1 t	433 m^2	69.2 m^3	9.4 t
	128 %	114 %	115 %	126 %	110 %	134 %
Low-rise (classical, wire busbars)	324 m^2	38.6 m^3	10.4 t	369 m^2	83.1 m^3	12.5 t
	100 %	138 %	132 %	107 %	131 %	179 %
1½-breaker (tubular busbars)	267 m^2	27.4 m^3	8.1 t	301 m^2	47.7 m^3	8.5 t
	83 %	98 %	103 %	88 %	76 %	121 %

Diagonal layout

With this arrangement, the (single-column) busbar disconnectors are arranged diagonally with reference to the busbars. It is commonly used for 245 kV and 420 kV stations.

A distinction is made between two versions, depending on the position (level) of the busbars.

"Busbars above"

The advantage of this layout (Fig. 11-19) is that when a feeder is disconnected, the busbar disconnectors are also disconnected and are thus accessible.

For installations with current ratings of more than 3000 A and high short-circuit stresses, the busbars and jumper connections are made of tubes. Fig. 11-19 shows a 420 kV station in a diagonal layout and using tubes. The tubes are in lengths of one bay and mounted on the post insulators with a fixed point in the middle and sliding supports at either end. The busbars can be welded together over several bays up to about 120 m.

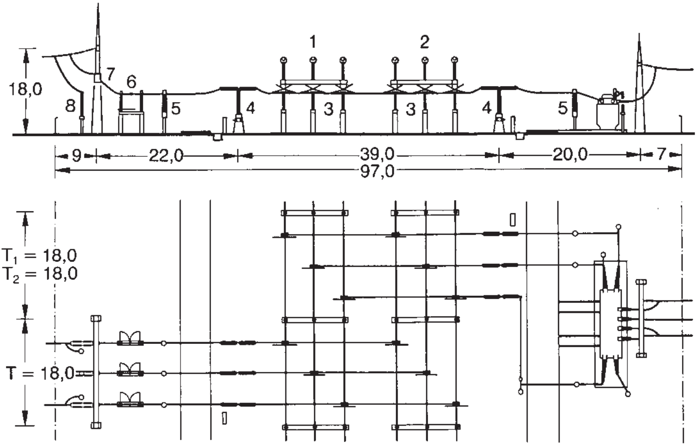


Fig. 11-19

420 kV outdoor switchyard with double busbars of tubular type, diagonal layout, busbars above: 1 Busbar system I, 2 Busbar system II, 3 Busbar disconnector, 4 Circuit-breaker, 5 Current transformer, 6 Feeder disconnector, 7 Line trap, 8 Capacitive voltage transformer. T Bay width, T_1 *Width initial bay,* T_2 *Width final bay*

"Busbars below"

With this arrangement, the busbars are mounted on the disconnectors with the outgoing lines strung at right angles to them. At their points of intersection, single-column disconnectors maintain the connection with their vertical isolating distance. This economical layout requires lightweight busbar strain portals only at the ends of the installation, and the bays are narrow. It can be of single or double-row form. The single-row arrangement (Fig. 11-20) is more space-saving. Compared with a two-row layout it requires about 20 % less area. The circuit-breakers for all outgoing lines are on the same side of the busbars so that only one path is needed for transport and operation. The lines to the transformers lie in a third plane.

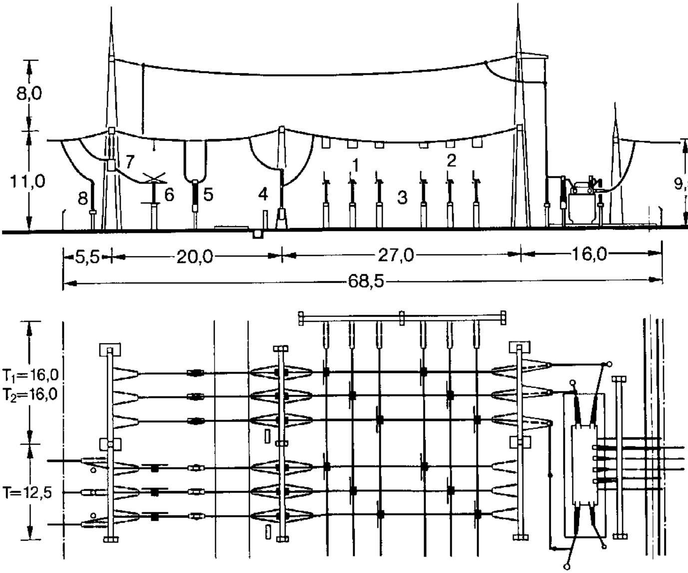


Fig. 11-20

245 kV outdoor switchyard with double busbars, diagonal layout, busbars below, single-row arrangement: 1 Busbar system I, 2 Busbar system II, 3 Busbar disconnector, 4 Circuit-breaker, 5 Current transformer, 6 Feeder disconnector, 7 Line trap, 8 Capacitive voltage transformer. T Bay width, T_1 Width initial bay, T_2 Width final bay with busbar dead-end.

The 420 kV switchyards of the German transmission grid are of the diagonal type. To meet the stringent demands of station operation and reliability, double or triple busbars with sectionalizing and an additional bypass bus are customary. Tube-type busbars are preferred. These can handle high current ratings and high short-circuit stresses.

The space-saving single-row layout with the circuit-breakers of all outgoing lines in one row is very effective here, too. Using two-column isolators on the feeders simplifies the layout. Single-column isolators are used for the busbars and the bypass bus (see Fig. 11-21).

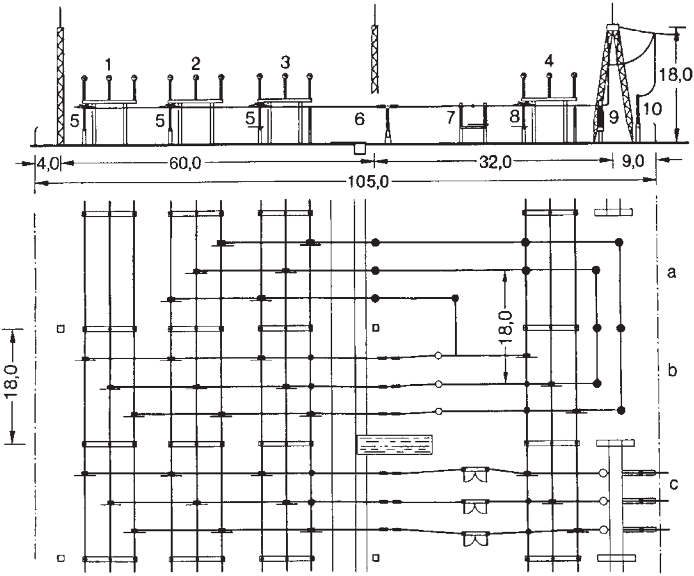


Fig. 11-21

420 kV outdoor switchyard with tubular conductors, triple busbars and bypass bus, diagonal layout, single-row arrangement:
1 Busbar system I, 2 Busbar system II, 3 Busbar system III, 4 Bypass bus, 5 Busbar disconnector, 6 Circuit-breaker, 7 Feeder disconnector, 8 Bypass disconnector, 9 Current transformer, 10 Voltage transformer; a and b Ties for busbars 1, 2 and 3 and bypass bus 4, c Outgoing line.

1 ½-breaker layout

The 1½-breaker configuration is used mainly in countries outside Europe. It is employed for all voltages above 110 kV, but predominantly in the very high voltage range.

The double busbars of these stations are arranged above, both outside or inside, and can be of tube or wire.

The more economical solution of stranded conductors is often used for the links to the apparatus, because with the relatively short distances between supports, even the highest short-circuit currents can exert only limited stresses on the equipment terminals.

The branches are always arranged in two rows. The disconnectors used are of the pantograph and two-column vertical-break types. Vertical-break disconnectors are employed in the outgoing line. Fig. 11-22 shows a section through one bay of a 525 kV station; the busbars are of wire. This arrangement allows the station to be operated on the ring bus principle while construction is still in progress, and before all the switchgear apparatus has been installed.

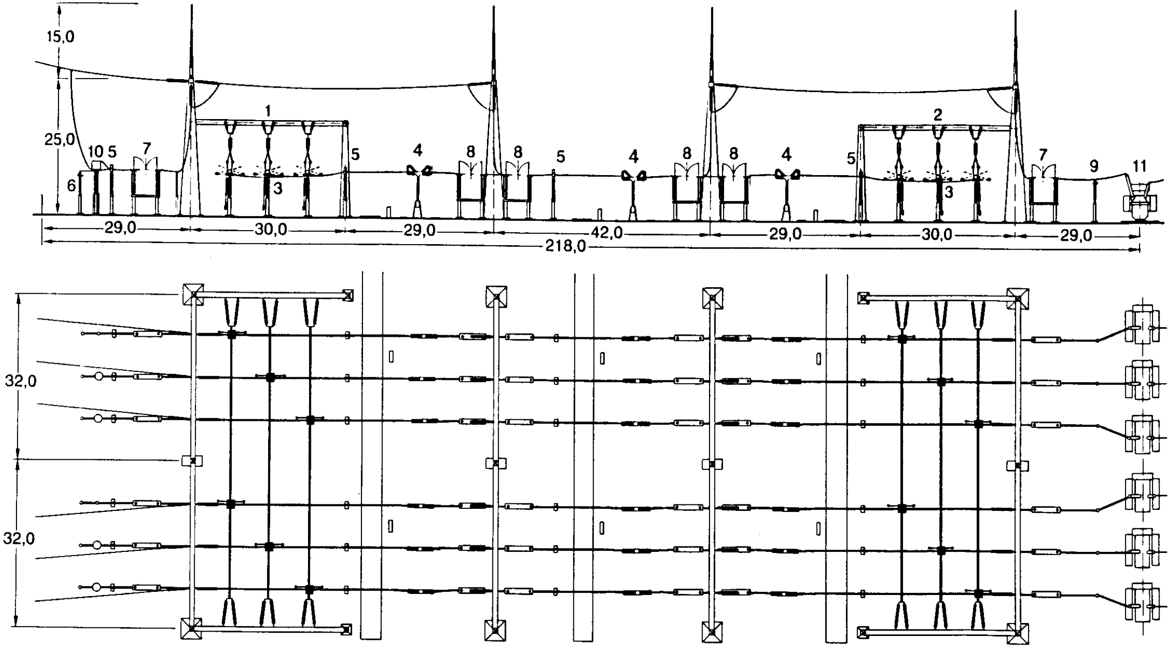


Fig. 11-22

525 kV outdoor switchyard, 1½-breaker layout: 1 Busbar system I, 2 Busbar system II, 3 Busbar disconnector, 4 Circuit-breaker, 5 Current transformer, 6 Voltage transformer, 7 Feeder disconnector, 8 Branch disconnector, 9 Surge arrester, 10 Line trap, 11 Transformer.

11.4 Innovative HV switchgear technology

11.4.1 Concepts for the future

The application of processors and modern information processing technology in substation and network control systems and also in secondary systems of switchgear installations, fast data bus systems that transmit over fibre-optic cables instead of copper wires and newly developed sensors for current and voltage can enable an evolutionary spring to smaller and more compact installations with a simultaneous significant increase in availability and ease of maintenance in the area of high- and very high-voltage equipment and switchgear installations.

11.4.1.1 Process electronics (sensor technology, PISA)

Decentralized distributed computer-supported modules (PISA = Process Interface for Sensors and Actuators) can now be used for direct control of the primary components of switchgear installations. At the same time, these modules enable all parameters, such as switch position, gas density, storage properties of operating mechanisms, to be recorded where they signify the current status of the equipment and therefore provide the necessary prerequisites for monitoring modern switchgear installations.

Examples of equipment used for this purpose are inductive (therefore insensitive to contamination), robust proximity sensors for detecting switch position of circuit-breakers and disconnector mechanisms, gas density sensors for SF_6 gas-insulated switchgear installations and circuit-breakers. Powerful microcomputers are used for decentralized preparation and preprocessing of the sensor signals (PISAS). Complex auxiliary switch packets in operating mechanisms are not needed because the software can double the signals without problems. The main advantages of this technology are therefore the ability to reduce the quantity of moving components, the smaller dimensions and the standardization of mass-produced components as is already done in other industries.

11.4.1.2 Monitoring in switchgear installations

Monitoring includes acquisition, recording and visualizing measured quantities to allow early detection of faults in important equipment such as circuit-breakers, power transformers or instrument transformers. According to international surveys conducted by CIGRÉ, the mechanisms and the electrical control circuits in circuit-breakers are the primary sources of serious faults, i.e. failures causing operational disruptions, and of less serious faults. The most common sources of failure are the mechanically actuated parts such as relays and signalling contacts in the electrical control circuits and the primary components in operating mechanisms.

The influence of the electronics on the total failure response of an installation is taken into consideration by implementing hardware and software processes for self-monitoring to achieve an increase in internal system reliability.

Condition monitoring requires careful evaluation of the large quantities of measured data, because only the combination of status acquisition with an intelligent assessment results in a knowledgeable diagnosis and initiation of the necessary maintenance steps. Special algorithms for reducing the data and calculating trends are basic requirements for a monitoring system. The P-F curve shown in Fig. 11-23 represents the qualitative connection between the state of a system and the time. As a result of the operational load on the system under observation, the fault mechanism starts at a specific time t_1, i.e. the state deteriorates until time t_2 at which the parameter(s) indicating the fault has/have gone down to a quantifiable value. This point P is designated a “potential fault”. In general, it can be assumed that from this time the state of the system continues to deteriorate, usually with increasing speed until the fault (point F) actually occurs at time t_3. A typical example for such a response is the ageing mechanism of oil/paper or plastic insulation. Leakage in a gas-insulated switchgear installation is another example of the above response.

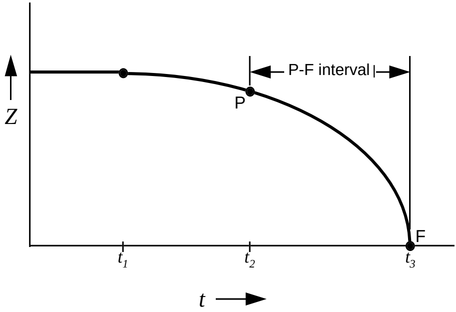


Fig. 11-23

P-F curve for the status of an equipment parameters as a function of time

Z	*status of the equipment*	*P*	*potential fault*
t	*time*	*F*	*fault*

The goal of a monitoring system must be to allow detection of point P with sufficient sensitivity, so there will be sufficient time, i.e. the P-F interval is still great enough to take appropriate action.

11.4.1.3 Status-oriented maintenance

From a technical system view, the monitoring system is an aid for recording the operational history and the current operating status of the equipment that is being monitored. The connection to the substation automation system allows installation-based data such as fault record data from the protection devices or the busbar voltage to be simultaneously included in the evaluation. The resulting status-oriented reproduction of the entire switchgear installation forms the basis for a maintenance concept.

When the importance of the equipment from the network point of view is also considered, an optimized sequence in which a maintenance process can be applied to the equipment in question can be determined. This is referred to as Reliability Centred Maintenance (RCM). Powerful computerized tools (e.g. CALPOS-MAIN®) and monitoring systems are now available, enabling this concept to be implemented in the field.

The principle of status-oriented and reliability-based maintenance planning is shown in Fig. 11-24

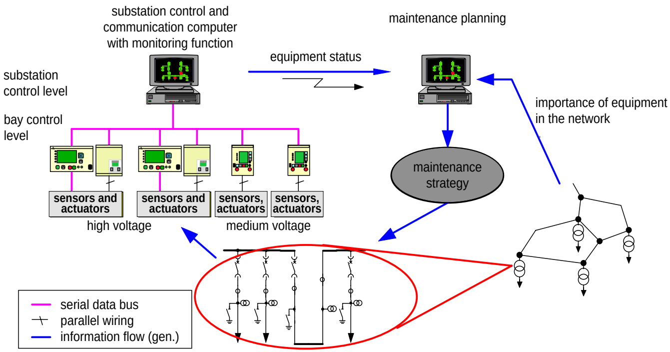
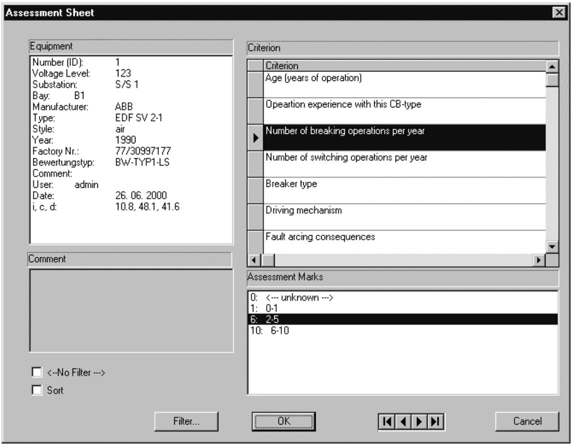


Fig. 11-24

General technical concept of status-oriented and reliability-based maintenance planning

Fig. 11-25 shows how an appropriate software tool can support this task. Fig. a) shows a valuation form for a single item of equipment, a circuit-breaker in this case, and b) shows the result of a simulation. The graph shows the weighted action requirement transferred to the "importance" of the equipment.

a)



Assessment Sheet

Equipment

Number (ID): 1
Voltage Level: 123
Substation: S/S 1
Bay: B1
Manufacturer: ABB
Type: EDF SV 2-1
Style: air
Year: 1990
Factory Nr.: 77/30997177
Bewertungstyp: BW-TYP1-LS
Comment:
User: admin
Date: 26. 06. 2000
i, c, d: 10.8, 48.1, 41.6

Comment

☐ <--No Filter --->
☐ Sort

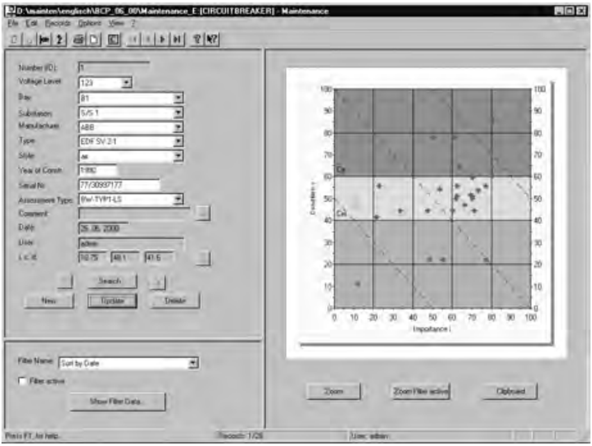
Criterion

Criterion
Age (years of operation)
Opeartion experience with this CB-type
Number of breaking operations per year
Number of switching operations per year
Breaker type
Driving mechanism
Fault arcing consequences

Assessment Marks

0: <--- unknown --->
1: 0-1
6: 2-5
10: 6-10

b)



D:\mainten\englisch\BCP_06_00\Maintenance_E-[CIRCUITBREAKER] - Maintenance

Number (ID): 1
Voltage Level: 123
Bay: 81
Substation: S/S 1
Manufacturer: ABB
Type: EDF SV 2-1
Serial No: 77/30937177
Date: 25.06.2000
User: admin
I, c, d: 10.75 48.1 41.6

Filter Name: Sort by Date
☐ Filter active

Press F1 for help. Record: 1/26 User: admin

Fig. 11-25

Input screen and results display of the software tool CALPOS-MAIN® for status-oriented maintenance planning of switchgear installations
a) Valuation form b) Results display

11.4.2 Innovative solutions

11.4.2.1 Compact outdoor switchgear installations

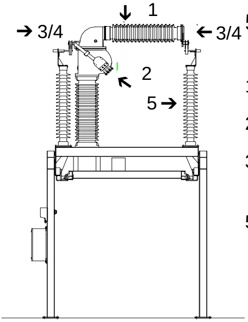
A significant step toward reducing the space requirements of switchgear installations has been made by combining primary devices into more and more compact multifunctional switchgear units. This concept is not new and has already been implemented many times in applications such as outdoor switchgear installations with draw-out circuit-breakers. The implementation of non-conventional current and voltage transformers now makes it possible to combine a large number of functions on one device bench. As a result, a range of combination switchgear has been developed in the last few years.

Another possibility for reducing the area required for outdoor installations significantly is to use hybrid installation designs. In this case, gas-insulated switchgear is used in which many primary components (circuit-breakers, transformers, disconnectors etc.) are installed in a common housing. Only the busbars and, depending on the basic design, the associated busbar disconnectors are installed outdoors

All new switchgear components are distinguished by consistent integration of non-conventional sensors (in this case primarily current and voltage sensors), processor-controlled mechanisms (see 11.4.1.1) and connection to the bay control with fibre optics. This yields the following:

– increased availability
– less space required
– shorter project runtimes and
– extended maintenance intervals with a significant increase in ease of maintenance.

Fig. 11-26 shows a design for compact outdoor switchgear installations for $U_n \leq 145$ kv with transverse LTB circuit-breakers and integrated SF_6 current transformers. The illustrated compact and prefabricated switchgear with prefabricated busbar connections makes it easy to set up simple secondary substations and H-configurations economically and quickly. The circuit is disconnected on both sides of the circuit-breaker by the module moving to the side.



5 Functions in 1 module

1 Circuit-breaker
2 Current transformer
3/4 Disconnector and earthing switch, if required
5 Surge arrester can replace the post insulator

Fig. 11-26

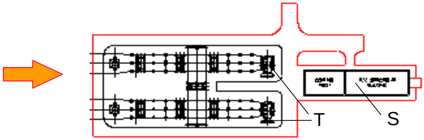
Slide-in, compact switching module with LTB circuit-breaker and integrated SF_6 current transformer for $U_n \leq 145$ kv

An example of the layout of a simple H-configuration with these modules is shown in comparison to a conventional H-configuration in Fig. 11-27. Dispensing with busbars and outgoing-feeder disconnectors allows smaller dimensions in comparison to conventional outdoor installations.

Conventional Design

total area: 2600 m²
switchgear installation: 930 m²

earthing system: 3700 m²



Compact Design

total area: 1200 m²
switchgear installation: 300 m²

earthing system: 1000 m²

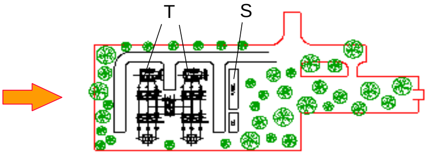


Fig. 11-27

View of two installation layouts in H-configuration for $U_n \leq 145$ kv in conventional and compact design, T Transformers, S Secondary technology

Another variation of a compact switching module for use up to 170 kV is shown in Fig. 11-28. The disconnector functions are realized with a draw-out circuit-breaker. This means that the conventional disconnectors are replaced by maintenance-free fixed contacts and moving contacts on the circuit-breaker. An option is to install conventional or optical current and voltage transformers and earthing switches. The circuit-breaker can be simply withdrawn for maintenance, or if necessary, quickly replaced by a spare breaker. The main advantages here are also significant space savings, smaller bases, steel frames and reduced cabling requirements. This switching module is particularly suited for single busbars and H-configurations.

1 Draw-out circuit-breaker

2 Circuit-breaker rails

3 Disconnector isolating contact, fixed side
(forms the isolating distance for circuit-breaker when withdrawn)

4 Current transformer

Fig. 11-28

Compact switching module for $U_n \leq 170$ kv with draw-out circuit-breaker

Fig. 11-29 shows a compact switching module for applications of up to 550 kV. It is a combination of a circuit-breaker with one or two non-conventional current transformers installed on the interruptor chambers and two pantograph disconnectors. This compact design is only possible using very small non-conventional current transformers. The current transformer signals are conducted through the tension insulators via fibre-optic cables to the control cubicle. Such compact modules make it possible to reduce the surface area required for an outdoor installation by up to 55 %. This concept is particularly suitable for installations in $1^1/_2$ circuit-breaker design.

1 Circuit-breakers of up to 550 kV

2 Disconnectors on both sides
(earthing switch possible)

3 Optical current transformer

4 Tension insulator for fibre optics

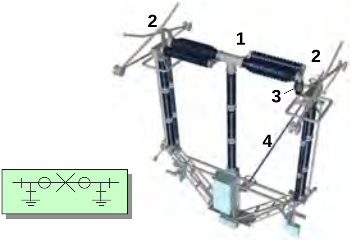


Fig. 11-29

Compact switching module for $U_n \leq 550$ kv with circuit-breaker, a built-in non-conventional current transformer and two pantograph disconnectors

Fig. 11-30 shows a comparison of a conventional 500 kV outdoor switchgear installation in $1^1/_2$ circuit-breaker design with an installation in compact design using the modules described above. This makes the saving in surface area with the same functionality particularly clear.

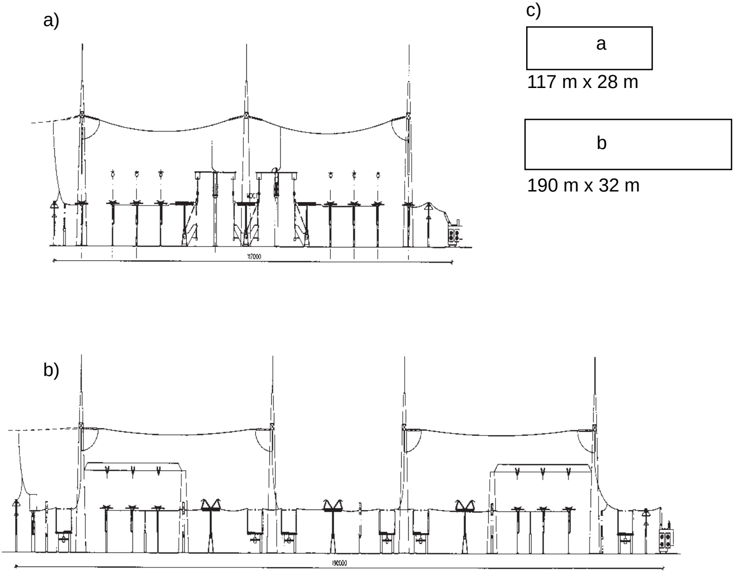


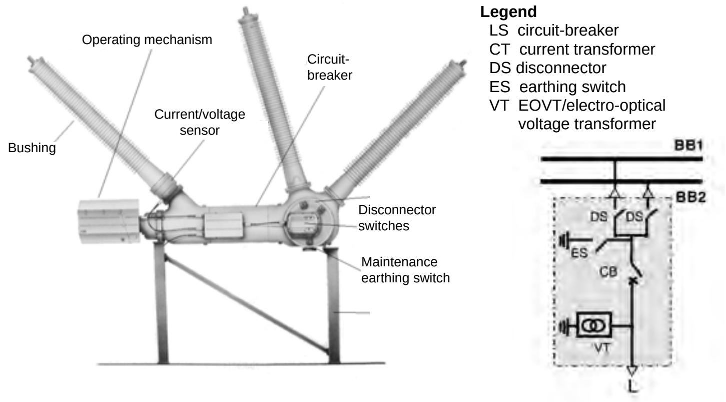
Fig. 11-30

Switchgear installation design of a 500 kV $1^1/_2$ circuit-breaker installation with compact switching modules a), compared to conventional design b), comparison of areas c)

11.4.2.2 Hybrid switchgear installations

Two insulation media, i.e. air and SF_6, can be combined in high-voltage installations with the modular principle of SF_6-isolated installations. This type of installation is referred to as a “hybrid installation”.

Fig. 11-31 shows a hybrid switching device for voltage levels of up to 550 kV. The name “Plug And Switch System” – PASS – indicates the philosophy of this concept. The highly integrated components allow that in new installations and in retrofit projects compact PASS units can be erected and comissioned quickly. These units are connected to the secondary equipment of the substation by prefabricated cable links, which include both the auxiliary voltage supply cables and the fibre-optic cables to connect to the station control system.



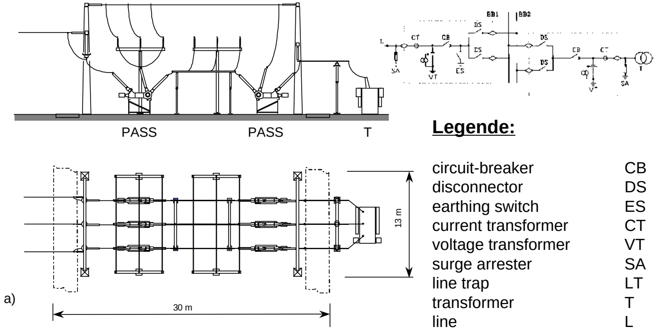
Legend

LS	circuit-breaker
CT	current transformer
DS	disconnector
ES	earthing switch
VT	EOVT/electro-optical voltage transformer

Fig. 11-31

Plug and Switch System, PASS, in single-phase design for U_n of up to 550 kV

Fig. 11-32 shows a double-busbar installation with PASS modules. The saving of space amounts to as much as 60% in new installations. For retrofit projects, the space required by the switchgear installations is generally dictated by the existing busbars and the gantries. In this case, the advantages of the PASS solutions are primarily in the savings in foundations, drastically reduced cabling requirements and fast installation and commissioning.



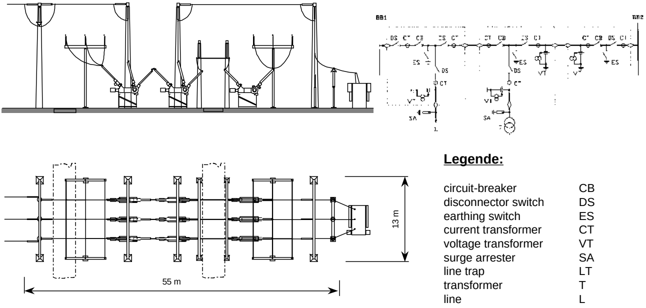
Legende:

circuit-breaker	CB
disconnector	DS
earthing switch	ES
current transformer	CT
voltage transformer	VT
surge arrester	SA
line trap	LT
transformer	T
line	L

Fig. 11-32

Switchgear installation design with PASS for double-busbar installations for U_n of up to 550 kV

The $1^1/_2$ circuit-breaker method can also be successfully implemented in hybrid design, see Fig. 11-33.



Legende:

circuit-breaker	CB
disconnector switch	DS
earthing switch	ES
current transformer	CT
voltage transformer	VT
surge arrester	SA
line trap	LT
transformer	T
line	L

Fig. 11-33

1½ circuit-breaker hybrid switchgear installation with PASS modules for U_n to 550 kV

In addition to saving up to 60 % in surface area required, PASS is also characterized by quick assembly and easy replaceability. It can be connected to the overhead lines as easily as conventional installations.

11.4.2.3 Prefabricated, modular transformer substations (MUW®)

The prefabricated, modular transformer substations (MUW®) with gas or air-insulated switchgear are a special design for transformer substations. The abbreviation “MUW” at ABB is a fixed and defined product term.

The individual modules are delivered ready for installation as flexible assemblies. A number of these modules (e.g. medium voltage, control system/control room, auxiliary power etc.) are fully assembled and tested in the factory in prefabricated and transportable housings, every one conforming to the ISO 668 standard dimensions. The modular principle enables solutions tailor-made to requirements with a high degree of standardization.

Prefabricated ISO steel pit modules with the following dimensions are used as transformer bases:

– up to 16 MVA:	3 pit modules 20 feet x 8 feet
– from 20 to 40 MVA:	3 pit modules 30 feet x 8 feet
– from 63 to 125 MVA:	3 pit modules 40 feet x 8 feet

The pit includes the transformer rails for longitudinal and transverse movement, a flame-suppressant cover and as an option, the required racks for power cables and neutral treatment. Depending on the size of pit selected, space for an auxiliary transformer is also provided. Three pad modules can fit an ISO standard container for shipping. Modular fire-protection walls are available for fire protection between the transformers and towards the building.

Prefabricated, modular transformer substations can be set up and commissioned in a very short time. They also meet the requirements for multiple use. The entire switchgear installation can be converted with minimal effort. Standardized modules that can largely be prefabricated reduce planning, delivery and erection times.

Some advantages of MUW® are:

- faster construction of infrastructure
- shortest possible interruption of power supply in the event of faults and on installation of new equipment and retrofit and service of existing installations
- reusable interim solution (temporary solution)
- stationary, space saving permanent solution
- auxiliary supply in power stations and power station generator busducts

The modular housing design for the MUW consists of hot-galvanized sandwich wall panels for extremely high durability. The steel base frame comprises hot-galvanized rolled steel sections with additional equipment racks. Heating and air-conditioning units in the individual modules allow installation independent of the local climate conditions.

Figs. 11-34 and 11-35 show the ground plan and the sectional view of a 123/24 kV transformer substation with two 63 MVA transformers and an H-configuration with 5 circuit-breakers on the high-voltage side.

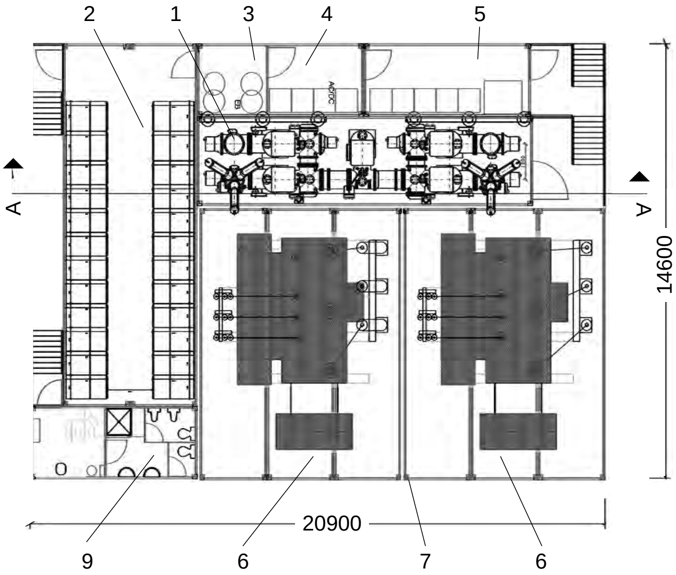


Fig. 11-34

Ground plan of a prefabricated, modular transformer substation, 1 High-voltage substation: H-configuration ELK-0 with 5 circuit-breakers, 2 Medium-voltage switchgear: 24 bays, 3 Neutral treatment (under module 1), 4 Auxiliary supply, 5 Control system/control room, 6 Modular transformer oil pit with 63 MVA transformer, 7 Modular fire protection wall, 9 Personnel module with small sewage system and oil separator

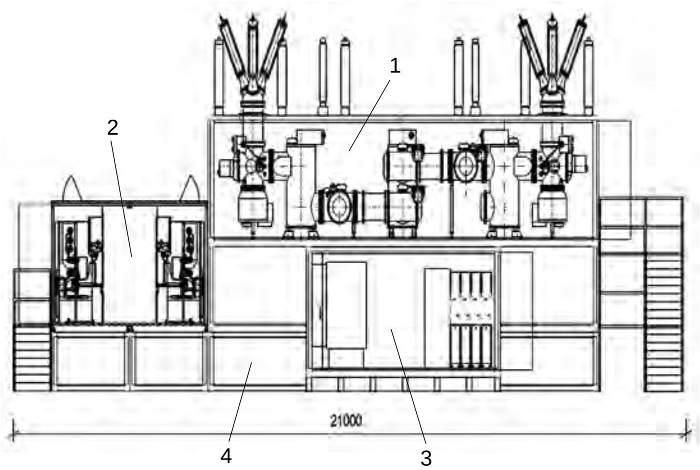


Fig. 11-35

Section through the installation, view A - A:
1 High voltage module, 2 Medium voltage module, 3 Neutral treatment, 4 Foundation modules as cable basement

In addition to transformer substations with gas-insulated switchgear technology, the modular concept can also be implemented with air-insulated components. The modular systems include an outdoor module, which is shown in Fig. 11-36, detail 1, as well as the compact switching modules shown in Section 11.4.2.1. Conventional devices such as circuit-breakers and current or voltage transformers are installed on a steel ISO base frame and the disconnectors are installed on a steel support fixed to the base frame. This module allows all current switchgear configurations to be implemented. The complete module is prefabricated, tested in the factory and then compactly packed for shipping on the base frame under an ISO container cover.

The method of assembly allows direct connections to existing overhead lines without requiring additional gantries with a one-level tower configuration.

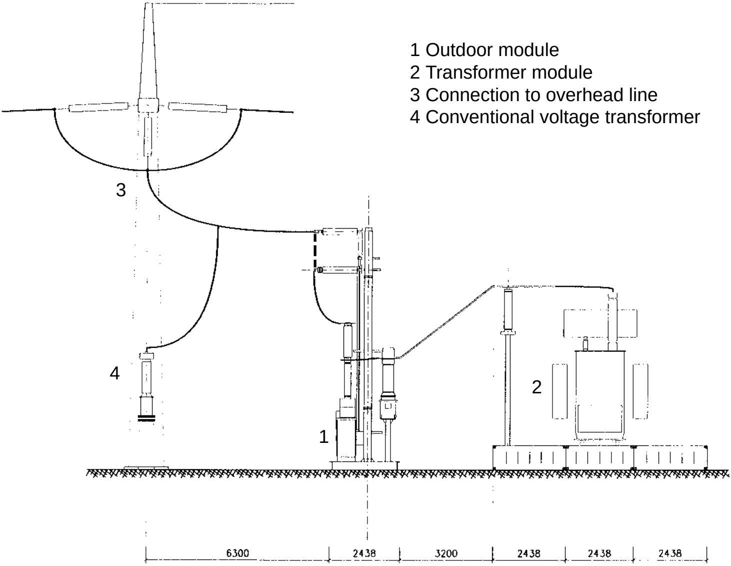


Fig. 11-36

Section through a prefabricated modular transformer substation in air-insulated design for a single transformer feeder connected to a 123 kV overhead line

11.4.3 Modular planning of transformer substations

To deal with ever tighter project schedules, it is essential to continue to increase the degree of prefabrication of switchgear components, to support project management with computerized aids as much as possible, to reduce engineering during the project and to save as much time as possible in assembling and commissioning the equipment.

Efforts similar to the previously achieved progress in modularization and standardization in

– LV switchgear design using type-tested switchgear assemblies (TTA, PTTA) as modular NS switchgear system (ABB MNS system),
– MV switchgear design using type-tested switchbays with standard programs,
– high-current technology with modular structure of generator busducts and circuit-breakers,
– HV switchgear design with gas-insulated switchbay series in modular technology as preassembled, type-tested and pretested bays

have been made with optimized primary and secondary technical design in the area of HV outdoor switchgear installations. Section 11.4.2.3 describes examples of these applications.

11.4.3.1 Definition of modules

More highly integrated modules and function groups as modules are required to reduce the project periods for switchgear installations.

A module in this sense is a unit or a function group,

- that can execute a self-contained function,
- that has a minimum of interfaces, which are as standardized as possible,
- whose complex function can be described with few parameters,
- that can be prefabricated and pretested to a great extent and
- that can be altered within narrow limits by the smallest possible degree of adaptation engineering for customer demands and requirements while adhering to standards as much as possible.

It is essential that any changes to modules do not detract from the rationalization and quality achieved by type testing, degree of prefabrication and pre-testing.

11.4.3.2 From the customer requirement to the modular system solution

The progressive deregulation in energy markets and the accompanying downward pressure on costs is resulting in new requirements on the project planning of transformer substations. In addition to the engineering of classical customized installations, the modular switchgear installation concept offers the chance of developing largely standardized and therefore more economical solutions. This is done by implementing a systematic pattern of thinking to yield products with high functionality and combined installation modules. This means that the interfaces are unified and also reduced in number by grouping products into modules.

For project planning and engineering, this means that system solutions are generated from a modular system of components in which the individual modules are precisely described as derived from the technical and economical requirements of a new transformer substation in the network. The available CAD systems are ideally suited for quick and easy combination of complete station components from a catalogue of individual components. The current integrated enterprise resource planning (ERP) software also offer suitable databases and structures that enable quick access to descriptions, parts lists and prices.

The substation planner will have the greatest optimization effect when the customer provides requirements that describe functions only instead of detailed requirements in the form of comprehensive specifications. This gives the engineer the greatest possible freedom to bring the system requirements into conformity with the available modular solutions. In the modular concept, detailed installation requirements that go far beyond the description of functions result in expensive adaptation work, making the overall installation more expensive. Adaptation work in the modular concept is possible, but it always results in extra work in preparing the tender, project planning, engineering, processing and documentation of the installation.

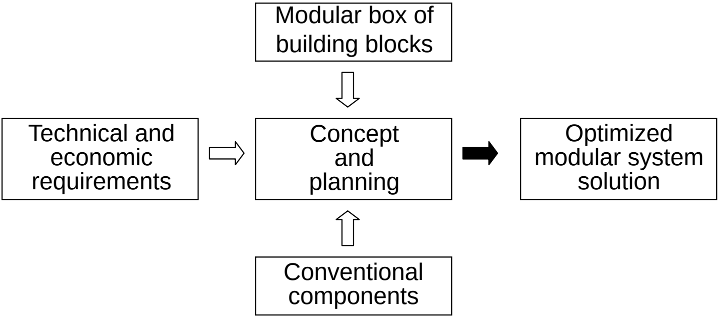


Fig. 11-37

From the functional requirements of the network to the modular system solution

11.5 Installations for high-voltage direct-current (HVDC) transmission

11.5.1 General

Transmitting energy in the form of high-voltage direct current is a technical and economic alternative to alternating-current transmission. It is used for transferring power in bulk over large distances by overhead line or cable, for coupling non-synchronous networks and for supplying densely populated areas if there is a shortage of transmission routes.

The basic principle of a HVDC link is shown in Fig. 11-38. The alternating voltage of a supply system, which may also be a single power station, is first transformed to a value suitable for transmission. It is then rectified in a converter arrangement with controlled valves. A second converter is required at the other end of the link. This is operated as an inverter and converts the direct current back into alternating current, which is then transformed to the voltage of the network being supplied.

The flow of power along the line is determined by the difference between the d.c. voltages at the ends of the line and by the ohmic resistance of the line, according to the formula

$$P_d = U_d \cdot I_d = \frac{U_{d1} + U_{d2}}{2} \cdot \frac{U_{d1} - U_{d2}}{R} = \frac{U^2_{d1} - U^2_{d2}}{2R}.$$

Here, P_d is the power relating to the middle of the line, U_{d1} and U_{d2} are the d.c. voltages at the beginning and end of the line, respectively, and R is the ohmic line resistance.

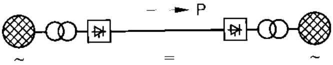


Fig. 11-38

Block diagram of a HVDC link

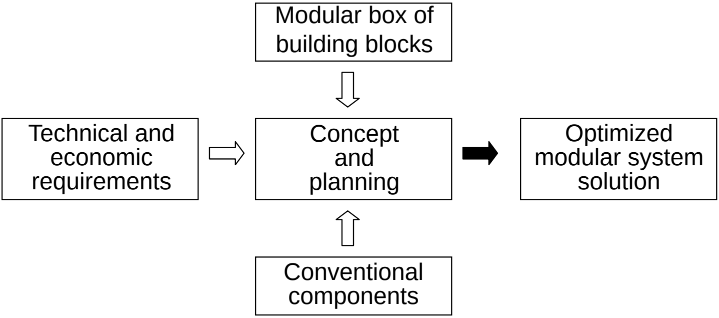


Fig. 11-37

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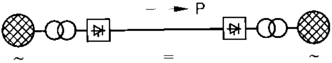


Fig. 11-38

Block diagram of a HVDC link

The frequency and phase shift of the two networks connected via the HVDC link have no effect on the transmitted power and so transmission stability is no problem; networks of different frequency can be coupled without difficulty. With the three-phase bridge circuit used in HVDC systems, the equation for the d.c. voltage of the converter is

$$U_d = k\, U_v \,(\cos\alpha - \frac{u_k}{2}\,\frac{I_\mathrm{d}}{I_{dN}})$$

where U_v is the valve-side voltage of the transformer, α the control angle of the converter, u_k the transformer's relative impedance voltage, I_d the d.c. transmission current and I_dN the nominal d.c. transmission current.

Since the d.c. voltage can be altered almost instantly with the phase-angle control system of the converters, the transmitted power can be varied very quickly and within wide limits.

By changing control from rectifier to inverter mode ($\alpha > 90$ °), it is possible to reverse the d.c. voltage and hence the energy flow direction, whereby the speed of reversal can be adapted as necessary to the needs of the coupled networks. The quick response of the converter control can even be used to support stability by slightly modulating the transmitted power to attenuate power fluctuations in one of the networks.

Because of delayed ignition and commutation overlap, line-commutated converters require fundamental-frequency reactive power:

$Q = P_\mathrm{d} \tan\varphi$; $\varphi = \arccos(\cos\alpha - \frac{u_\mathrm{k}}{2}\frac{I_\mathrm{d}}{I_\mathrm{dN}})$ where φ is the displacement angle of the fundamental frequency.

The fundamental-frequency reactive power requirement of a HVDC converter at rated load is about 50 to 60 % of the active power. By means of special control modes, it can be varied within certain limits, so a HVDC converter can assist to maintain voltage stability in the three-phase network.

11.5.2 Selection of main data for HVDC transmission

The described technical characteristics of HVDC transmission are completely independent of the transmission distance and the kind of DC connection used, overhead line or cable; they are also valid for system interties in which rectifier and inverter are assembled in one station.

On the other hand, the main data of a HVDC link are very much influenced by the type of conductor and transmission distance. With an overhead line, optimization of the line costs and losses calls for the highest possible transmission voltage, a limit usually being set by the line's permissible surface voltage gradient. Countering this is the fact that the station costs, which increase with DC voltage, become less significant as the length of line increases. Voltages of up to ± 600 kV already exist.

Submarine cables with a transmission voltage of 450 kV and a length of 250 km are already in use. Links more than twice as long and with transmission voltages of 500 kV are being planned.

For system interties, the main data are governed by optimization of the converter valves. One chooses the rated current attainable with the largest available thyristor without paralleling, at present about 4000 A; the d.c. voltage then follows accordingly.

11.5.3 Components of a HVDC station

The basic circuit of a HVDC converter station is shown in Fig. 11-39.

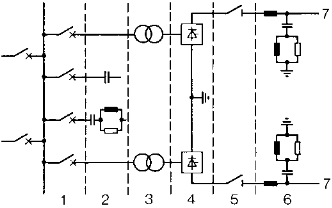


Fig. 11-39

Basic circuit of a HVDC converter station:

1 A.C. switchgear
2 A.C. filter and reactive power compensation
3 Converter transformers
4 Converter bridges
5 D.C. switchgear
6 Smoothing reactor and d.c. filter
7 D.C. line poles 1 and 2

The a.c. switchgear comprises not only the feeders to the converters, but also various branches for filter circuits and capacitor banks. The circuit-breakers must be capable of frequently switching large capacitive powers.

The *a.c. filters* are required to absorb current harmonics generated by the converter, and in this way, reduce distortion of the system voltage.

With 12-pulse converter units, it is customary to use tuned series resonant circuits for the 11th and 13th harmonics together with broad-band high-pass filters for the higher harmonics. These a.c. filters also furnish some of the fundamental-frequency reactive power needed by the converters. The remainder has to be provided by capacitor banks. At low system short-circuit outputs (S_K less than 3 P_D) it may be necessary to provide synchronous compensators instead of the capacitor banks.

The *converter transformers* convert the network voltage into the three-phase voltage needed by the converter bridges. As Fig. 11-40 shows, a 12-pulse converter unit requires two transformers connected differently to produce the two three-phase systems with a phase offset of 30°. Converter transformers for HVDC are built with two or three windings in single-phase or three-phase units. When the converter valves operate, the windings on the valve side are galvanically connected to a high d.c. potential, and the dielectric strength of their main insulation therefore has to be designed for high d.c. voltage. Windings and iron parts have to be specially dimensioned owing to the high harmonic currents and the consequent leakage flux.

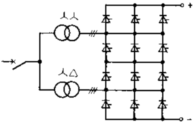


Fig. 11-40

Twelve-pulse converter unit, comprising two three-phase bridges connected in series on the d.c. side.

The converter units each consist of two three-phase bridge arrangements with their respective transformers, one of which is in YyO connection, the other in Yd5 connection. On the d.c. side, they are connected in series and on the a.c. side are brought to a common circuit-breaker to form a twelve-pulse unit. If the station has to be divided into more than two sections which can be operated independently, because of the maximum permissible power in the event of a fault, twelve-pulse units are connected in series or parallel.

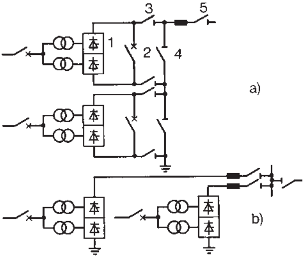


Fig. 11-41

One pole of a HVDC station with several converter units:
a) Series connection, b) Parallel connection of twelve-pulse units,
1 Twelve-pulse converter unit, 2 Bypass breaker, 3 Unit disconnector, 4 Shunt disconnector, 5 Line disconnector

A 12-pulse converter unit consists of twelve valves. HVDC converter valves are made up of thyristors. For high valve voltages, up to a hundred thyristors are connected in series. To obtain a uniform voltage distribution, the thyristors have additional circuitry consisting mainly of RC components. The heat sinks of the thyristors are cooled with forced-circulation air, oil or de-ionized water, the latter being the most common method. The valves are mostly ignited electronically by devices triggered by light pulses fed through fibre-optic cables. Converters with thyristors triggered directly by light are also used.

The d.c. switchgear has to perform a number of very different functions, depending on the converter station’s design (cf. Fig. 11-41). The equipment used is mainly apparatus which has proved its performance in a.c. installations and been modified to meet the particular requirements. The purpose of the bypass switch parallel with the twelve-pulse unit is to commutate the station direct current when the unit is put into, or taken out of, operation. The shunt disconnector enables the direct current to be diverted round a disconnected unit.

Ground faults on a d.c. line are cleared by controlling the voltage to zero. D.C. circuit-breakers are therefore not necessary with a straightforward HVDC link. Multiterminal HVDC systems can, however, benefit from HVDC breakers (Fig. 11-42) as these improve the system’s performance. A 500 kV HVDC circuit-breaker developed and tested by ABB has been proved in operation. The first multi-terminal HVDC transmission system entered service in North America in early 1992.

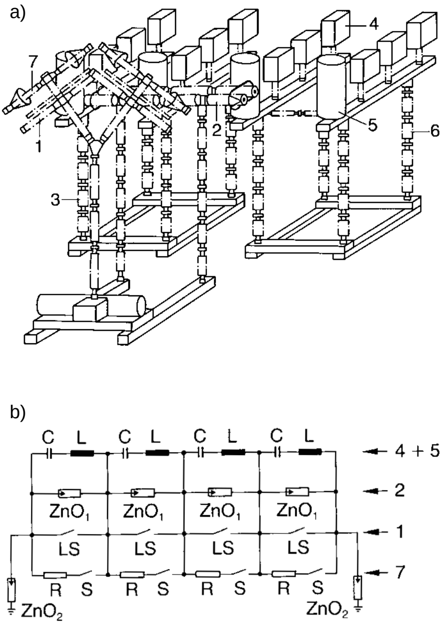


Fig. 11-42

500 kV HVDC circuit-breaker

a) Perspective arrangement
b) Equivalent circuit diagram

1 Air-blast breaker
2 Energy absorber (ZnO arrester)
3 Post insulators
4 Capacitor bank
5 Resonant-circuit reactor
6 Post insulators
7 Closing resistors (open during tripping), added as necessary

The smoothing reactors used on the d.c. side of HVDC stations smooth the direct current and limit the short-circuit current in the event of line faults. Their inductance is usually between 0.1 and 1 H. They are mostly built in the form of an air-insulated air-core reactor.

The d.c. voltage is filtered with DC filters. Their characteristics are matched to the data of the transmission line, it being particularly important to avoid resonance at the 1st and 2nd harmonics of the network frequency.

The lines for the two DC poles are usually carried on one tower. This is called a bipolar line. If there are special requirements for transmission reliability, two bipolar lines can be used on one or two towers. In the second case, the full power of the remaining healthy substation poles can be transmitted without earth return current even if a tower breaks with appropriate switchovers where two line poles fail. Both cases exploit the fact that the lines can take a high thermal overload under the standard economic design.

11.5.4 Station layout

In modern installations, the thyristor valves are air-insulated and placed in a valve hall. Generally, four valves are combined in a stack and connected to one AC phase. Three such assemblies constitute a twelve-pulse unit. Fig. 11-43 shows the layout of a station for bipolar transmission of 1000 MW at a d.c. voltage of ± 400 kV.

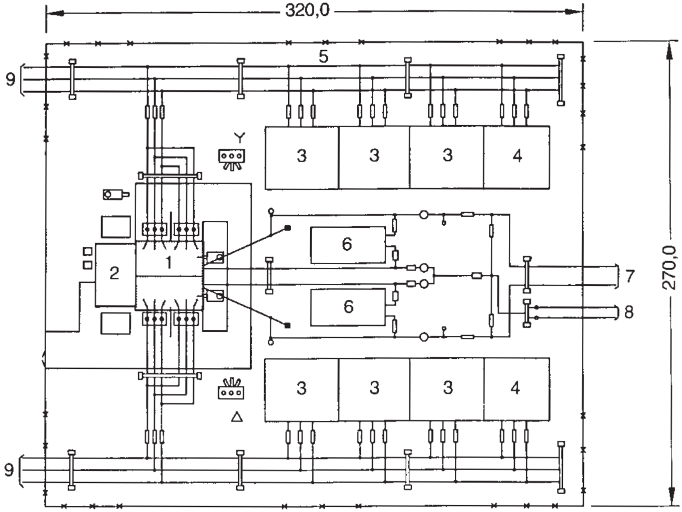


Fig. 11-43

Layout of a HVDC station for a rated voltage of ± 400 kV and rated power 1000 MW: 1 Valve hall, 2 Control house, 3 A.C. filter circuits, 4 Capacitor bank, 5 A.C. switchgear, 6 D.C. filters, 7 D.C. line ± 400 kV, 8 Earth electrode line, 9 A.C. infeed 345 kV

A particularly compact station arrangement is obtained by placing the converter transformers close to the valve hall so that their valve-side bushings pass through the wall. Fig. 11-44 shows the valve building and a single-phase three-winding converter transformer. An interesting feature, technically and practically, is that the valves are suspended from the hall ceiling.

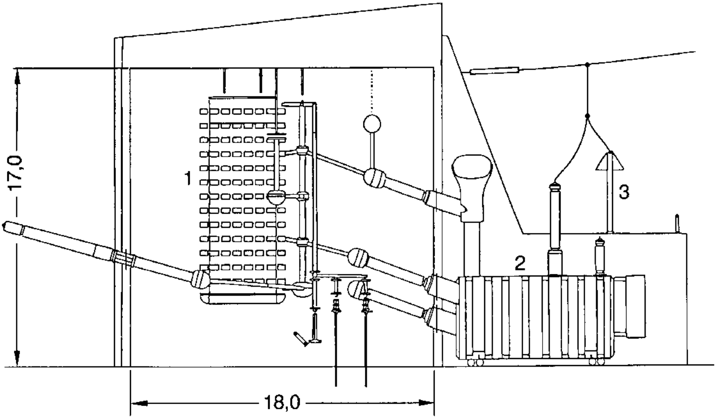


Fig. 11-44

Section through the valve hall of a 500 MW HVDC converter station (400 kV):
1 Converter valves, 2 Converter transformer, 3 Surge arrester.

11.6 Static var (reactive power) compensation (SVC)

11.6.1 Applications

In recent years, the control of reactive power has gained importance alongside active-power control. The use of mechanically switched choke and capacitor banks (see also Section 12.3.2 for the latter) has improved the reactive current balance in the networks. This has reduced transmission losses and kept stationary voltage deviations within the preset limits. In addition to this equipment, thyristor-controlled reactive-power compensators (SVC = Static Var Compensator) have also been implemented. They react virtually instantly and also offer the following advantages:

- very quick and infinitely variable reactive power conditioning,
- improvement of voltage stability in weak networks,
- increase of static and dynamic transmission stability and attenuation of power swings,
- enhancement of transmission capacity of lines,
- quick balancing of variable non-symmetrical loads,

- lower transmission losses,
- increased static and dynamic stability and reduced power fluctuations,
- increased transmission capacity,
- balancing of unsymmetrical loads,
- continuous regulation of power factor.

Equipped with electronic components, SVC systems respond almost instantaneously.

Unlike the reactive-power compensation considered in Section 12.3.2, SVC systems allow infinitely variable control across a whole band of reactive power. Also, the stability of networks can be improved.

11.6. 2 Types of compensator

Thyristor-Controlled Reactor (TCR)

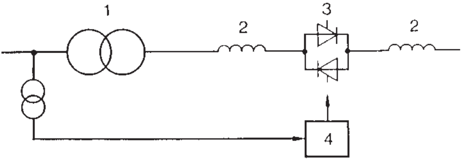
An inductance (reactor bank) is controlled by thyristors as shown in Fig. 11-45. The reactive power in this case is continuously changed between zero and the maximum value by conduction angle control of the thyristors. In many cases, this configuration is operated together with a parallel-switched capacitor bank. This occurs when the entire reactive power correcting range also includes a capacitive component.

Features of this type are:
- continuous correcting range,
- no transient influence,
- generation of harmonics.

To avoid harmonic overload of the network, the parallel capacitor banks must be upgraded to filter circuits.

Fig. 11-45

Thyristor-Controlled Reactor (TCR):
1 Transformer, 2 Reactor coil, 3 Thyristor valve, 4 Control system

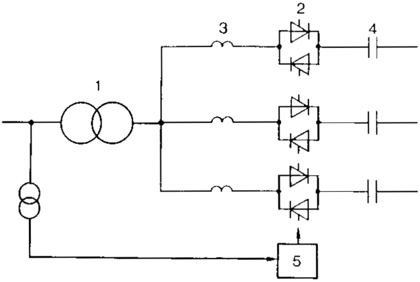


Thyristor-Switched Capacitor (TSC)

In this case, thyristor-switched capacitors (capacitor banks) are switched on or off, path by path as shown in Fig. 11-46. To avoid transients, the thyristors are fired when the thyristor voltage is zero.

Fig. 11-46

Thyristor-Switched Capacitor (TSC):
1 Transformer, 2 Thyristor valve, 3 Damping coil, 4 Capacitor, 5 Control system



Features of this method are:

- stepwise control,
- no transient interference,
- no harmonics,
- low losses.

Applying reactors instead of capacitors, again arranged as in Fig. 11-46, creates the Thyristor-Switched Reactor method (TSR), which provides similar features to those above.

Thyristor-Switched Capacitor/Thyristor-Controlled Reactor (TSC/TCR)

Often a combination of the two above methods provides the best solution.

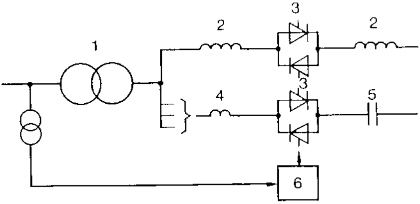
A compensator as shown in Fig. 11-47 allows low-loss thyristor control of the entire capacitive and inductive reactive-power correcting range. A smoothly varied output of reactive power is obtained by altering the TCR’s firing angle. As soon as the TSC range has been compensated by the TCR, the capacitive path is disconnected and the compensator functions as a reactor.

Features of this method are:

- continuous adjustment,
- no transient interference,
- slight generation of harmonics,
- low losses.

Fig. 11-47

Thyristor-Switched Capacitor/Thyristor-Controlled Reactor (TSC/ TCR)
1 Transformer, 2 Reactor coil, 3 Thyristor valve,
4 Damping coil,
5 Capacitor,
6 Control system



11.6.3 Systems in operation

SVC systems in routine network service are generally highly reliable and very effective. The first static compensator for a high-voltage network was installed in 1972. Advances in thyristor technology led to the first water-cooled thyristor valve in operation in 1975. A system with a total power rating of 445 Mvar has been operating since 1985 in the 765 kV network of EDELCA (Venezuela). The largest system supplied to date by ABB has a total power of 1066 Mvar, of which 600 Mvar are thyristor-controlled. The installation is located in Mexico in the 400 kV network of CFE (Comision Federal de Electricidad). Fig. 11-48 shows a typical layout of a static compensator installation for a long-distance transmission system.

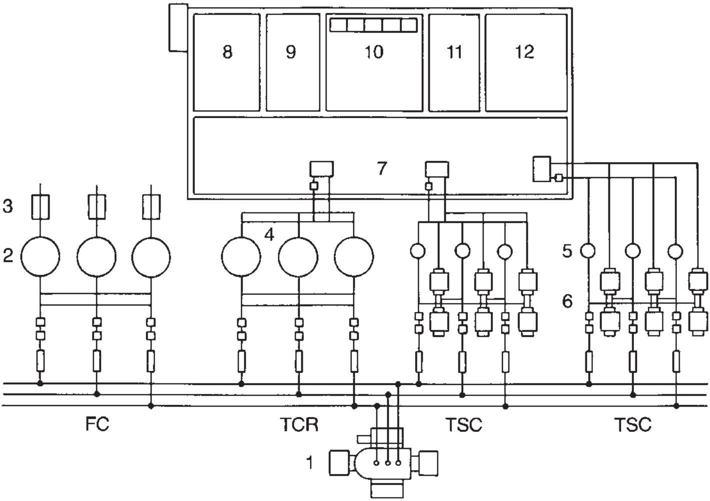


Fig. 11-48

Plan view of a static compensator installation for a long-distance transmission line: 1 Transformer, 2 Filter circuits, 3 Capacitor bank, 4 TCR reactor coil, 5 Damping coil, 6 TSC capacitor, 7 Thyristor valves, 8 Cooling plant, 9 Auxiliary power, 10 Control room, 11 Storage, 12 Workshop

12 Transformers and other Equipment for Switchgear Installations

12.1 Transformers

12.1.1 Design, types and dimensions

The purpose of transformers is to transfer electrical energy from systems of one voltage U_1 to systems of another voltage U_2.

Transformers can be differentiated according to their manner of operation (Fig. 12-1):

1. *Power transformers,* the windings of which are in parallel with the associated systems. The systems are electrically independent. The transfer of power is solely by induction.
2. *Autotransformers,* the windings of which are connected in line (series winding RW and parallel winding PW). The throughput power S_D is transferred partly by conduction and partly by induction.
3. *Booster transformers;* their windings are electrically independent, one winding being connected in series with one system in order to alter its voltage. The other winding is connected in parallel with its associated system (excitation winding EW). The additional power S_Z is transferred purely inductively.

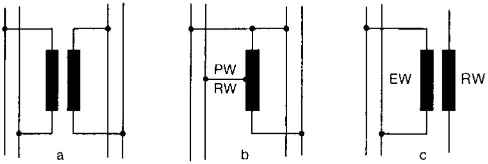


Fig. 12-1

Different types of transformers according to their manner of operation: a) Power transformer, b) Autotransformer, RW Series winding, PW Parallel winding, c) Booster transformer, EW Excitation winding, RW Series winding.

The following distinctions are made according to applications:

1. Transformers for the supply of power DIN EN 60076-1 (VDE 0532 Part 101), such as distribution or main transformers, machine transformers and system-tie transformers,
2. Industrial transformers, such as welding transformers, furnace transformers, starting transformers and converter transformers,
3. Transformers for traction systems,
4. Special transformers, e.g. for testing, protection and control purposes.

Three-phase distribution transformers are covered by standards DIN 42500 (≙ HD 428.151) and DIN 42523 (≙ HD 538.151).

Transformers are divided into the following categories:

1. *Class A:* dry-type transformers (e.g. cast-resin transformers)
   Core and windings are not contained in an insulating liquid. Heat losses are dissipated direct to the ambient air, hence large surface area and low current density.
   Up to approximately 20000 kVA and a maximum of 36 kV.
   ABB resin-encapsulated transformers of the RESIBLOC type are characterized by extremely high mechanical resistance of the windings because of fibre-glass-reinforced resin insulation and a very high resistance to fluctuations in temperature.

2. *Class 0:* oil-immersed transformers
   Core and windings are contained in mineral oil or similarly flammable synthetic liquid with a fire point ≤ 300 °C which is simultaneously a coolant and insulating medium.

3. *Class K*
   Core and windings are contained in a synthetic liquid having a fire point > 300 °C which is also a coolant and insulating medium. In construction, they are much like oil-immersed transformers.

   ABB uses silicone liquid for transformers with ratings of up to 10 000 kVA and service voltages of up to 36 kV.
   Silicone liquid is flame-retardant and non-polluting. Other synthetic liquids (ester) with a fire point > 300 °C may be encountered, besides silicone liquid.

   Askarel is no longer used as a coolant (environmental hazard).

Ratio variability

Ability to vary the ratio is important particularly with main transformers; it is used for matching the service voltage in the event of load fluctuations, for load distribution or for adjusting active and reactive current in interconnected networks, and for voltage correction with electric furnaces, rectifier stations, etc. In the simplest case, this is done with the transformer dead, by altering the connection between winding sections with the aid of extra winding terminals, so-called tappings (normally ± 4 % or ± 5 %).

For *stepwise variation under load,* the tap changer (available in oil-insulated and dry design) is preferably installed at the neutral end of the HV winding with power transformers, and at the series winding with series transformers and autotransformers.

The tap changer, which connects the respective tappings while under load, consists basically of a load switch and a selector (or alternatively just a selector switch) with or without preselection.

The number of tappings and range of adjustment for power transformers of up to 40 MVA and 110 kV are standardized (DIN 42515).

Continuous variation under load can be done with moving windings in the form of a special design as a rotary transformer or moving-coil regulator.

Fig. 12-2 shows an oil-insulated transformer (a) which has the currently preferred hermetically encapsulated design without expansion tank and a resin-encapsulated transformer (b) without enclosure. There are no standards for the dimensions of distribution transformers. Table 12-1 lists the main dimensions of a number of distribution transformers as examples of practical transformer designs with varying technical data from the ABB production range.

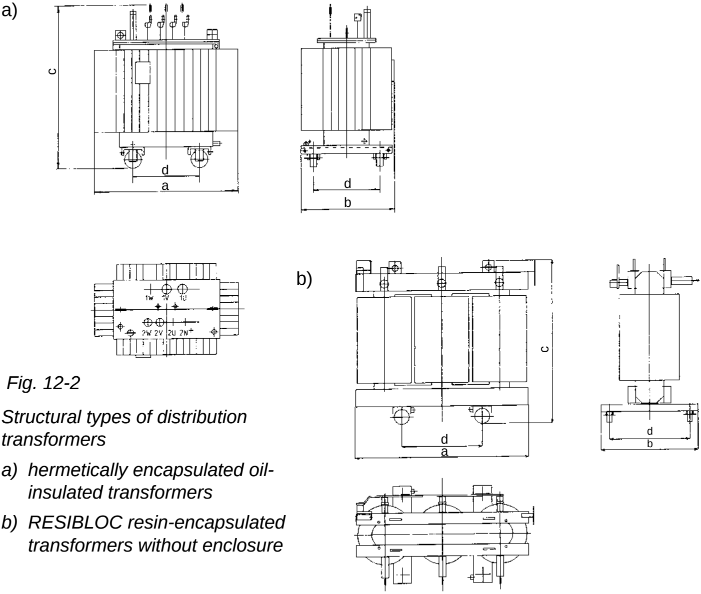


Fig. 12-2

Structural types of distribution transformers

a) hermetically encapsulated oil-insulated transformers

b) RESIBLOC resin-encapsulated transformers without enclosure

Table 12-1

Main dimensions of ABB distribution transformers, as shown in Fig. 12-2
a) Oil-insulated transformers, hermetically encapsulated
b) RESIBLOC resin-encapsulated transformers without enclosure

	Tech. data	Main dimensions in mm			
		a	b	c	d
a)	10 kV, 250 kVA, 4%	1170	740	1440	520
	20 kV, 250 kVA, 4%	1170	770	1510	520
	10 kV, 630 kVA, 6%	1420	870	1440	670
	20 kV, 630 kVA, 6%	1460	930	1525	670
b)	10 kV, 250 kVA, 4%	1110	660	1250	520
	20 kV, 250 kVA, 4%	1350	660	1560	520
	10 kV, 630 kVA, 6%	1500	810	1360	670
	20 kV, 630 kVA, 6%	1560	810	1820	670

12.1.2 Vector groups and connections

Vector groups

The vector group denotes the way in which the windings are connected and the phase position of their respective voltage vectors. It consists of letters identifying the configuration of the phase windings and a number indicating the phase angle between the voltages of the windings.

With three-phase a.c. the winding connections are categorized as follows:

a) Delta (D, d)
b) Star (Y, y)
c) Interconnected star (Z, z)
d) Open (III, iii)

Capital letters relate to the high-voltage windings, lower-case letters to the medium and low-voltage windings. The vector group begins with the capital letter. In the case of more than one winding with the same rated voltage, the capital letter is assigned to the winding with the highest rated power; if the power ratings are the same, to the winding which comes first in the order of connections listed above. If the neutral of a winding in star or interconnected star is brought out, the letter symbols are YN or ZN, or yn or zn, respectively.

To identify the phase angle, the vector of the high-voltage winding is taken as a reference. The number, multiplied by 30° denotes the angle by which the vector of the LV winding lags that of the HV winding. With multi-winding transformers, the vector of the HV winding remains the reference; the symbol for this winding comes first, the other symbols follow in descending order according to the winding's rated voltages.

Example:

For a transformer with three power windings (HV windings 220 kV in neutral connection with brought-out neutral, MV winding 110 kV in neutral connection with brought-out neutral, and LV winding 10 kV in delta connection), if the vectors of the neutral voltage of HV and MV winding are in phase and the vector of the neutral voltage of the LVwinding lags behind them by 5 · 30 = 150°, the identifying symbols are:

YN, yn 0, d 5.

Preferred connections

Yyn 0	for *distribution transformers.* The neutral point can be loaded continuously with up to 10 % of the rated current, or with up to 25 % of the rated current for a maximum of 1.5 hours. Example: for connecting arc suppression coils.
YNyn 0	with *compensating winding,* used for large system-tie transformers. The neutral point can be loaded continuously with the rated current.
YNd 5	intended for *machine and main transformers* in large power stations and transformer stations. The neutral point can be loaded with the rated current. Arc suppression coils can be connected (delta winding dimensioned for the machine voltage).
Yzn 5	for *distribution transformers,* used up to approx. 250 kVA for local distribution systems. The neutral point can be loaded with the rated current.

Dyn 5	for *distribution transformers* above approx. 315 kVA, for local and industrial distribution systems. The neutral point can be loaded with the rated current.
Ii 0	for *single-phase transformers,* intended for traction power supply or for three-phase banks with very high voltages and powers.

If single-phase transformers are combined to form three-phase banks, the switchgear, instrument transformers and conductor cross-sections must be designed for the voltage and current ratings given in Table 12-2.

Table 12-2

Values of Ur and Ir for transformers of connection III iii

Connection of windings	Rated voltage U_r	Rated current I_r
Star	$\sqrt{3}\ U_{ph}$	I_{ph}
Delta	U_{ph}	$\sqrt{3}\ I_{ph}$

U_{ph} phase (conductor/earth) voltage, I_{ph} phase (winding) current.

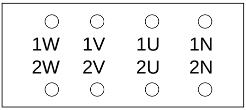
Identification and arrangement of terminals

Terminations of the windings (coils) brought out in the same winding sense are denoted 1U1,1V1,1W1 for the primary windings and 2U1, 2V1, 2W1 for the secondary windings. The terminations at the other ends of the windings, brought out in the inverse winding sense, are designated 1U2, 1V2, 1W2 for the primary windings and 2U2, 2V2, 2W2 for the secondary windings.

As a rule, the terminals of a transformer (1U,1V,1W for the primary side and 2U, 2V, 2W for the secondary side) are arranged from right to left as viewed from the low-voltage side, with their inscriptions visible from the low-voltage side, Fig. 12-3.

Fig. 12-3

Identification and arrangement of the terminals of a transformer (in accordance with DIN 42402)



12.1.3 Impedance voltage, voltage variation and short-circuit current withstand

Voltage drops

The *impedance voltage* U_{kr} *is* defined as that voltage having the rated frequency which must be applied to the primary side of a transformer so that the rated current I_r flows when the secondary terminals are short-circuited. Since only the short-circuit impedance is present in the circuit,

$$U_{kr} = \sqrt{3} \cdot I_r \cdot Z_k.$$

The rated impedance voltage is usually stated as a percentage of the voltage rating U_r of the winding to which the voltage is applied:

$$u_{kr} = \frac{U_{kr}}{U_r} \cdot 100\ \%.$$

The impedance voltage is composed of the ohmic voltage drop (U_R, u_R) which is in phase with the current, and the reactive voltage (U_x, u_x), which leads the current in time by 90°.

Ohmic voltage drop:

$$u_{Rr} = \frac{P_{kr}}{S_r} \cdot 100\ \% = \frac{\text{Impedance losses at rated power}}{\text{rated power}}\ 100\ \%.$$

Reactive voltage:

$$u_{Xr} = \sqrt{u_{kr}^2 - u_{Rr}^2}.$$

In the case of a partial load, the short-circuit voltage U_k is proportional to the load on the transformer:

$$u_k = u_{kr} \frac{I}{I_r} = u_{kr} \frac{S}{S_r}$$

For distribution transformers, according to DIN 42500 a rated impedance voltage u_{kr} is allocated to each power rating S_r, Table 12-3.

Table 12-3

Rated impedance voltage u_{kr}

Rated output S_r in kVA 1)										u_{kr}
50	(63)	100	160	(200)	250	(315)	400	(500)	630	4 %
630	(800)	1000	(1250)	1600	(2000)	2500				6 %

1) Rated outputs not in brackets are preferred.

Transformers with a rated impedance voltage $u_{kr} = 4\ \%$ are used mainly in distribution networks in order to keep the voltage drop small.

Transformers with a rated impedance voltage $u_{kr} = 6\ \%$ are preferably to be used in industrial networks and in high-power distribution networks in order to limit the short-circuit stress. The rated impedance voltages of medium-size and large transformers are even higher so as to achieve sufficient short-circuit strength.

Voltage variation

The voltage variation between no-load and a symmetrical load of any magnitude for any $\cos \varphi$ can be calculated from the rated impedance voltage and the impedance losses at rated load. It is denoted u_φ, and referred to the rated voltage.
For a given part load $a = S/S_r$ and a given power factor $\cos \varphi$,

$$u_\varphi = a \cdot u'_\varphi + \frac{1}{2} \cdot \frac{(a \cdot u''_\varphi)^2}{10^2} + \frac{1}{8} \cdot \frac{(a \cdot u''_\varphi)^4}{10^6} + \ldots^{1)}$$

where

$$u'_\varphi = u_{Rr} \cdot \cos \varphi + u_{Xr} \cdot \sin \varphi$$

and

$$u''_\varphi = u_{Rr} \cdot \sin \varphi - u_{Xr} \cdot \cos \varphi$$

The actual voltage at the terminals on the output side of the loaded transformer will then be

$$U_a = U_r \left(1 - \frac{u_\varphi}{100\ \%}\right)$$

Example:

Find the full-load voltage U_a for a transformer with rated load on the output side at $\cos \varphi = 0.8$ ($\sin \varphi = 0.6$).

Rated output: $S_r = 2500$ kVA,
Impedance losses: $P_{kr} = 24$ kW,
Impedance voltage: $u_{kr} = 6\ \%$.

$$u_{Rr} = \frac{P_{kr}}{S_r} \cdot 100\ \% = \frac{24\ \text{kW}}{2500\ \text{kVA}}\ 100\ \% = 0.96\ \%$$

$$u_{xr} = \sqrt{u_{kr}^2 - u_{Rr}^2} = \sqrt{6^2 - 0.96^2\ \%} = 5.923\ \%$$

$$u'_\varphi = u_{Rr} \cos \varphi + u_{xr} \sin \varphi = 0.96 \cdot 0.8 + 5.923 \cdot 0.6 = 4.32\ \%$$

$$u''_\varphi = u_{Rr} \sin \varphi - u_{xr} \cos \varphi = 0.96 \cdot 0.6 - 5.923 \cdot 0.8 = -4.16\ \%$$

$$u_\varphi = u'_\varphi + \frac{1}{2} \frac{(u''_\varphi)^2}{10^2} = 4.32 + \frac{1}{2} \cdot \frac{(-4.16)^2}{10^2} = 4.4\ \%.$$

$$U_a = U_r \ (1 - \frac{u_\varphi}{100\ \%}) = 0.965 \cdot U_r.$$

---

1) If $u_{kr} < 20\ \%$ the third summand can be disregarded. The second summand may also be disregarded if $u_{kr} < 4\ \%$.

Short-circuit current and its limitation

The criterion for the short-circuit is a reference impedance composed of the impedances of the network (Z_Q) and transformer (Z_k). This is

$$I_{k3p} = \frac{U_r}{\sqrt{3}|Z_Q + Z_k|} \approx \frac{I_k}{u_{kr}\,\%} \cdot 100\,\%.$$

With distribution transformers of ratings up to 3150 kVA and $Z_Q \leq 0.05 \cdot Z_k$, the network impedance Z_Q can usually be disregarded.

The short-circuit impedance limits the short-circuit current. Thermal stress is governed by the sustained short-circuit current I_k. The maximum permissible short-circuit duration is 2 s as per DIN 57532-5 (VDE 0532 Part 5), unless otherwise specified by the customer.

With transformers of vector groups Dy and Yd, the single-phase sustained short-circuit current is about the same as the three-phase value. At windings in interconnected star connection, the single-phase sustained short-circuit current can reach roughly 1.4 times the three-phase value, as its zero-sequence impedance is usually very small.

Table 12-4

Reference impedances for two-winding transformers (to VDE 0532 Part 5)

Rated power kVA	Typical values of z_k (or u_{kr}) %	Maximum system voltage kV	Typical values of reference system fault level S_{kQ}[1] MVA
to 630	4.0	7.2 12 17.5 and 24	500
from 630 to 1 250	5.0	36	1 000
from 1 250 to 3 150	6.25	52 and 72.5	3 000
from 3 150 to 6 300	7.15	100 and 123	6 000
from 6 300 to 12 500	8.35	145 and 170	10 000
from 12 500 to 25 000	10.0	245	20 000
from 25 000 to 200 000	12.5	300	30 000
		420	40 000

[1] If not specified

12.1.4 Losses, cooling and overload capacity

Transformer losses

Fig. 12-4 shows the usual values of no-load losses P_0 and impedance loss P_k for two-winding transformers. The total losses P_v of a transformer at any loading a = S/S_r can be calculated from the relationship:

$$P_v = P_0 + a^2 P_k.$$

The no-load losses P_0 are composed of the hysteresis losses and eddy-current losses in the iron, and leakage losses in the dielectric. These losses are not affected by the load.

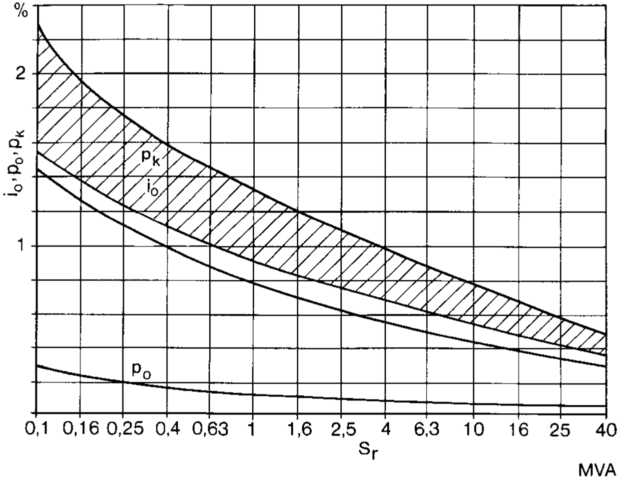


Fig. 12-4

Typical values for two-winding transformers. i_0 *(percentage no-load current),* p_0 *(percentage no-load losses) and* p_k *(percentage impedance losses) as a function of rated power* S_r*.*

Power range 2.5 MVA to DIN 42500

Power range 2 to 10 MVA to DIN 42504 and 12.5 to 80 MVA to DIN 42508
Upper limit of p_k *for rated high voltage 123 kV,*
Lower limit of p_k *for rated high voltage 36 kV.*

The *impedance losses* P_k comprise the copper losses in the windings and the additional losses. Impedance losses, which are caused by eddy currents inside and outside the windings, vary as the square of the load. The efficiency η of a transformer at any load is determined sufficiently accurately from

$$\eta \; = \; 100\,\% - \frac{P_0 + a^2\,P_k}{a \cdot S_r \cdot \cos\varphi + P_0} \cdot 100\,\%$$

Example

Find the efficiency of a 250 kVA transformer for 20/0.4 kV with P_0 = 610 W and P_k = 4450 W at half-load (a = 0.5) and cos φ = 0.8.

$$\eta \; = \; 100\,\% - \frac{0.61 + 0.5^2 \cdot 4\;45}{0.5 \cdot 250 \cdot 0.8 + 0.61} \cdot 100\,\% \; = \; 98.29\,\%.$$

In order to assess a transformer, however, it is more informative to evaluate the losses and their distribution, rather than the efficiency.

Cooling

The method of cooling is stated by the manufacturer in the form of four capital letters, the first two letters denoting the coolant and the manner of circulation for the winding, and the last two letters indicating the coolant and manner of circulation for cooling the outside of the transformer. These code letters are explained in Table 12-5.

Table 12-5

Key to cooling systems

Coolant	Symbols
Mineral oil or equiv. synth. liquid with fire point ≤ 300 °c	O
Other synth. liquids	K
Gas with fire point > 300 °C	G
Air (dry-type transformers)	A
Water	W

Coolant circulation	Symbols
Natural circulation	N
Forced circulation (non-directed)	F
Forced circulation (directed)	D

Examples

AN = Dry-type transformer with natural air circulation,
ONAN = Oil-immersed self-cooled transformer.

Overload capacity to DIN 57536 (VDE 0536)

The maximum time for which transformers can be overloaded at a given bias load and coolant temperature is shown in Fig. 12-5 for air-cooled oil-immersed transformers in the case of two different loads recurring regularly in a 24-hour cycle.

In the diagram:

K_1 Initial load as a proportion of rated power,
K_2 Permitted overload as a proportion of rated power (normally > 1),
t Duration of K_2 in h,
Θ_a Coolant temperature in °C.

Hence

$$K_1 = \frac{S_1}{S_r};\ K_2 = \frac{S_2}{S_r};\ \frac{K_2}{K_1} = \frac{S_2}{S_1}$$

Here, S_1 is the initial load, S_2 the maximum permitted load and S_r the rated power. Under normal circumstances, K_2 should not exceed 1.5.

Example:

Transformer 1250 kVA with ONAN cooling. Bias load 750 kVA. What is the maximum permitted load over 4 hours at 20 °C?

$K_1 = 0.6$; $t = 4$ h. Fig. 12-5a yields $K_2 = 1.29$.

$S_2 = K_2 \cdot S_r = 1.29 \cdot 1250$ kVA = 1612 kVA.

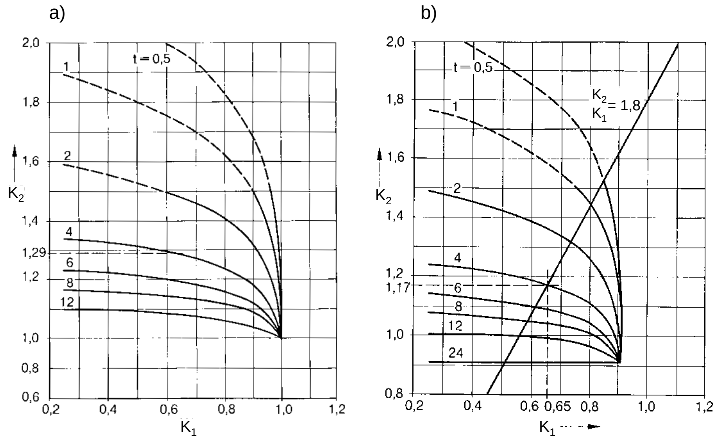


Fig. 12-5

Transformer with ONAN and ONAF cooling. Values of K_2 for given values of K_1 and t (in hours), a) Θ_a = 20 °C, b) Θ_a = 30 °C

For a given case of transformer loading, the power rating S_r can be calculated from:

$$S_r = \frac{S_1}{K_1} = \frac{S_2}{K_2}$$

Example:

At Θ_a = 30 °C, a transformer with ONAN cooling is to run for 4 hours at 450 kVA and otherwise at 250 kVA. What power rating is required?

$$S_1 = 250 \text{ kVA}, \quad t_1 = 20 \text{ h}; \qquad S_2 = 450 \text{ kVA}, \quad t_2 = 4 \text{ h}.$$

$$\frac{S_2}{S_1} = \frac{450}{250} = 1.8 = \frac{K_2}{K_1}$$

From Fig. 12-5 b for K_2/K_1 = 1.8 when t = 4 h: K_1 = 0.65; K_2 = 1.17.

$$S_r = \frac{450}{1.17} = \frac{250}{0.65} = 385 \text{ kVA} \rightarrow 400 \text{ kVA}.$$

12.1.5 Parallel operation

Transformers are in parallel operation if they are connected in parallel on at least two sides. A distinction is made between busbar interconnection and network interconnection. The following conditions must be satisfied in order to avoid dangerous transient currents:

1. vector groups should have the same phase angle number; terminals of the same designation must be connected together on the HV and LV sides; Exception: Phase angle numbers 5 and 11 (Table 12-6);
2. the ratios should be as similar as possible, i.e. the same rated voltages on the HV and LV sides;
3. approximately the same impedance voltages u_k maximum permissible discrepancies ± 10 %. In the event of larger differences, an inductance (reactor) can be connected ahead of the transformer with the lower impedance voltage.
4. rated output ratio smaller than 3:1.

Table 12-6 Parallel operation of transformers with phase angle numbers 5 and 11

Phase angle number required	Phase angle number available		Connection to conductors HV side			Connection to conductors LV side		
			L1	L2	L3	L1	L2	L3
5	5		1U	1V	1W	2U2	2V2	2W2
5	11		1U	1W	1V	2W1	2V1	2U1
		or	1W	1V	1U	2V1	2U1	2W1
		or	1V	1U	1W	2U1	2W1	2V1
11	11		1U	1V	1W	2U1	2V1	2W1
11	5		1U	1W	1V	2W2	2V2	2U2
		or	1W	1V	1U	2V2	2U2	2W2
		or	1V	1U	1W	2U2	2W2	2V2

Load distribution of parallel transformers with different rated impedance voltages

Transformers connected in parallel assume a partial load such that all the transformers have the same average impedance voltage. If the impedance voltage of a transformer is referred to an output other than its rated output, its magnitude varies in accordance with the output. A 100 kVA transformer with u_{kr} = 4 % has at 60 kVA an impedance voltage u_k of 0.6 · 4 = 2.4%.

Example:

transformer 1: S_{r1} = 100 kVA, u_{kr1} = 4.0 %
transformer 2: S_{r2} = 250 kVA, u_{kr2} = 6.0 %
transformer 3: S_{r3} = 500 kVA, u_{kr3} = 4.5 %

total S = 850 kVA

We have:

$$\frac{S}{u_k} = \frac{S_{r1}}{u_{k1}} + \frac{S_{r2}}{u_{k2}} + \ldots$$

The resultant impedance voltage is then:

$$u_k = \frac{S}{\frac{S_{r1}}{u_{kr1}} + \frac{S_{r2}}{u_{kr2}} + \frac{S_{r3}}{u_{kr3}}} = \frac{850}{\frac{100}{4} + \frac{250}{6} + \frac{500}{4.5}} = 4.78\ \%$$

The power assumed by the individual transformers is:

$$S_1 = S_{r1}\,\frac{u_k}{u_{kr1}} = 100 \cdot \frac{4.78}{4} = 120\ \text{kVA}$$

$$S_2 = S_{r2}\,\frac{u_k}{u_{kr2}} = 250 \cdot \frac{4.78}{6} = 199\ \text{kVA}$$

$$S_3 = S_{r3}\,\frac{u_k}{u_{kr3}} = 500 \cdot \frac{4.78}{4.5} = 531\ \text{kVA}$$

$$S_{tot} = S_1 + S_2 + S_3 = 120\ \text{kVA}$$

Transformer 1 is thus overloaded by 20 % and transformer 3 by 6 %. Since the individual transformers should not be subjected to overload, the transformers may only assume a partial load such that the impedance voltage of each is u_k = 4 %, as in the case with transformer 1. Therefore,

$$S_1 = 100 \cdot \frac{4}{4} = 100\ \text{kVA}$$

$$S_2 \quad = 250 \cdot \frac{4}{6} \quad = 167 \text{ kVA}$$

$$S_3 \quad = 500 \cdot \frac{4}{4.5} = 444 \text{ kVA}$$

$$S_{\text{tot}} \quad = S_1 + S_2 + S_3 = 711 \text{ kVA}$$

If this output is not sufficient, another 160 kVA transformer with u_{kr} = 4 % will have to be installed.

Effect of dissimilar transformation ratios of transformers connected in parallel

Dangerous transient currents can occur if transformers with different voltages between taps are operated in parallel. Disregarding any dissimilarity in impedance phase angle φ_k, the voltage difference Δu proportional to the difference in ratio drives through both sides a circulating current of

$$I_a = \frac{\Delta u}{u_{k1}/I_{r1} + u_{k2}/I_{r2}}$$

If, for example, $u_{k1} = u_{k2} = 6$ %, I_{r1} = 910 A, I_{r2} = 1445 A und Δu = 4 %, then

$$I_a = \frac{4\ \%}{6\ \% / 910\ A + 6\ \% / 1445\ A} = 377.34 \text{ A.}$$

This balancing current is superimposed on the transformer load currents that are supplied to the network. It is added to the current of that transformer which has the greater secondary no-load voltage.

12.1.6 Protective devices for transformers

Overcurrent time relays respond to short circuits; they trip the circuit-breakers.

Thermal relays respond to unacceptable temperature rises in the transformer, and signal overloads.

Make-proof percentage differential relays detect internal short circuits and faults, including those on lines between the current transformers; they trip the appropriate transformer breakers, but do not respond to the inrush current of a sound transformer.

Buchholz relays detect internal damage due to gassing or oil flow; they signal minor disturbances and trip the breaker if the trouble is serious.

Temperature monitors signal when a set temperature is reached, or trip circuit-breakers.

Dial-type telethermometers indicate the temperature in the transformer’s topmost oil layer with maximum and minimum signal contacts.

Oil level alarms respond if the oil level is too low.

Oil flow indicators detect any disruption in the circulation in closed-circuit cooling and trigger an alarm.

Airflow indicators detect any break in the flow of forced-circulation air, and trigger an alarm.

12.1.7 Noise levels and means of noise abatement

Since transformers are located in or near residential areas, the noise they produce must be determined so as to assess the need for any countermeasures.

The noise of transformers is defined as the A-weighted sound pressure level measured in dB (A) at a specified measuring surface with a sound level meter, and then converted to a sound power level with the following formula:

$L_{WA} = L_{PA} + L_S$

In which:

L_{WA}	A-weighted sound power level in dB
L_{PA}	A-weighted sound pressure level in dB
L_S	Measuring-surface level in dB

The measurements must be performed according to DIN EN 60551 (VDE 0532 Part 7). For transformers with water cooling or fan-less air cooling, at least 6 measurements must be taken at a distance of 0.3 m from the surface of the transformer. For transformers with other cooling systems, the relevant measurement regulations as per DIN EN 60551 (VDE 0532 Part 7) apply.

Table 12-7

A-weighted sound power level in dB (A) for transformers up to a rated power of 2.5 MVA

Rated power	Oil-insulated transformers as per DIN 42500			Resin-encapsulated transformers
kVA	List A'	B'	C'	as per DIN 42523[1]
50	55	50	47	–
100	59	54	49	59 (51)
160	62	57	52	62 (54)
250	65	60	55	65 (57)
400	68	63	58	68 (60)
630	70	65	60	70 (62)
1 000	73	68	63	73 (65)
1 600	76	71	66	76 (68)
2 500	81	76	71	81 (71)

[1] Values in parentheses for the reduced series

The causes and effects of the noise produced by transformers and their cooling systems are so diverse that it is not possible to recommend generally applicable noise abatement measures. Each case must be carefully investigated as necessary.

Possible measures include:

Actions by the transformer manufacturer to reduce airborne and structure-borne noise.

Structural measures against airborne noise, e.g. sound-absorbent walls or enclosures.

Anti-vibration treatment of the foundations to reduce transmission of structure-borne noise, e.g. spring-mounted supporting structure.

12.2 Current-limiting reactors EN 60289 (VDE 0532 Part 20)

12.2.1 Dimensioning

Current-limiting reactors (series reactors) to DIN VDE 0532, Part 2 are reactances employed to limit short-circuit currents. They are used when one wishes to reduce the short-circuit power of networks or installations to a value which is acceptable with regard to the short-circuit strength of the equipment or the breaking capacity of the circuit-breaker.

Since the reactance of a series reactor must remain constant when short-circuit currents occur, only the air-core type of construction is suitable1). If iron cores were used, saturation of the iron brought about by the short-circuit currents would cause a drop in the inductance of the coil, thus seriously reducing the protection against short circuits.

Voltage drop and voltage variation

The rated impedance is the impedance per phase at rated frequency. The resistance of a current-limiting reactor is negligible and in general, amounts to not more than some 3 % of the reactance X_L.

The rated voltage drop ΔU_r is the voltage induced in the reactor when operating with rated current and rated reactance:

$$\Delta U_r = I_r \cdot X_L$$

When referred to the nominal voltage of the system, the rated voltage drop is denoted Δu_r and usually stated in %:

$$\Delta u_r = \frac{\Delta U_r \cdot \sqrt{3}}{U_n} 100\ \%.$$

Example:

A reactor in a three-phase system with a rated voltage of 10 kV has a reactance of 5 %. Its rated current is 400 A. This statement indicates that the voltage drop at the reactor is 5 % of the system phase-to-earth voltage. The absolute value in volts is

$$\Delta U_r = \frac{\Delta U_r \cdot U_n}{\sqrt{3} \cdot 100\ \%} = \frac{5\ \% \cdot 10\ 000\ \text{V}}{\sqrt{3} \cdot 100\ \%} = 289\ \text{V}.$$

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1) Air-core reactors can cause the frequency of the recovery voltage to assume extremely high values (150 to 250 kHz). Reduction of these natural frequencies to the values for circuit-breakers defined by VDE 0670 Part 104 can be achieved by fitting capacitors.

Possible measures include:

Actions by the transformer manufacturer to reduce airborne and structure-borne noise.

Structural measures against airborne noise, e.g. sound-absorbent walls or enclosures.

Anti-vibration treatment of the foundations to reduce transmission of structure-borne noise, e.g. spring-mounted supporting structure.

12.2 Current-limiting reactors EN 60289 (VDE 0532 Part 20)

12.2.1 Dimensioning

Current-limiting reactors (series reactors) to DIN VDE 0532, Part 2 are reactances employed to limit short-circuit currents. They are used when one wishes to reduce the short-circuit power of networks or installations to a value which is acceptable with regard to the short-circuit strength of the equipment or the breaking capacity of the circuit-breaker.

Since the reactance of a series reactor must remain constant when short-circuit currents occur, only the air-core type of construction is suitable1). If iron cores were used, saturation of the iron brought about by the short-circuit currents would cause a drop in the inductance of the coil, thus seriously reducing the protection against short circuits.

Voltage drop and voltage variation

The rated impedance is the impedance per phase at rated frequency. The resistance of a current-limiting reactor is negligible and in general, amounts to not more than some 3 % of the reactance X_L.

The rated voltage drop ΔU_r is the voltage induced in the reactor when operating with rated current and rated reactance:

$$\Delta U_r = I_r \cdot X_L$$

When referred to the nominal voltage of the system, the rated voltage drop is denoted Δu_r and usually stated in %:

$$\Delta u_r = \frac{\Delta U_r \cdot \sqrt{3}}{U_n} 100\ \%.$$

Example:

A reactor in a three-phase system with a rated voltage of 10 kV has a reactance of 5 %. Its rated current is 400 A. This statement indicates that the voltage drop at the reactor is 5 % of the system phase-to-earth voltage. The absolute value in volts is

$$\Delta U_r = \frac{\Delta U_r \cdot U_n}{\sqrt{3} \cdot 100\ \%} = \frac{5\ \% \cdot 10\ 000\ \text{V}}{\sqrt{3} \cdot 100\ \%} = 289\ \text{V}.$$

1) Air-core reactors can cause the frequency of the recovery voltage to assume extremely high values (150 to 250 kHz). Reduction of these natural frequencies to the values for circuit-breakers defined by VDE 0670 Part 104 can be achieved by fitting capacitors.

For given values of reactance and current, the voltage variation U_φ in the network, i.e. the difference between the network voltage before and after the reactor, is also dependent on cos φ, Fig. 12-6. Thus, whereas the voltage difference U_φ across the reactor is small under normal operating conditions, it increases in the event of a short circuit

1. in proportion to the short-circuit current and
2. with the increase in phase displacement angle under fault conditions.

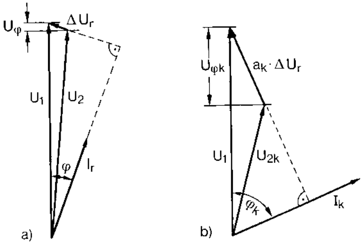


Fig. 12-6

Vector diagram of a reactor:

a) *Normal operation*
b) *Short-circuit operation*
U_1 *System voltage before reactor*
U_2 *System voltage after reactor*
U_φ *Voltage variation in system*

According to Fig. 12-6, for a given load a= I/I_r and a given power factor cos φ

$$U_\varphi = a \cdot \Delta U_r \cdot \cos(90° - \varphi)$$

or $$u_\varphi = a \cdot \Delta u_r \cdot \sin \varphi.$$

Example:

At a power factor of cos $\varphi = 0.8$ and rated current, a reactor with $\Delta u_r = 6$ % causes a voltage variation in the network of $u_\varphi = 6 \% \bullet 0.6 = 3.6 \%$.

If large motors are connected after reactors and the current ratings of the motor and the reactor are of the same order of magnitude, account must be taken of the voltage drop due to the large starting current of the motor. The drop must not be so large as to endanger the safe run-up of the motor.

Inherent power and throughput power

The inherent power of a reactor is the product of the voltage drop ΔU_r and the rated current I_r.

$$S_E = 3 \cdot \Delta U_r \cdot I_r \text{ (three-phase).}$$

The throughput of a reactor is the product of the line-to-earth voltage $U_n/\sqrt{3}$ and the rated current I_r.

$$S_D = \sqrt{3} \cdot U_n \cdot I_r \text{ (three-phase).}$$

Selection of a current-limiting reactor

If the given short-circuit power S''_{k1} of a grid system is to be reduced to a value of S''_k by fitting a reactor, its required percentage rated voltage drop is

$$\Delta u_r = 1.1 \cdot 100 \% \cdot S_D \cdot \frac{S''_{k1} - S''_{k2}}{S''_{k1} \cdot S''_{k2}}.$$

Example:

$$U_n = 6\text{ kV},\quad I_r = 600\text{ A};$$
$$S''_{k1} = 600\text{ MVA},\quad S''_{k2} = 100\text{ MVA};$$

$$\Delta u_r = 1.1 \cdot 100\,\% \cdot \sqrt{3} \cdot 6\text{ kV} \cdot 0.6\text{ kA}\,\frac{600\text{ MVA} - 100\text{ MVA}}{600\text{ MVA} \cdot 100\text{ MVA}} = 5.72\,\%.$$

In practice, one will select the next-highest standardized value, 6 % in this instance.

If the short-circuit power S''_{k1} before a reactor is given, and its percentage rated voltage drop is Δu_r, the short-circuit power S''_{k2} after the reactor is:

$$S''_{k2} = \frac{1.1 \cdot 100\,\% \cdot S_D \cdot S''_{k1}}{1.1 \cdot 100\,\% \cdot S_D + \Delta u_r \cdot S''_{k1}}.$$

Taking the values of the example above, this yields:

$$S''_{k2} = \frac{1.1 \cdot 100\,\% \cdot \sqrt{3} \cdot 6\text{ kV} \cdot 0.6\text{ kA} \cdot 600\text{ MVA}}{1.1 \cdot 100\,\% \cdot \sqrt{3} \cdot 6\text{ kV} \cdot 0.6\text{ kA} + 6\,\% \cdot 600\text{ MVA}} = 96\text{ MVA}.$$

12.2.2 Reactor connection

The scheme shown in Fig. 12-7 under a), with the reactors in the tee-offs, is the one most commonly used. The circuit shown in b), with the reactors in the feeder, is often chosen for reasons of saving space. For the same degree of protection, the costs of purchase and operation are higher than with reactors in the branches.

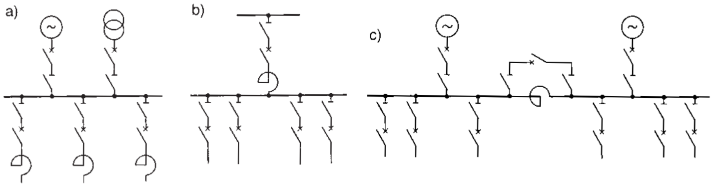


Fig. 12-7

The most common reactor connections:
a) Feeder connection, b) Tee-off connection, c) Busbar sectionalizer connection.

In power stations with a high short-circuit power, it is usual to fit busbar sectionalizing reactors together with bypass circuit-breakers, as shown in c). In this way, a permanent connection is established between the busbars, although in the event of a fault, when the circuit-breaker opens, the short-circuit power is limited approximately to that of the individual systems.

It is even better to use I_s-limiters (Section 8.1.6) instead of circuit-breakers for bypassing reactors, because these devices interrupt the bypass without any delay and therefore prevent hazardous peak current values from occurring.

12.2.3 Installation of reactors

When installing reactors, care must be taken to ensure that the heat losses occurring during operation are dissipated by adequate ventilation. As a rough estimate, one can assume a fresh air requirement of 4 to 5 m^3/min per kilowatt of heat loss. The air flow cross-sections necessary in the rooms can be calculated more accurately using the method described in Section 4.4.2 for transformers.

Care must also be taken that reactors are situated sufficiently far away from neighbouring metal parts to ensure that these are not heated excessively by eddy currents.

Reactors should not be situated at distances of less than 500 mm from constructional items of steel, and steel reinforcement in ceilings, floors and walls. If the floor is steel-reinforced, the reactor must be placed on a concrete pedestal, Fig. 12-8.

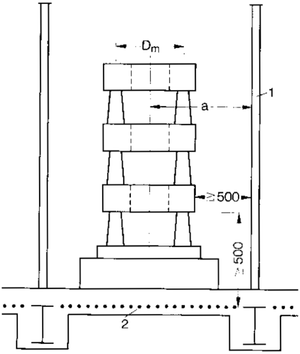


Fig. 12-8

Installation of a current-limiting reactor: D_m mean diameter of reactor, a distance between centre line of reactor and metal item
1 Steel-reinforced wall
2 Reinforcing bars
(dimensions in mm)

With cell enclosures of non-magnetic materials (aluminium alloys), the minimum clearance for the highest equipment voltage in question (DIN VDE 0101) is sufficient. Closed structures (short-circuit loops) with a good electrical conductivity must be avoided in the vicinity of strong magnetic fields. If necessary, the short-circuit loop should be split and the junction joined by means of non-conducting material to prevent excessive heating by circulating currents.

If one is forced to use magnetic materials, the distance between reactor and metal structure should be selected so that under rated conditions, the root-mean-square value of the magnetic field strength does not exceed 20 A/cm. The field strength is calculated as

$$H = 0.1 \cdot \frac{I_r \cdot w \cdot D_m}{a^2}$$

Here, I_r rated current in A, w number of turns in reactor, for D_m and a, see Fig. 12-8.

12.3 Capacitors

12.3.1 Power capacitors

The term power capacitor is chiefly applied to capacitors having a rated frequency of 50 or 60 Hz which compensate the reactive power at points of heavy demand in public and industrial networks. This general designation also includes “furnace capacitors” and “medium-frequency capacitors”, which cover the high reactive power requirement of melting furnaces and inductive heating coils, and also “welding machine capacitors” and “fluorescent lamp capacitors” used for compensating welding transformers and the ballasts of fluorescent lamps. The design of power capacitors is regulated by the following standards: DIN VDE 0560-1 (VDE 0560 Part 1), and DIN EN 60831-1 (VDE 0560 Part 46) – self-restoring up to 1000 V –, DIN EN 60931-3 (VDE 0560 Part 45) – non-self-restoring up to 1000 V – and DIN EN 60871-1 (VDE 0560 Part 410) – over 1000 V –.

The reactive power of a capacitor is determined by its capacitance, the rms value of the operating voltage and the system frequency:

$$Q_c = U^2 \cdot \omega \cdot C.$$

The rated power of a capacitor as stated on its nameplate is always in relation to its rated voltage U_r and rated frequency f_r.

In three-phase networks, the capacitors, always three of the same size, are connected in either star or delta. If

C_1 is the capacitance in one phase with star connection, and

C_{12} is the capacitance in one phase with delta connection,

then for the same reactive power:

$$C_1 = 3\, C_{12}.$$

The temperature range for power capacitors is specified by the temperature classes (DIN EN 60831-1, Table 1). The following temperature values are applicable for the permissible ambient temperatures, e.g. for the -25°C class (preferred temperature class),

maximum: 50 °C,
max. average over 24 h: 40 °C,
max. average over 1 year: 30 °C,
minimum: -25 °C.

Voltage and frequency increases and total harmonic distortion of the voltage or the current place additional stress on capacitors.

Capacitors must be able to carry continuously 1.3 times the current flowing with sinusoidal rated voltage and frequency at an ambient air temperature corresponding to its temperature class. With this loading, the voltage must not be higher than 1.1 U_r, no account being taken of transient overvoltages.

If the limiting conditions stated above are exceeded, the chosen capacitor must be replaced by one with a higher voltage rating and a rated power according to the equation

$$Q_{r2} = Q_{r1}\,(U_{r2}/U_{r1})^2.$$

Where such a capacitor is directly connected to the system, the connection lines and the switching and protection devices must be rated correspondingly higher. However, this does not ensure that the system conditions are compatible for other consumers. For this reason, in most cases it is better to include inductor-capacitor units.

When selecting the switchgear apparatus, protective devices and conductors, attention must be paid to the possibility of overloading mentioned above. Taking account of the permissible difference in capacitance, this is $(1.1 \cdot 1.3) = 1.43$ times the capacitor current rating.

HRC fuses serve only as short-circuit protection and do not provide adequate protection against overcurrents. Bimetal and secondary thermal relays are recommended as thermal protection for capacitor banks of above 300 kvar. The tripping current of these relays should be set to 1.43 times the rated current of the capacitor (capacitor bank). Protection by means of overcurrent relays does not at the same time provide protection against overvoltages.

All capacitor installations must be connected direct to a means of discharge, without intervening isolators or fuses. Low-voltage capacitors must discharge to a residual voltage $\leq$ 75 V within 3 minutes. A maximum discharge time of 10 minutes is stipulated for high-voltage capacitors.

The residual voltage at the capacitator must not exceed 10 % of the nominal voltage before switching on.

When capacitors are connected in star, the neutral point must not be directly earthed. Earthing via surge arresters (blow-out fuses) is permissible.

For installation, connection and special protective measures, note must be taken of specifications DIN VDE 0100, DIN VDE 0101, DIN VDE 0105 and the “Technical connection requirements for power installations” of VDEW.

12.3.2 Compensation of reactive power

Only the active power produced by the active current is utilized at the point of consumption. The reactive power produced by the reactive current does not contribute to the conversion into useful power and is therefore not counted by the active power meter. However, the reactive power has an unfavourable effect on the electrical equipment in that it constitutes an additional load on generators, transformers and conductors. It gives rise to additional voltage drops and heat losses.

Static reactive-power (var) compensation in systems with the aid of thyristors is dealt with in Section 11.6.

It is economically sound to draw the reactive power from capacitors, Fig. 12-9. These are located in the vicinity of the largest reactive loads (motors and transformers) in order to relieve the transmission networks, including transformers and generators, from the corresponding share of the reactive current. If the capacitors are properly positioned, by reducing the reactive current in this way, it is possible in many instances to connect additional loads to existing supply systems without having to increase the power or extent of the network.

Fig. 12-10 shows the reactive power before compensation with $Q_1 = P \cdot \tan \varphi_1$ and after compensation with $Q_2 = P \cdot \tan \varphi_2$, where φ_2 is the phase displacement angle of the desired cos φ_2. The capacitor rating required for this is

$$Q_c = P \cdot (\tan \varphi_1 - \tan \varphi_2)$$

Table 12-8 provides an aid to calculation.

Example:

A motor draws active power of P = 60 kW from a system at cos φ = 0.6. Since tan φ = 1.333, the reactive power consumed by the motor is Q = 60 · 1.333 = 80 kvar.

If one wishes to compensate this reactive power to cos φ = 1 by means of a capacitor, the capacitor must also have a power rating of 80 kvar. In most cases, such extensive compensation, to cos φ = 1, will not be necessary. If a power factor of cos φ = 0.8 is sufficient in this particular instance, the capacitor rating can be calculated as follows:

$\cos \varphi_1 = 0.6$; $\tan \varphi_1 = 1.333$; desired $\cos \varphi_2 = 0.8$; $\tan \varphi_2 = 0.750$:

$Q_c = P\ (\tan \varphi_1 - \tan \varphi_2) =$

$= 60\ (1.333 - 0.75) = 60 \cdot 0.583 = 35$ kvar.

Thus the capacitor only has to be sized for this reactive power.

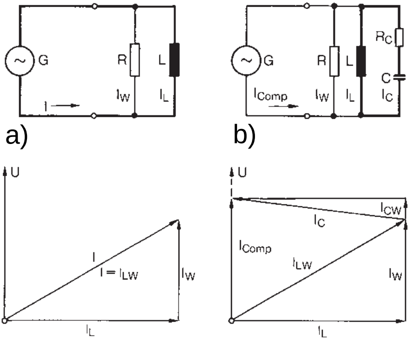


Fig. 12-9
Active and reactive currents in an electrical installation:
a) uncompensated,
b) compensated with capacitors.
With full compensation, the generator G supplies only the current I_w for the purely active load R, and active current I_{cw} for the capacitor loss resistance R_c.

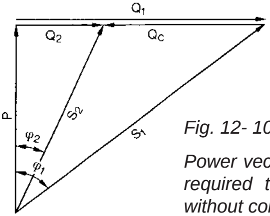


Fig. 12- 10

Power vector diagram for determining the capacitor rating Q_c required to compensate reactive power; Index 1: Values without compensation, Index 2: Values with compensation.

Table 12-8

To determine the factor ($\tan \varphi_1 - \tan \varphi_2$) for calculating reactive power at different power factors

Existing	Desired power factor $\cos \varphi_2$										
$\cos \varphi_1$	0.7	0.75	0.8	0.82	0.84	0.86	0.88	0.9	0.92	0.94	0.98
0.30	2.16	2.30	2.42	2.48	2.53	2.59	2.65	2.70	2.76	2.82	2.89
0.35	1.66	1.80	1.93	1.98	2.03	2.08	2.14	2.19	2.25	2.31	2.38
0.40	1.27	1.41	1.54	1.60	1.65	1.70	1.76	1.81	1.87	1.93	2.00
0.45	0.97	1.11	1.24	1.29	1.34	1.40	1.45	1.50	1.56	1.62	1.69
0.50	0.71	0.85	0.98	1.04	1.09	1.14	1.20	1.25	1.31	1.37	1.44
0.52	0.62	0.76	0.89	0.95	1.00	1.05	1.11	1.16	1.22	1.28	1.35
0.54	0.54	0.68	0.81	0.86	0.92	0.97	1.02	1.08	1.14	1.20	1.27
0.56	0.46	0.60	0.73	0.78	0.84	0.89	0.94	1.00	1.05	1.12	1.19
0.58	0.39	0.52	0.66	0.71	0.76	0.81	0.87	0.92	0.98	1.04	1.11
0.60	0.31	0.45	0.58	0.64	0.69	0.74	0.80	0.85	0.91	0.97	1.04
0.62	0.25	0.39	0.52	0.57	0.62	0.67	0.73	0.78	0.84	0.90	0.97
0.64	0.18	0.32	0.45	0.51	0.56	0.61	0.67	0.72	0.78	0.84	0.91
0.66	0.12	0.26	0.39	0.45	0.49	0.55	0.60	0.66	0.71	0.78	0.85
0.68	0.06	0.20	0.33	0.38	0.43	0.49	0.54	0.60	0.65	0.72	0.79
0.70		0.14	0.27	0.33	0.38	0.43	0.49	0.54	0.60	0.66	0.73
0.72		0.08	0.22	0.27	0.32	0.37	0.43	0.48	0.54	0.60	0.67
0.74		0.03	0.16	0.21	0.26	0.32	0.37	0.43	0.48	0.55	0.62
0.76			0.11	0.16	0.21	0.26	0.32	0.37	0.43	0.50	0.56
0.78			0.05	0.11	0.16	0.21	0.27	0.32	0.38	0.44	0.51
0.80				0.05	0.10	0.16	0.21	0.27	0.33	0.39	0.46
0.82					0.05	0.10	0.16	0.22	0.27	0.33	0.40
0.84						0.05	0.11	0.16	0.22	0.28	0.35
0.86							0.06	0.11	0.17	0.23	0.30
0.88								0.06	0.11	0.17	0.25
0.90									0.06	0.12	0.19
0.92										0.06	0.13
0.94											0.07

The value read from the table is multiplied by the active power P in kW to obtain the required capacitor rating in kvar.

The electricity supply utilities generally specify a power factor of 0.8 to 0.9. Compensation beyond $\cos \varphi = 1$ (over-compensation $Q_c > Q_1$) must be avoided as this gives rise to capacitive reactive power which stresses the conductors in the same way as inductive reactive power, and in addition, unwelcome voltage increases can occur.

Reactor-less capacitor banks cannot be used directly for compensating reactive power in systems to which sources of harmonics such as converters are connected.

Network impedance and capacitor bank form a parallel resonant circuit, the resonant frequency of which is

$$\omega_r = \frac{1}{\sqrt{L_N \cdot C}} \quad \text{or} \quad \upsilon_r = \frac{1}{w_1 \cdot \sqrt{L_N \cdot C}}$$

ω_1 = Angular frequency at nominal network frequency
L_N = Phase value of network/consumer inductance
C = Phase value of bank capacitance
υ_r = Mode number of resonant frequency

In a first approximation, this resonant frequency can also be calculated from the network fault power S_k'' and the compensating power at nominal network frequency Q_{c1}:

$$\upsilon_r = \frac{\omega_r}{\omega_1} = \sqrt{\frac{S_k''}{Q_{c1}}}$$

At this resonant frequency, the source of harmonics (e.g. rectifiers) encounters a higher network impedance.

In consequence, the harmonic current causes a larger drop in harmonic voltage than in an uncompensated network (X_L), which can result in unacceptably severe distortion of the voltage.

Between network and capacitor flow transient currents whose values can be a multiple of the exciting current harmonic. Transformers and particularly capacitors are thus subjected to additional stresses and can become overloaded.

Since the position of the point of parallel resonance can be calculated from the network inductance and the capacitor rating, it would be possible to position the resonant point so that it creates less disturbance. In practice, however, the network impedance is not constant because it depends on the system fault level and the consumers connected to the network.

Since the system fault level can alter according to the state of the circuit, and also loads are constantly being connected and disconnected, the point of parallel resonance will move according to the network configuration, so passing through zones of disturbance. The situation is more difficult if compensation is arranged to be switched in stages.

Measures must therefore be taken which in fact cannot avoid parallel resonance with the network, but shift the point of resonance into non-critical areas. Compensation facilities in networks containing harmonic sources must hence be provided with series reactors.

Capacitor banks with reactors constitute a series resonant circuit which exhibits the smallest resistance, theoretically zero, at the point of resonance.

Such series resonant circuits can be tuned to defined harmonics frequencies occurring in the network.

If the reactor coil is designed to subject the filter to a minimum amount of harmonic currents, this is called a “heavily detuned filter circuit”.

Heavily detuned filter circuits are used when harmonic sources in the network must be expected, but their extent is unknown. In practice, it can be taken that:

$$a = \frac{Q_L}{Q_{c1}} \, 100\,\% = \frac{X_L}{X_c} \, 100\,\%$$

referred to the nominal
network frequency,
with *'a'* having a value of 6 %.

The resulting frequency ratio of the series resonant frequency is calculated as:

$$\upsilon_r = \frac{\omega_r}{\omega_1} = \frac{10}{\sqrt{a}}$$

with '*a*' in %.

When *a* = 6 % therefore, the point of series resonance is at ν_r = 4.08 times the nominal network frequency.

In systems with audio-frequency ripple control, the capacitors damp the audio frequency. The electricity supply utilities therefore stipulate special measures, such as the fitting of suppression chokes ahead of capacitors.

Single compensation

The phase-shifting capacitor is coupled direct to the terminals of the load and switched in common with it.

The advantages are: reduced load on distribution lines and switchgear, no capacitor switches or discharge resistors required, installation simple and inexpensive.

This technique is used when relatively large loads (e.g. motors) are as far as possible in continuous operation.

Single compensation of three-phase motors

Motor and capacitor are connected in parallel. They are switched on and off by the same switching device and are supervised by the same protective system. No discharging device is needed. The capacitor discharges through the motor windings.

The switchgear must be selected according to the capacitor making current, and the electrical connections according to the compensated full-load current of the motor. The capacitor should be located in the immediate vicinity of the motor.

To avoid over-compensation at part-load and self-excitation of the motor as it runs down after disconnection, compensation should amount to only 90 % of the open-circuit reactive power. This will give cos φ ≈ 0.9 at full load, and roughly 0.95 to 0.98 at no-load.

The capacitor power rating required is

$$Q_c \approx 0.9 \cdot \sqrt{3} \cdot U \cdot I_0$$

where I_0 is the no-load current of the motor.

For star-delta starting of motors equipped with capacitors, see Fig. 12-11.

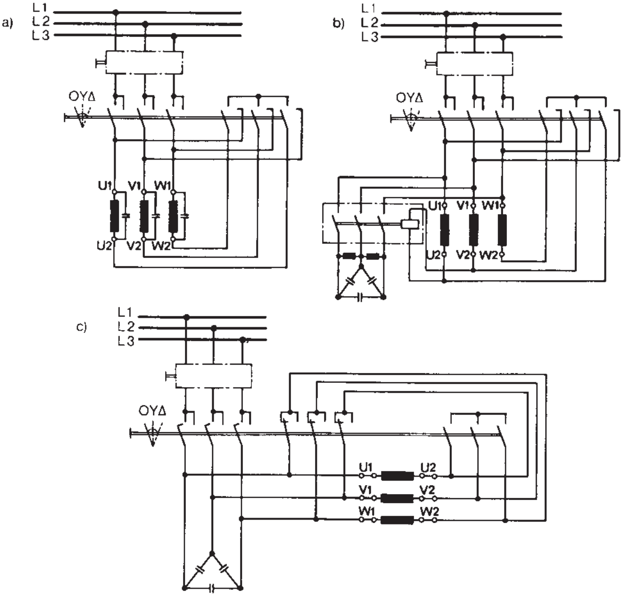


Fig. 12-11

Compensation of a three-phase motor.

a) When using a normal star-delta switch, b) Capacitor connected to delta position of star-delta switch, c) With special star-delta switch;

Operating sequence of switching elements on starting: Change from “off” to “star”: 1. Delta connections open, 2. Network connection closes, 3. Neutral point connections close;

Change from “star” to “delta”: 1. Neutral point connections open, 2. Delta connections close. The sequence is reversed when stopping.

Single compensation of transformers

Direct connection of a capacitor to a transformer, together with which it is switched on and off, is possible and permissible on both the HV and LV sides.

According to VDEW specifications, when connecting capacitors on the low-voltage side, the capacitor ratings must be as stated in Table 12-9.

If the capacitor is fitted on the low-voltage side of the transformer, in the case of networks having a high harmonics content, it is necessary to check whether a voltage resonance at a harmonic present in the network (usually the 5th and 7th harmonic) can occur between the capacitance of the capacitor and the leakage inductance of the transformer. The maximum capacitor rating can be defined approximately as

$$Q_c < \frac{S_{rT} \cdot 100\ \%}{\nu^2 \cdot u_{kr}}$$

where S_{rT} is the transformer rated power in kVA, and Q_c the capacitor rating in kvar, and u_{kr} the rated impedance voltage (in per cent) of the transformer and the feeding network, and ν is the number of the highest critical harmonic.

Table 12-9

Capacitors connected on the low-voltage side of transformers

Transformer rated power kVA	Transformer voltage, HV side 5 to 10 kV capacitor rating kvar	15 to 20 kV capacitor rating kvar	25 to 30 kV capacitor rating kvar
25	2	2.5	3
50	3.5	5	6
75	5	6	7
100	6	8	10
160	10	12.5	15
250	15	18	22
315	18	20	24
400	20	22.5	28
630	28	32.5	40

Example:

In order to avoid resonance up to and including the 7th harmonic, for a 400 kVA transformer and $u_{kr} = 6.2\ \%$, the rating of the capacitor must definitely be less than

$$Q_c < \frac{400\ \text{kVA} \cdot 100\ \%}{7^2 \cdot 6.2\ \%} = 130\ \text{kvar}$$

It must also be noted that the capacitor has the effect of raising the voltage. Under low-load conditions, this can lead to unwelcome increases in voltage if the capacitor rating selected is more than covers the reactive current requirement of the transformer. The voltage at the capacitively loaded transformer then rises instead of falling. The increase can be calculated with sufficient accuracy from

$$\Delta u \approx u_{kr} \cdot \frac{Q_c}{S_{rT}}.$$

Single compensation of welding equipment

The capacitor rating for welding transformers and resistance welding machines can be between 30 and 50 % of the transformer rating. In the case of welding rectifiers, a capacitor rating of approximately 10% of the nominal rating is sufficient.

Group compensation

The phase-shifting capacitor is connected to the distribution bus feeding, for example, a large number of small motors running continuously or intermittently, Fig. 12-12.

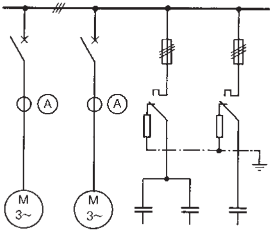


Fig. 12-12

Group compensation

The motors and capacitors are switched by separate switches and supervised by separate protection systems. The capacitors can be switched on and off individually or in groups, as required.

Centralized compensation

In comparatively large installations with many small and medium-size loads (motors, etc.) which are not usually in operation at the same time, the phase-shifting capacitors are connected centrally to the main busbar. The capacitors are switched either jointly by hand (Fig. 12-13a) or automatically via regulators responding to time or reactive load (Fig. 12-13b).

Advantages: automatic control allows the capacitor rating to be closely matched to the reactive power required at any time, thus keeping cos φ closer to the specified value.

Disadvantage: distributing lines between busbar and points of consumption still carry the same reactive current.

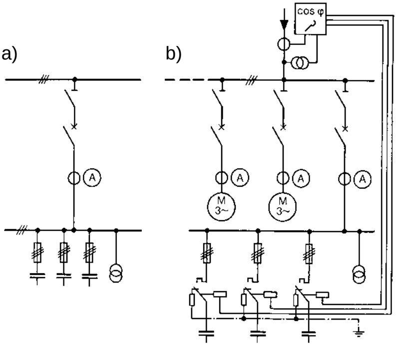


Fig. 12-13

Centralized compensation:

a) Total compensation,
b) Compensation with automatic control

Short-circuit protection should consist of HV fuses, for each capacitor if required. Voltage transformers in V connection are necessary for discharging after disconnection.

Centralized compensation can be used for all voltages.

12.4 Resistor devices

Resistor devices for low and high voltage are used in switchgear installations as

- Damping resistors for high-pass filters, in conjunction with arc suppression coils and for limiting capacitive and inductive overvoltages,
- Earthing resistors for earthing the neutrals of transformers and generators and also for earth fault protection,
- Loading resistors,
- Voltage dividers,
- Discharge resistors for capacitors,
- Transition and series resistors for tap changers,
- Starting and braking resistors and rheostats for electric motors.

The live parts are in the form of wire or cast elements or corrugated sheet-steel lattices. These components are made up into assemblies with ceramic insulators and can take the form of banks mounted on a frame.

Insulators are used for medium and high voltages.

In a resistor unit, electrical energy is converted into heat which the body of the resistor can absorb only partly and only for a very short time. It must always be dissipated to the ambient air. Resistor units are therefore usually air-cooled. Natural ventilation is generally sufficient. Separate ventilation or oil cooling is advisable in special cases.

The resistor elements normally have a tolerance of $\underline{+}$ 10 %. Smaller tolerances are possible in special cases.

The rise in temperature, which can be up to about 400 K, increases the resistance. With cast iron resistors, for example, the resistance increase is 7.5 %/100 K (Table 12-10). When the maximum temperature of about 400 °C is reached, a nominal initial current of 600 A has fallen to 460 A.

Resistors are often not designed for a 100 % load factor, but only to operate for a limited time. If during this short period the load duration $t_B < T_\vartheta$, a higher loading is permissible. The maximum load duration t_{Bmax} during which the resistor element heats up to the permitted temperature limit with an overload of $I_a = a \cdot I_r$, is

$$t_{Bmax} = T_\vartheta \cdot \ln \left(\frac{a^2}{a^2 - 1} \right).$$

A sufficiently long interval must then follow to allow complete cooling.

Example:

Earthing resistors in medium and high-voltage installations for impedance earthing of generator and transformer neutrals must limit the earth fault current to values of 0.5 to 0.75 I''_{k3}. The resulting values are no danger, particularly with regard to electrical machines, and voltage rises due to any capacitive effects of network asymmetry are avoided. Also, in branched networks, a defined active current can be produced which makes it easier to measure and localize an earth fault. The load factor for these earthing resistors is governed by the protective devices in question and their speed of response.

For example, an earth resistor of this kind must limit the earth fault current to 400 A. The fault is cleared quickly. Cast iron resistors are chosen with a continuous load capacity of I_r = 60 A. Their thermal time constant is T_ϑ = 450 s. The maximum load duration is thus

$$t_{\text{Bmax}} = T_\vartheta \cdot \ln\left(\frac{a^2}{a^2-1}\right) = 450\text{ s} \cdot \ln\left(\frac{(400/60)^2}{(400/60)^2-1}\right) = 10.25\text{ s}.$$

Such earthing resistors are usually sized to operate for 10 s.

Table 12-10

Characteristics of commercially available resistor elements

Characteristics	Form of resistor elements Wire elements	Cast iron elements	Sheet steel grid
Material	CuNi44 (Constantan) NiCr8020	Surface-treated cast iron	Corrosion-resistant steel sheet CrNi alloy steel sheet
Resistance of individual elements at 20 °C	150–0.5 Ω	02–0.01 Ω	0.75–0.04 Ω
Continuous load capacity of elements	0.5–20 A[3]	25–125 A[3]	25–250 A
Therm. time constant T_ϑ	20-90 s	240-600 s	120 s
Resistance increase with temperature	0.4%/100 K[1]	7.5%/100 K	5%/100 K[2]
Insulation level to housing to earth across insulators	 600 V/1 kV 3.6-52 kV	 1 kV 3.6-52 kV	 1 kV 3.6-52 kV

[1] Resistance variation of CuNi44 (constantan) negligible.
[2] For CrNi alloy sheet 2 % / 100 K.
[3] Wire elements cease to be economical at about 15 A. From 25 A, use cast-metal or steel-sheet elements.

12.5 Rectifiers

Semiconductor rectifiers are used exclusively today for rectifying alternating currents.

Rectifier assemblies are identified according to DIN VDE 0556. The identity code shows the connection, rated connected voltage, rated DC voltage and rated DC current of the assembly.

Example: Code letter for connection
Rated connected voltage in V
Rated DC voltage in V
Rated DC current in A
Code letter for assisted cooling
(omitted with natural cooling)

F separate ventilation
O oil cooling

B 275 / 220 – 10
or: S 400 / 224 – 162 F

If a rectifier assembly consists of several stacks (e.g. 4) a single stack is designated:

1/4 B 275 / 220 – 10

Table 12-11 shows a summary of calculation data for common rectifier circuits. The symbols denote the following:

u_2 = Instantaneous value of applied AC voltage

U_2 = Root-mean-square value of applied AC voltage

u_g = Instantaneous value of rectified voltage

U_g = Arithmetic mean of rectified voltage

U_{go} = Open-circuit DC voltage

i_g = Instantaneous value of rectified current

I_g = Arithmetic mean of rectified current

Table 12-11

Basic calculation data for common rectifier connections

Connection to	Alternating current		3-phase AC			
Connection	Half-wave	Centre-tap	Bridge	Star	3-phase bridge	Double-star
Circuit diagram	Fig. 12-14	Fig. 12-16	Fig. 12-17	Fig. 12-18	Fig. 12-19	Fig. 12-20
No. of pulses p	1	2	2	3	6	6
Fundamental frequency of superimposed AC voltage (Hz)	50	100	100	150	300	300
Open-circuit DC voltage U_{go}/U_2	$\frac{\sqrt{2}}{\pi} = 0.45$	$\frac{\sqrt{2}}{\pi} = 0.45$	$\frac{2\sqrt{2}}{\pi} = 0.9$	$\frac{3\sqrt{2}}{2\pi} = 0.67$	$\frac{3\sqrt{2}}{\pi} = 1.35$	$\frac{3\sqrt{2}}{2\pi} = 0.67$
Rating of each valve						
as regards voltage for	U_2	U_2	U_2	U_2	U_2	U_2
as regards current for	I_g	$\frac{1}{2}I_g$	$\frac{1}{2}I_g$	$\frac{1}{2}I_g$	$\frac{1}{3}I_g$	$\frac{1}{6}I_g$
Connected network power $P_1 / (U_{go} \cdot I_g)$	2.69	1.23 1.11¹⁾	1.23 1.11¹⁾	1.23	1.05	1.05
Mean transformer rating	3.09	1.49 1.34¹⁾	1.23 1.11¹⁾	1.37	1.05	1.55
Voltage ripple (in % of U_{go})	121.1	48.3	48.3	18.3	4.2	4.2

1) For operation with inductive load (e.g. large smoothing reactor)
All other figures apply to purely resistive load.

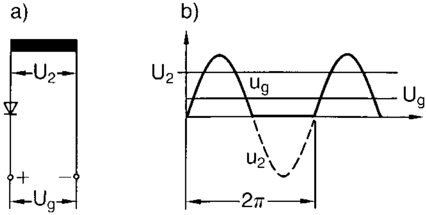
Common rectifier connections

1. *Half-wave connection, symbol E, see Fig. 12-14*

   The simplest of all rectifier connections. It consists of a branch which blocks one half-wave of the applied AC voltage. The result is a pulsating DC voltage with gaps while the voltage is negative. This arrangement is normally used only for small currents (often in conjunction with capacitors) and up to very high voltages with a suitable number of plates or stacks connected in series. The rectifier assembly must block the full transformer voltage and when capacitors are used, their charging voltage as well.

Fig. 12-14

Half-wave connection
a) Circuit diagram
b) Voltage curve

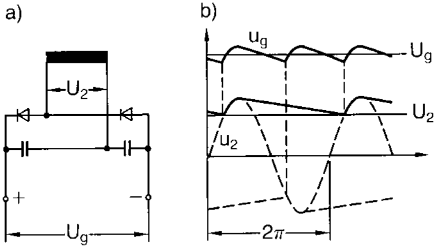


2. *Doubler connection, symbol V, see Fig. 12-15*

   This arrangement is again suitable only for small currents and relatively high voltages. It always requires two capacitors which are charged in each half-cycle and when connected in series, produce at no-load a DC voltage corresponding to twice the peak voltage of the applied AC voltage. Under load, the DC voltage decreases according to the relationship between capacitance and load current. Each branch of the rectifier assembly has to block the sum of transformer voltage and capacitor voltage.

Fig. 12-15

Doubler connection
a) Circuit diagram
b) Voltage curve



3. *Centre-tap connection, symbol M, see Fig. 12-16*

   This arrangement requires a transformer which has a centre tap on its secondary winding. In the blocking direction, each branch carries the full transformer voltage. The connection is economical only for low voltages using the basic unit. For higher voltages requiring semiconductor devices to be connected in series, it is inferior to the following bridge connection because of the special transformer construction for the same number of plates. It is then appropriate only if suitable transformers are already available, i.e. when hot cathode or mercury vapour rectifiers are to be replaced by semiconductor units.

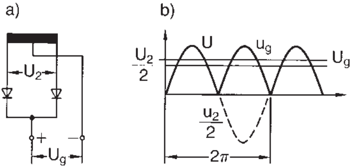


Fig. 12-16

Centre-tap connection
a) Circuit diagram
b) Voltage curve

4. *Bridge connection, symbol B, see Fig. 12-17.*

Provided the voltages involved are not very low, in which case the centre-tap connection may be preferable, the bridge connection is the most practical and economical over a wide range of currents and voltages, and therefore the most commonly used of all single-phase arrangements. In the blocking direction, each of the 4 branches is subjected to the full transformer voltage.

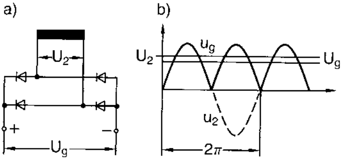


Fig. 12-17

Bridge connection
a) Circuit diagram
b) Voltage curve

5. *Star connection, symbol S, see Fig. 12-18.*

This three-phase arrangement requires transformers, or networks in the case of straight connection, whose neutral is able to withstand the full direct current. The connection's power rating is unlimited. However, it is practically used only when mercury vapour rectifiers require replacement. Each branch is subjected to the phase-to-phase voltage. With voltages which exceed the nominal blocking voltage of one rectifier device, the following three-phase bridge connection will probably be preferable with the same number of devices. When directly linked to 380 V three-phase networks with loadable neutral, the star connection provides a DC voltage of the order of 220 to 230 V.

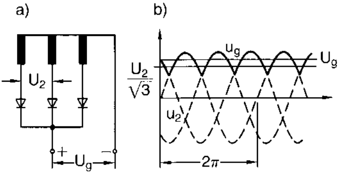


Fig. 12-18

Star connection
a) Circuit diagram
b) Voltage curve

6. *Three-phase bridge connection, symbol DB, see Fig. 12-19*

This is the most convenient and economical connection for all relatively high powers at voltages exceeding those of the basic star or double-star connections. Here again, each of the 6 branches carries the phase-to-phase voltage in the blocking direction.

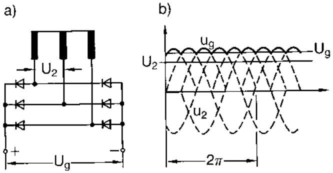


Fig. 12-19

Three-phase bridge connection
a) Circuit diagram
b) Voltage curve

7. *Double-star connection, symbol DS, see Fig. 12-20*

This arrangement corresponds to the centre-tap connection of the single-phase configurations. Again, it is used almost exclusively only with low voltages requiring one basic unit, but currents can be high. With higher voltages, it can be recommended only when replacing the glass or iron cells of mercury vapour rectifiers. In the blocking direction, each of the 6 branches carries twice the phase voltage.

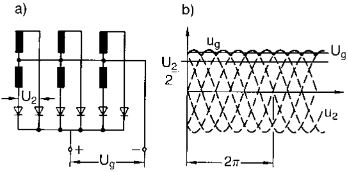


Fig. 12-20

Double-star connection
a) Circuit diagram
b) Voltage curve

13 Conductor Materials and Accessories for Switchgear Installations

13.1 Busbars, stranded-wire conductors and insulators

13.1.1 Properties of conductor materials

Busbars for switchgear installations are made either of copper (E-Cu) or of aluminium (E-Al). Aluminium alloys with good electrical and mechanical properties are also used.

An advantage of aluminium is that a short-circuit arc gives rise only to non-conducting, dust-like residues of aluminium oxide. No metal is deposited on the neighbouring insulators or other components of the installation, thus limiting the extent of the damage. Switchgear installations with aluminium busbars can therefore be reconnected much more quickly after a short-circuit arc.

The values given in Table 13-1 are typical values to be used in calculations concerning the construction of switchgear installations; the most important physical properties of commonly used conductor materials are compared in Table 13-2.

Table 13-1

Typical values for the properties of conductor materials

Symbol	Tensile strength R_m min. N/mm²	Young's modulus E Elasticity modulus N/mm²	Yield strength R_{p02} min. N/mm²	R'_{p02} max. N/mm²	Brinell hardness HB 10 N/mm²	Conductivity κ at 20 °C min. m/Ωmm²
Copper						
E-Cu F 20	200	$11 \cdot 10^4$		120	450… 700	57
E-Cu F 25	250	$11 \cdot 10^4$	200	290	700… 950	56
E-Cu F 30	300	$11 \cdot 10^4$	250	360	800…1050	56
E-Cu F 37	370	$11 \cdot 10^4$	330	400	950…1150	55
Aluminium						
E-Al F 6.5/7	65/70	$6.5 \cdot 10^4$	25	80	200… 300	35.4
E-Al F 8	80	$6.5 \cdot 10^4$	50	100	220… 320	35.2
E-Al F 10	100	$6.5 \cdot 10^4$	70	120	280… 380	34.8
E-Al F 13	130	$6.5 \cdot 10^4$	90	160	320… 420	34.5
Al F 10	100	$\approx 6.5 \cdot 10^4$	70		280… 300	34
Malleable aluminium alloy						
E-Al Mg Si 0.5 F 17	170	$7 \cdot 10^4$	120	180	450… 650	32
E-Al Mg Si 0.5 F 22	220	$7 \cdot 10^4$	160	240	650… 900	30
Copper-clad aluminium						
Cu comprises 15 %	130	$8 \cdot 10^4$	100	130	—	42.3

Table 13-2

Comparison of the most important properties of common conductor materials

Property		Copper (E-Cu)	Pure aluminium (E-Al)	Pantal (E-AlMg Si 0.5)	Brass (Ms 58)	Steel (galvanized)
Density	kg/dm^3	8.9	2.7	2.7	8.5	7.85
El. conductivity at 20 °C	m/Ω · mm^2	56	35	30	≈ 18	≈ 7
El. conductivity at 60 °C	m/Ω · mm^2	48	30	26	≈ 16	≈ 6
Conductivity.../density...		6.3	13	11	≈ 2	≈ 1
Spec. resistance at 20 °C	Ω · mm^2/m	0.0178	0.0286	0.0333	≈ 0.0555	≈ 0.143
Temperature coeff. of el. resistance between 1 °C and 100 °C	K^{-1}	0.0038	0.0040	0.0036	0.0024	0.005
Melting point	° C	1083	658	630	≈ 912	1400
Heat of fusion	Ws/g	181.28	386.86	376.81	167.47	293.07
	Ws /cm^3	1612	1047	1017	1444	2 302
Mean spec. heat between 1 °C and 100 °C	Ws /g · K	0.393	0.92	0.92	0.397	0.485
	Ws /cm^3 · K	3.475	2.386	2.386	3.391	3.558
Thermal conductivity between 1 °C and 100 °C	Ws /cm · s · K	3.85	2.2	1.9	1.1	0.46
Mean coeff. of expansion between 1 °C and 100 °C	mm /m · K	0.017	0.024	0.023	0.018	0.012
Young's modulus	N/mm^2	110 000	65 000	70 000	≈ 90 000	210 000
Thermal limit current density1)	A/mm^2	154	102	89	91	
Melting current density1)	A/mm^2	3 060	1910	1 690	1900	

1) Thermal limit current density is the current density at which the conductor temperature rises from 35 °C to 200 °C when loaded for 1 s. Conductive heat removal disregarded.

Melting current density is the current density at which the conductor temperature rises to the melting temperature when loaded for 1⁄100 s. Values according to Müller-Hillebrand.

13.1.2 Busbars for switchgear installations

Maximum continuous temperatures to DIN 43 670 and DIN 43 671

for bar conductor screw connections to DIN 43 673,
non-oxidized and greased approx. 120 °C,
silvered, or equivalent treatment, approx. 160 °C,
for post insulators and bushings to DIN VDE 0674 Part 1 approx. 85 °C,
for equipment terminals DIN EN 60694 bare approx 90 °C,
(VDE 0670 Part 1000) tinned, silvered approx. 105 °C.

A convenient method of monitoring for thermal overload temperatures is to use temperature-sensitive paints. These change their original colour when certain temperatures are exceeded. The change persists after the painted item has cooled. The original colour is regained only gradually, under the influence of moisture in the air. The colour can be restored immediately by wetting. Temperature-sensitive paints can be applied to any surface. Oil or grease should first be removed with petrol or white spirit.

Influence of bar temperature on strength of conductor material

The strength of the conductor material decreases with rising temperature, and much more rapidly with aluminium than with copper. The values in Table 13-3 are valid for aluminium. For temperatures above 160 °C, they also depend on the duration of heating.

Table 13-3

Influence of temperature on the strength of aluminium

Temperature	20	100	160	250	°C
Tensile strength σ_B	90…130	90…120	80…110	70…30	N/mm^2
Yield point $R_{p0.2}$	80…120	80…110	70…100	60…30	N/mm^2
Elongation at fracture	10…5	10…5	11…7	to 60	%

Under short-circuit conditions, therefore, conductor temperatures of 200 °C for aluminium and for copper must not be exceeded, see VDE 0103.

If items of equipment are influenced only very slightly, or not at all, by the thermal behaviour of the busbars, the maximum permissible conductor temperature is governed only by the long-term thermal strength of the conductors and their insulation.

This is the case, for example, with busbars which owing to sufficiently long connections are not thermally coupled to their associated equipment.

Profile selection and arrangement for alternating current

The cross-sectional shape of busbar conductors has a considerable influence not only on their bending strength, but also on their electrical load capacity.

With direct current, there is no skin effect, so in this case the shape of the conductor is important only with regard to the heat-emitting surface area. For direct current, therefore, it is preferable to use flat bars or continuously cast conductors of large cross section.

With alternating current, on the other hand, skin effect and other factors cause an increase in the conductor resistance, and this must be kept small by selecting an appropriate section profile. The effect the shape and arrangement of component conductors of the same total cross-section area can have on the current-carrying capacity of busbars for AC is illustrated in Fig. 13-1.

If the current permits, one or two flat conductors per phase are provided, thus simplifying installation. Two conductors is the most favorable number from the standpoint of losses, and is therefore to be preferred.

For higher currents, four flat conductors have proved to be an effective arrangement. The distance between the second and third conductor has to be increased in order to achieve a better current distribution. Increasing the distance from 10 to 30 mm produces no significant improvement. It has been shown that with a distance of 70 mm, the relative currents in the individual conductors differ by only ± 7%.

The loading on the four conductors is then:

Conductor	1	2	3	4
Current carried as % of total current	26.7	23.3	23.3	26.7

If four flat conductors per phase are not sufficient, then channel sections are considered. These have favorable skin effect properties. If even more flat conductors were to be used, the result would be a comparatively large cross-section which, in addition, is very uneconomical. For example, an arrangement with seven conductors would give the following current distribution among the conductors:

Conductor	1	2	3	4	5	6	7
Relative current %	25.6	14.2	7.5	5.4	7.5	14.2	25.6

For high currents in low-voltage installations, when using flat conductors, the simplest solution is to split up large composite conductors by dividing the three phases among smaller cross sections, Fig. 13-2. These then have a significantly lower eddy-current factor and also a smaller inductive voltage drop.

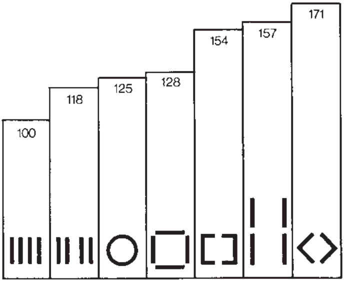


Fig. 13-1

Current-carrying capacity per cent of some busbar conductor arrangements of the same total cross-section area

Fig. 13-2

Arrangement of a three-phase bus with four parallel conductors per phase:
a) Usual arrangement with the three phases L_1, L_2, L_3 next to each other
b) Conductors in split phase arrangement L_1, L_2, L_3, L_1, L_2, L_3 …

Continuous current-carrying capacity

The Tables 13-4 to 13-12 below give values for the continuous current-carrying capacity of different cross-sections of *copper* (see DIN 43671) and *aluminium* (see DIN 43670).

For *indoor installations*[1], the tables are based on the following assumptions:

1. ambient air still,
2. bare conductors partly oxidized, giving a radiation coefficient of 0.40 (Cu) and 0.35 (Al), or
3. conductors painted (only the outside surfaces in the case of composite busbars), giving a radiation coefficient of approx. 0.90.

For *outdoor installations,* the tables are based on the following assumptions:

1. slight air movement, e.g. due to ground thermals, of 0.6 m/s,
2. bare conductors normally oxidized, giving a radiation coefficient of 0.60 (Cu) and 0.50 (Al), possible solar irradiation 0.45 (Cu) and 0.35 (Al) kW/m^2, or
3. conductors painted, giving a radiation coefficient of approx. 0.90 and solar irradiation of 0.7 kW/m^2.
   The values for outdoor installations thus correspond to central European conditions.

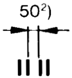
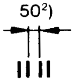
---

[1] For open-type indoor installations, the values stated in the tables can be multiplied by between 1.05 and 1.1 since it is found that slight air movements independent of the busbars occur in such cases.

Continuous current-carrying capacity of copper conductors (DIN 43 671)

Table 13-4

Copper conductors of rectangular cross-section in indoor installations. Ambient temperature 35 °C. Conductor temperature 65 °C. Conductor width vertical: clearance between conductors equal to conductor thickness; with alternating current, clearance between phases > 0.8 × phase centre-line distance.

Width × thickness	Cross-section	Weight 1)	Material 3)	Continuous current in A AC up to 60 Hz								Continuous current in A DC and AC 16⅔ Hz							
				painted no. of conductors				bare no. of conductors				painted no. of conductors				bare no. of conductors			
				1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
mm	mm^2	kg/m																	
12 × 5	59.5	0.529	E-Cu F 37	203	345	411		177	312	398		203	345	411		177	312	398	
12 × 10	119.5	1.063	E-Cu F 37	326	605	879		285	553	811		326	605	879		285	553	811	
20 × 5	99.1	0.882	E Cu F 37	319	560	728		274	500	690		320	562	729		274	502	687	
20 × 10	199	1.77	E-Cu F 30	497	924	1 320		427	825	1 180		499	932	1 300		428	832	1 210	
30 × 5	149	1.33	E-Cu F 37	447	760	944		379	672	896		448	766	950		380	676	897	
30 × 10	299	2.66	E-Cu F 30	676	1 200	1 670		573	1 060	1 480		683	1 230	1 630		579	1 080	1 520	
40 × 5	199	1.77	E-Cu F 37	573	952	1 140		482	836	1 090		576	966	1 160		484	848	1 100	
40 × 10	399	3 55	E-Cu F 30	850	1 470	2 000	2 580	715	1 290	1 770	2 280	865	1 530	2 000		728	1 350	1 880	

---

1) Calculated for a density of 8.9 kg/dm^3.

2) Minimum clearance given in mm.

3) Material: E-Cu or other material to DIN 40500 Part 3, preferred semi-finished material. Flat bars with rounded edges to DIN 46433 Selection Part 3.

Continued on next page

Table 13-4 (continued)

Copper conductors of rectangular cross-section in indoor installations. Ambient temperature 35 °C. Conductor temperature 65 °C. Conductor width vertical: clearance between conductors equal to conductor thickness; with alternating current, clearance between phases > 0.8 × phase centre-line distance.

Width × thickness	Cross-section	Weight[1]	Material[3]	Continuous current in A AC up to 60 Hz								Continuous current in A DC and AC 16⅔ Hz							
				painted no. of conductors				bare no. of conductors				painted no. of conductors				bare no. of conductors			
				1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
				❙	❙❙	❙❙❙	50[2] ❙❙ ❙❙	❙	❙❙	❙❙❙	50[2] ❙❙ ❙❙	❙	❙❙	❙❙❙	❙❙ ❙❙	❙	❙❙	❙❙❙	❙❙ ❙❙
mm	mm^2	kg/m																	
50 × 5	249	2.22	E-Cu F 37	679	1 140	1 330	2 010	583	994	1 240	1 920	703	1 170	1370		588	1 020	1 300	
50 × 10	499	4.44	E-Cu F 30	1 020	1 720	2 320	2 950	852	1510	2 040	2 600	1 050	1 830	2 360		875	1 610	2 220	
60 × 5	299	2.66	E-Cu F 30	826	1 330	1 510	2 310	688	1 150	1 440	2 210	836	1 370	1 580	2 060	696	1 190	1 500	1 970
60 × 10	599	5.33	E-Cu F 30	1 180	1 960	2 610	3 290	985	1 720	2 300	2 900	1 230	2 130	2 720	3 580	1 020	1 870	2 570	3 390
80 × 5	399	3.55	E-Cu F 30	1 070	1 680	1 830	2 830	885	1 450	1 750	2 720	1 090	1 770	1 990	2 570	902	1 530	1 890	2 460
80 × 10	799	7.11	E-Cu F 30	1 500	2 410	3 170	3 930	1 240	2 110	2 790	3 450	1 590	2 730	3 420	4 490	1 310	2 380	3 240	4 280
100 × 5	499	4.44	E-Cu F 30	1 300	2 010	2 150	3 300	1 080	1 730	2 050	3 190	1 340	2 160	2 380	3 080	1 110	1 810	2 270	2 960
100 × 10	988	8.89	E-Cu F 30	1 810	2 850	3 720	4 530	1 490	2 480	3 260	3 980	1 940	3 310	4100	5 310	1 600	2 890	3 900	5 150
120 × 10	1 200	10.7	E-Cu F 30	2 110	3 280	4 270	5 130	1 740	2 860	3 740	4 500	2 300	3 900	4 780	6 260	1 890	3 390	4 560	6 010
160 × 10	1 600	14.2	E-Cu F 30	2 700	4 130	5 360	6 320	2 220	3 590	4 680	5 530	3 010	5 060	6 130	8 010	2 470	4 400	5 860	7 710
200 × 10	2 000	17.8	E-Cu F 30	3 290	4 970	6 430	7 490	2 690	4 310	5 610	6 540	3 720	6 220	7 460	9 730	3 040	5 390	7 150	9 390

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[1] Calculated for a density of 8.9 kg/dm^3.

[2] Minimum clearance given in mm.

[3] Material: E-Cu or other material to DIN 40500 Part 3 preferred semi-finished material. Flat bars with rounded edges to DIN 46433 Selection Part 3.

Table 13-5

Copper conductors of annular cross-section, ambient temperature 35 °C, conductor temperature 65 °C, with alternating current, phase centre-line distance ≧ 2.5 × outside diameter

Outside diameter D mm	Wall-thickness a mm	Cross-section mm²	Weight[1] kg/m	Material[2]	Continuous in A DC and AC up to 60 Hz indoor painted	bare	outdoor painted	bare
20	2	113	1.01	E-Cu F 37	384	329	460	449
	3	160	1.43	E-Cu F 37	457	392	548	535
	4	201	1.79	E-Cu F 30	512	438	613	599
	5	236	2.10	E-Cu F 30	554	475	664	648
	6	264	2.35	E-Cu F 25	591	506	708	691
32	2	188	1.68	E-Cu F 37	602	508	679	660
	3	273	2.44	E-Cu F 37	725	611	818	794
	4	352	3.14	E-Cu F 30	821	693	927	900
	5	424	3.78	E-Cu F 30	900	760	1 020	987
	6	490	4.37	E-Cu F 25	973	821	1 100	1 070
40	2	239	2.13	E-Cu F 37	744	624	816	790
	3	349	3.11	E-CU F 37	899	753	986	955
	4	452	4.04	E-Cu F 30	1 020	857	1 120	1 090
	5	550	4.90	E-Cu F 30	1 130	944	1 240	1 200
	6	641	5.72	E-Cu F 25	1 220	1 020	1 340	1 300
50	3	443	3.95	E-Cu F 37	1 120	928	1 190	1 150
	4	578	5.16	E-Cu F 30	1 270	1 060	1 360	1 310
	5	707	6.31	E-Cu F 30	1 410	1 170	1 500	1 450
	6	829	7.40	E-Cu F 25	1 530	1 270	1 630	1 570
	8	1 060	9.42	E-Cu F 25	1 700	1 420	1 820	1 750
63	3	565	5.04	E-Cu F 30	1 390	1 150	1 440	1 390
	4	741	6.61	E-Cu F 30	1 590	1 320	1 650	1 590
	5	911	8.13	E-Cu F 30	1 760	1 460	1 820	1 750
	6	1 070	9.58	E-Cu F 25	1 920	1 590	1 990	1 910
	8	1 380	12.3	E-Cu F 25	2 150	1 780	2 230	2 140
80	3	726	6.47	E-Cu F 30	1 750	1 440	1 760	1 690
	4	955	8.52	E-Cu F 30	2 010	1 650	2 020	1 930
	5	1 180	10.5	E-Cu F 30	2 230	1 820	2 230	2 140
	6	1 400	12.4	E-Cu F 25	2 430	1 990	2 440	2 340
	8	1 810	16.1	E-Cu F 25	2 730	2 240	2 740	2 630
100	3	914	8.15	E-Cu F 30	2 170	1 770	2 120	2 020
	4	1 210	10.8	E-Cu F 30	2 490	2 030	2 430	2 320
	5	1 490	13.3	E-Cu F 30	2 760	2 250	2 700	2 580
	6	1 770	15.8	E-Cu F 25	3 020	2 460	2 950	2 820
	8	2 310	20.6	E-Cu F 25	3 410	2 780	3 330	3 180

[1] Calculated for a density of 8.9 kg/dm³. Preferred outside diameters in heavy type.

[2] Material: E-Cu or other material to DIN 40500 Part 2; preferably semi-finished material to be used: tube to DIN 1754.

Table 13-6

Copper conductors of round cross-section (round copper bar), ambient temperature 35 °C, conductor temperature 65 °C; with alternating current, phase centre-line distance ≧ 2 × diameter.

Diameter D mm	Cross-section a mm²	Weight[1] kg/m	Material[2]	Continuous current in A DC and AC up to 60 Hz painted	 bare
5	19.6	0.175	E-Cu F 37	95	85
8	50.3	0.447	E-Cu F 37	179	159
10	78.5	0.699	E-Cu F 37	243	213
16	210	1.79	E-Cu F 30	464	401
20	314	2.80	E-Cu F 30	629	539
32	804	7.16	E-Cu F 30	1 160	976
50	1960	17.50	E-Cu F 30	1 930	1 610

[1] Calculated for a density of 8.9 kg/dm³.

[2] Material: E-Cu or other material to DIN 40500 Part 3, preferably semi-finished product to be used: round bars to DIN 1756.

Continuous current-carrying capacity of aluminium conductors (DIN 43670)

Table 13-7

Aluminium conductors of rectangular cross-section in indoor installations. Ambient temperature 35 °C. Conductor temperature 65 °C. Conductor width vertical: clearance between conductors equal to conductor thickness; with alternating current, clearance between phases > 0.8 × phase centre-line distance.

Width × thickness	Cross-section	Weight[1]	Material[3]	Continuous current in A AC up to 60 Hz								Continuous current in A DC and AC 16⅔ Hz							
				painted no. of conductors				bare no. of conductors				painted no. of conductors				bare no. of conductors			
				1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
mm	mm²	kg/m		▮	▮▮	▮▮▮	50[2]) ▮▮ ▮▮	▮	▮▮	▮▮▮	50[2]) ▮▮ ▮▮	▮	▮▮	▮▮▮	▮▮ ▮▮	▮	▮▮	▮▮▮	▮▮ ▮▮
12 × 5	59.5	0.160	E-Al F 10	160	292	398		139	263	375		160	292	398		139	263	375	
12 × 10	119.5	0.322	E-Al F 10	257	490	720		224	440	652		257	490	720		224	440	652	
20 × 5	99.1	0.268	E-Al F 10	254	446	570		214	392	537		254	446	576		214	392	539	
20 × 10	199	0.538	E-Al F 10	393	730	1 060		331	643	942		393	733	1 020		331	646	943	
30 × 5	149	0.403	E-Al F 10	356	606	739		295	526	699		356	608	749		296	528	703	
30 × 10	299	0.808	E-Al F 10	536	956	1340		445	832	1 200		538	964	1 280		447	839	1 180	
40 × 5	199	0.538	E-Al F 10	456	762	898		376	658	851		457	766	915		376	662	862	
40 × 10	399	1.08	E-Al F 10	677	1 180	1 650	2 190	557	1 030	1 460	1 900	682	1200	1 570		561	1 040	1 460	
50 × 5	249	0.673	E-Al F 10	556	916	1 050	1 580	455	786	995	1 520	558	924	1 080		456	794	1 020	
50 × 10	499	1.35	E-Al F 10	815	1 400	1 940	2 540	667	1 210	1 710	2 210	824	1 140	1 850		674	1 250	1 730	
60 × 5	299	0.808	E-Al F 10	655	1 070	1 190	1 820	533	910	1 130	1 750	658	1 080	1 240	1 610	536	924	1 170	1 530
60 × 10	599	1.62	E-Al F 10	951	1 610	2 200	2 870	774	1 390	1 940	2 480	966	1 680	2 130	2 810	787	1 450	2 000	2 650

Continued on next page

Table 13-7 (continued)

Width × thickness	Cross-section	Weight[1]	Material[3]	Continuous current in A AC up to 60 Hz								Continuous current in A DC and AC 16⅔ Hz							
				painted no. of conductors				bare no. of conductors				painted no. of conductors				bare no. of conductors			
				1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
				▮	▮▮	▮▮▮	50[2] ▮▮ ▮▮	▮	▮▮	▮▮▮	50[2] ▮▮ ▮▮	▮	▮▮	▮▮▮	▮▮ ▮▮	▮	▮▮	▮▮▮	▮▮ ▮▮
mm	mm²	kg/m																	
80 × 5	399	1.08	E-Al F 10	851	1 360	1 460	2 250	688	1 150	1 400	2 180	858	1 390	1 550	2 010	694	1 180	1 470	1 920
80 × 10	799	2.16	E-Al F 10	1 220	2 000	2 660	3 460	983	1 720	2 380	2 990	1 250	2 150	2 670	3 520	1 010	1 840	2 520	3 340
100 × 5	499	1.35	E-Al F 6.5	1 050	1 650	1 730	2 660	846	1 390	1 660	2 580	1 060	1 710	1 870	2 420	858	1 450	1 780	2 320
100 × 10	999	2.70	E-Al F 6.5	1 480	2 390	3 110	4 020	1 190	2 050	2 790	3 470	1 540	2 630	3 230	4 250	1 240	2 250	3 060	4 050
100 × 15	1 500	4.04	E-Al F 6.5	1 800	2 910	3 730	4 490	1 450	2 500	3 220	3 380	1 930	3 380	4 330	5 710	1 560	2 900	4 070	5 400
120 × 10	1 200	3.24	E-Al F 6.5	1 730	2 750	3 540	4 560	1 390	2 360	3 200	3 930	1 830	3 090	3 770	4 940	1 460	2 650	3 580	4 730
120 × 15	1 800	4.86	E-Al F 6 5	2 090	3 320	4 240	5 040	1 680	2 850	3 650	4 350	2 280	3 950	5 020	6 610	1 830	3 390	4 740	6 280
160 × 10	1 600	4.32	E-Al F 6.5	2 220	3 470	4 390	5 610	1 780	2 960	4 000	4 820	2 380	4 010	4 820	6 300	1 900	3 420	4 590	6 060
160 × 15	2 400	6.47	E-Al F 6.5	2 670	4 140	5 230	6 120	2 130	3 540	4 510	5 270	2 960	5 090	6 370	8 380	2 370	4 360	6 040	8 000
200 × 10	2 000	5.40	E-Al F 6.5	2 710	4 180	5 230	6 660	2 160	3 560	4 790	5 710	2 960	4 940	5 880	7 680	2 350	4 210	5 620	7 400
200 × 15	3 000	8.09	E-Al F 6.5	3 230	4 950	6 240	7 190	2 580	4 230	5 370	6 190	3 660	6 250	7 740	10 160	2 920	5 350	7 370	9 750

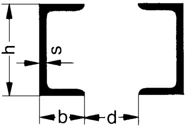
[1] Calculated for a density of 2.7 kg/dm³.

[2] Minimum clearance given in mm.

[3] Material: E-Al or other material to DIN 40501 Part 3, preferred semi-finished material. Flat bars with rounded edges to DIN 46 433 Selection Part 3.

Table 13-8

Aluminium conductors of U-section in indoor installations, ambient temperature 35 °C, conductor temperature 65 °C.



When facing [ ], gap vertical; with alternating current, phase centre-line distance $\geqq 2h$

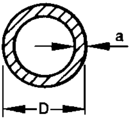
Material: E-Al or other material to DIN 40501 Part 3; semi-finished product to be used; channel sections to DIN 46424.

Dimensions				Cross-section		Weight1)		Material	Continuous current in A DC and AC up to 60 Hz			
									painted		bare	
h	*b*	*s*	*d*	[	[]	[	[]		[	[]	[	[]
mm	mm	mm	mm	mm^2	mm^2	kg/m	kg /m					
60	30	4	25	448	896	1.22	2.44	E-Al F 6.5	880	1 800	685	1 370
80	37.5	6	25	858	1 720	2.32	4.64	E-Al F 8	1 460	2 540	1 140	2 000
100	37.5	8	25	1 270	2 540	3.47	6.94	E-Al F 8	2 000	3 450	1 550	2 700
120	45	10	30	1 900	3 800	5.17	10.3	E-Al F 8	2 720	4 700	2 100	3 750
140	52.5	11	35	2 450	4 900	6.66	13.3	E-Al F 8	3 350	5 800	2 600	4 600
160	60	12	40	3 070	6 140	8.34	16.7	E-Al F 8	4 000	7 000	3 100	5 400
180	67.5	13	45	3 760	7 520	10.2	20.4	E-Al F 8	4 750	8 200	3 800	6 400
200	75	14	50	4 510	9 020	12.2	24.4	E-Al F 8	5 500	9 500	4 300	7 400

1) Calculated for a density of 2.7 kg/dm^3.

Table 13-9

Aluminium conductors of annular cross-section, ambient temperature 35 °C, conductor temperature 65 °C; with alternating current, phase centre-line distance $\geqq 2.0 \times$ outside diameter.



Outside diameter	Wall-thickness	Cross-section	Weight1)	Material2)	Continuous current in A DC and AC up to 60 Hz		Continuous current in A	
D	a				indoor		outdoor	
mm	mm	mm^2	kg/m		painted	bare	painted	bare
20	2	113	0.305	E-Al F 10	305	257	365	354
	3	160	0.433	E-Al F 10	363	305	435	421
	4	201	0.544	E-Al F 10	407	342	487	472
	5	236	0.636	E-Al F 10	440	370	527	511
	6	264	0.713	E-Al F 10	465	392	558	540

1) Calculated for a density of 2.7 kg/dm^3. Preferred outside diameters in heavy type.

2) Material: E-Al or other material to DIN 40501 Part 2; preferably semi-finished product to be used. Tube to DIN 1795, DIN 9107.

Continued on next page

Table 13-9 (continued)

Outside diameter D mm	Wall-thickness a mm	Cross-section mm²	Weight1) kg/m	Material2)	Continuous current in A DC and AC up to 60 Hz indoor		Continuous current in A outdoor	
					painted	bare	painted	bare
32	2	188	0.509	E-Al F 10	478	395	539	519
	3	273	0.739	E-Al F 10	575	476	649	624
	4	352	0.950	E-Al F 10	653	539	737	708
	5	424	1.15	E-Al F 10	716	592	808	777
	6	490	1.32	E-Al F 10	769	636	868	835
40	2	239	0.645	E-Al F 10	591	485	648	621
	3	349	0.942	E-Al F 10	714	595	783	750
	4	452	1.22	E-Al F 10	813	667	892	854
	5	550	1.48	E-Al F 10	896	734	982	941
	6	641	1.73	E-Al F 10	966	792	1 060	1020
50	4	578	1.56	E-Al F 10	1 010	822	1 080	1030
	5	707	1.91	E-Al F 10	1 120	909	1 190	1 140
	6	829	2.24	E-Al F 10	1 210	983	1 290	1 230
	8	1 060	2.85	E-Al F 7	1 370	1 110	1 460	1390
	10	1 260	3.39	E-Al F 7	1 490	1 210	1 580	1 510
63	4	741	2.00	E-Al F 10	1 270	1 020	1 310	1 240
	5	911	2.46	E-Al F 10	1 400	1 130	1 450	1 380
	6	1 070	2.89	E-Al F 10	1 520	1 230	1 570	1 490
	8	1 380	3.73	E-Al F 7	1 730	1 390	1 790	1 700
80	4	955	2.58	E-Al F 10	1 600	1 280	1 600	1 510
	5	1 180	3.18	E-Al F 10	1 770	1 420	1 780	1 680
	6	1 400	3.77	E-Al F 10	1 920	1 540	1 930	1 820
	8	1 810	4.89	E-Al F 7	2 200	1 760	2 200	2 080
	10	2 200	5.94	E-Al F 7	2 410	1 920	2 420	2 280
100	4	1 210	3.26	E-Al F 10	1 980	1 570	1 930	1 820
	5	1 490	4.03	E-Al F 10	2 200	1 750	2 150	2 020
	6	1 770	4.78	E-Al F 10	2 390	1 900	2 340	2 200
	8	2 310	6.24	E-Al F 7	2 740	2 170	2 670	2 510
120	4	1 460	3.94	E-Al F 10	2 360	1 860	2 250	2 100
	5	1 810	4.88	E-Al F 10	2 620	2 070	2 500	2 340
	6	2 150	5.80	E-Al F 10	2 860	2 250	2 730	2 550
	8	2 820	7.60	E-Al F 7	3 270	2 580	3 120	2 920
	10	3 460	9.33	E-Al F 7	3 590	2 830	3 420	3 200
160	4	1 960	5.29	E-Al F 10	3 110	2 430	2 910	2 710
	5	2 440	6.57	E-Al F 10	3 460	2 710	3 240	3 010
	6	2 900	7.84	E-Al F 10	3 780	2 950	3 530	3 290
	8	3 820	10.3	E-Al F 7	4 340	3 390	4 060	3 780
	10	4 710	12.7	E-Al F 7	4 760	3 720	4 460	4 140

Continued on next page

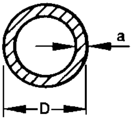
Table 13-9 (continued)

Outside diameter D mm	Wall-thickness a mm	Cross-section mm^2	Weight1) kg/m	Material2)	Continuous current in A DC and AC up to 60 Hz indoor painted	bare	Continuous current in A outdoor painted	bare
200	5	3 060	8.27	E-Al F 10	4 290	3 330	3 960	3 670
	6	3 660	9.87	E-Al F 10	4 690	3 640	4 320	4 000
	8	4 830	13.0	E-Al F 7	5 390	4 180	4 970	4 600
	10	5 970	16.1	E-Al F 7	5 920	4 600	5 460	5 060
	12	7 090	19.1	E-Al F 7	6 330	4 910	5 830	5 400
250	5	3 850	10.4	E-Al F 10	5 330	4 100	4 840	4 460
	6	4 600	12.4	E-Al F 10	5 810	4 480	5 280	4 870
	8	6 080	16.4	E-Al F 7	6 690	5 160	6 080	5 610
	10	7 540	20.4	E-Al F 7	7 360	5 680	6 690	6 170
	12	8 970	24.2	E-Al F 7	7 870	6 070	7 150	6 600

Continuous current-carrying capacity of Al Mg Si conductors

Table 13-10

Conductors of E-AlMgSi 0.5 F 22, annular cross-section, κ = 30 m/Ωmm^2 at ambient temperature 35 °C and conductor temperature 85 °C with AC, phase centre-line distance ≧ 2 × outside diameter



Outside diameter D mm	Wall-thickness a mm	Cross-section mm^2	Weight kg/m	Continuous current in A1) DC and AC up to 60 Hz indoor painted	bare	outdoor painted	bare
20	2	113	0.305	372	314	446	432
	3	160	0.433	443	372	531	514
	4	201	0.544	497	418	595	576
	5	236	0.636	537	452	643	624
	6	264	0.713	568	479	681	659
32	2	188	0.509	584	482	658	634
	3	273	0.739	702	581	792	762
	42)	352	0.950	797	658	900	864
	5	424	1.15	874	723	987	949
	6	490	1.32	939	777	1 060	1 020
40	2	239	0.645	721	592	791	758
	3	349	0.942	872	714	958	916
	4	452	1.22	993	814	1 089	1 042
	52)	550	1.48	1 094	896	1 199	1 149
	6	641	1.73	1 179	967	1 294	1 245

Continued on next page

Table 13-10 (continued)

Outside diameter D mm	Wall-thickness a mm	Cross-section mm²	Weight kg/m	Continuous current in A 1) DC and AC up to 60 Hz indoor painted	bare	outdoor painted	bare
50	4 2)	578	1.56	1 233	1 004	1 319	1 258
	5	707	1.91	1 368	1 110	1 453	1 392
	6	829	2.24	1 477	1 200	1 575	1 502
	8 2)	1 060	2.85	1 673	1 355	1 783	1 697
	10	1 260	3.39	1 819	1 477	1929	1844
63	4	741	2.00	1 551	1 245	1 600	1 514
	5 2)	911	2.46	1 709	1 380	1 770	1 685
	6	1 070	2.90	1 856	1 502	1 917	1 819
	8 2)	1 380	3.73	2 112	1 697	2 186	2 076
80	4	955	2.58	1 954	1 563	1 954	1 844
	5 2)	1 180	3.18	2 161	1 734	2 173	2 051
	6 2)	1 400	3.77	2 344	1 880	2 357	2 222
	8 2)	1 810	4.89	2 686	2 149	2 686	2 540
	10	2 200	5.94	2 943	2 344	2 955	2 784
100	4	1 210	3.26	2 420	1 915	2 355	2 220
	5	1 490	4.03	2 685	2 135	2 625	2 466
	6	1 770	4.78	2 920	2 320	2 855	2 685
	8	2 310	6.24	3 345	2 650	3 260	3 065
120	4	1 460	3.94	2 880	2 270	2 745	2 565
	5	1 810	4.88	3 200	2 525	3 055	2 855
	6	2 150	5.80	3 490	2 745	3 335	3 115
	8	2 820	7.60	3 995	3 150	3 810	3 565
	10	3 460	9.33	4 385	3 455	4 175	3 905
160	4	1 960	5.29	3 795	2 965	3 555	3 310
	5	2 440	6.57	4 225	3 310	3 955	3 675
	6	2 900	7.84	4 615	3 600	4 310	4 015
	8	3 820	10.3	5 300	4 140	4 955	4 615
	10	4 710	12.7	5 810	4 540	5 445	5 055
200	5	3 060	8.27	5 240	4 065	4 835	4 480
	6	3 660	9.87	5 725	4 445	5 275	4 885
	8	4 830	13.0	6 580	5 105	6 070	5 615
	10	5 970	16.1	7 230	5 615	6 665	6 180
	12	7 090	19.1	7 730	5 995	7 120	6 595
250	5	3 850	10.4	6 510	5 005	5 910	5 445
	6	4 600	12.4	7 095	5 470	6 445	5 945
	8	6 080	16.4	8 170	6 300	7 425	6 850
	10	7 540	20.4	8 985	6 945	8 170	7 535
	12	8 970	24.2	9 610	7 410	8 730	8 060

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1) The currents have been calculated from Table 13-9 with account taken of the correction factors k_1 = 0.925 as in Fig. 13-3 and k_2 = 1.32 as in Fig. 13-4. With an ambient temperature of 50 °C and a conductor temperature of 85 °C, the currents must be multiplied by the correction factor 0.82.

2) Preferred wall thickness

Continuous current-carrying capacity of copper-clad aluminium conductors (DIN 43 670, Part 2)

Table 13-11

Copper-clad aluminium conductors of rectangular cross-section in indoor installations, ambient temperature 35 °C, conductor temperature 65 °C. Conductor width vertical: clearance between conductors equal to conductor thickness; with alternating current, clearance between phases > 0.8 × phase centre-line distance.

Width × thickness	Cross-section	Weight1)	Continuous current in A AC up to 60 Hz								Continuous current in A DC and AC 16⅔ Hz							
			painted				bare				painted				bare			
			no. of conductors				no. of conductors				no. of conductors				no. of conductors			
			1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
			|	||	|||	502) || ||	|	||	|||	502) || ||	|	||	|||	|| ||	|	||	|||	|| ||
mm	mm^2	kg/m																
12 × 5	59.8	0.217	177	324	440		154	292	416		177	324	442		154	292	416	
12 × 10	120	0.434	284	542	796		248	488	722		285	544	778		248	488	722	
20 × 5	98.7	0.358	265	464	594		225	415	562		265	464	600		225	415	565	
20 × 10	192	0.698	408	760	1 100		350	680	985		408	763	1 060		350	632	985	
30 × 5	148	0.538	370	630	772		313	555	733		370	632	780		313	556	736	
30 × 10	292	1.06	555	993	1 390		472	870	1 260		558	1 000	1 330		475	876	1 240	
40 × 5	198	0.719	474	794	937		400	700	895		475	798	953		400	702	905	
40 × 10	392	1.42	705	1 230	1 720	2 280	595	1 090	1 540	2 000	710	1 250	1 640		600	1 100	1540	

Material: E-Al to DIN 40 501 Parts 2 and 3 and E-Cu to DIN 40 500 Parts 2 and 3, copper cladding comprises 15 % of cross-section area.

1) Calculated for a density of 3.63 kg/dm^3

2) Minimum clearance given in mm.

(continued)

Table 13-11 (continued)

Copper-clad aluminium conductors of rectangular cross-section in indoor installations. Ambient temperature 35 °C. Conductor temperature 65 °C. Conductor width vertical: clearance between conductors equal to conductor thickness; with alternating current, clearance between phases > 0.8 × phase centre-line distance.

Width × thickness	Cross-section	Weight[1]	Continuous current in A AC up to 60 Hz								Continuous current in A DC and AC 16⅔ Hz							
			painted no. of conductors				bare no. of conductors				painted no. of conductors				bare no. of conductors			
			1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
mm	mm^2	kg/m	❙	❙❙	❙❙❙	50[2] ❙❙ ❙❙	❙	❙❙	❙❙❙	50[2] ❙❙ ❙❙	❙	❙❙	❙❙❙	❙❙ ❙❙	❙	❙❙	❙❙❙	❙❙ ❙❙
50 × 5	248	0.901	577	953	1 100	1 650	485	830	1 040	1 580	580	962	1 130		485	840	1 070	
50 × 10	492	1.79	850	1 460	2 020	2 650	705	1 280	1 890	2 340	860	1 500	1 930		713	1 320	1 810	
60 × 5	298	1.08	680	1 120	1 250	1 900	566	965	1 190	1 840	685	1 130	1 300	1 690	570	980	1 230	1 620
60 × 10	592	2.15	990	1 680	2 290	2 990	820	1 470	2 030	2 590	1 010	1 750	2 220	2 930	836	1 530	2 100	2 770
80 × 5	398	1.45	890	1 420	1 540	2 340	733	1 230	1 480	2 260	900	1 450	1 630	2 110	740	1 260	1 550	2 020
80 × 10	792	2.88	1 270	2 070	2 780	3 600	1 030	1 820	2 500	3150	1 310	2 240	2 800	3 670	1 070	1 950	2 650	3 500
100 × 10	992	3.60	1 540	2 500	3 230	4 180	1 270	2 170	2 940	3 670	1 600	2 740	3 360	4 420	1 320	2 390	3 200	4 200
120 × 10	1 192	4.32	1 870	2 850	3 640	4 540	1 540	2 480	3 250	3 980	1 980	3 320	4 330	5 620	1 630	2 880	4 130	5 360

Material: E-Al to DIN 40 501 Parts 2 and 3 and E-Cu to DIN 40 500 Parts 2 and 3, copper cladding comprises 15 % of cross-section area.

[1] Calculated for a density of 3.63 kg/dm^3

[2] Minimum clearance given in mm

Table 13-12

Copper-clad aluminium conductors of round cross-section in indoor installations, ambient temperature 35 °C, conductor temperature 65 °C; with alternating current, phase centre-line distance ≥ 1.25 × diameter.

Diameter mm	Cross section mm²	Weight[1] kg/m	Continuous current in A DC and AC up to 60 Hz painted	bare
5	19.6	0.0713	78	70
8	50.3	0.182	148	132
10	78.5	0.285	201	177
16	201	0.730	386	335
20	314	1.14	525	452
32	804	2.92	1 000	850
50	1960	7.13	1 750	1 500

Material: E-Al to DIN 40501 Parts 2 and 3 and E-Cu to DIN 40500 Parts 2 and 3, copper cladding comprises 15 % of cross-section area.

[1] Calculated for a density of 3.63 kg/dm³

Correction factors for deviations from the assumptions

If there are differences between the actual conditions and the assumed conditions, the value of the continuous current taken from Tables 13-4 to 13-9, 13-11 and 13-12 must be multiplied by the following correction factors (DIN 43670, DIN 43670 Part 2 and DIN 43671):

k_1 correction factor for load capacity variations relating to conductivity,

k_2 correction factor for other air and/or busbar temperatures,

k_3 correction factor for thermal load capacity variations due to differences in layout,

k_4 correction factor for electrical load capacity variations (with alternating current) due to differences in layout,

k_5 correction factor for influences specific to location.

The current-carrying capacity is then

$$I_{\text{cont}} = I_{\text{table}} \cdot k_1 \cdot k_2 \cdot k_3 \cdot k_4 \cdot k_5.$$

The load capacity values for three-phase current with a frequency of 16⅔ Hz are the same as for direct current.

For frequencies $f_x > 50$ Hz, the load capacity value are calculated with the formula

$$I_x = I_{50} \sqrt{\frac{50}{f_x}}$$

Correction factor k_1

for load capacity variations relating to conductivity, see Fig. 13-3.

For example, in the case of the aluminium alloy E-AlMgSi 0.5 (κ = 30 m/Ωmm^2), the factor k_1 = 0.925.

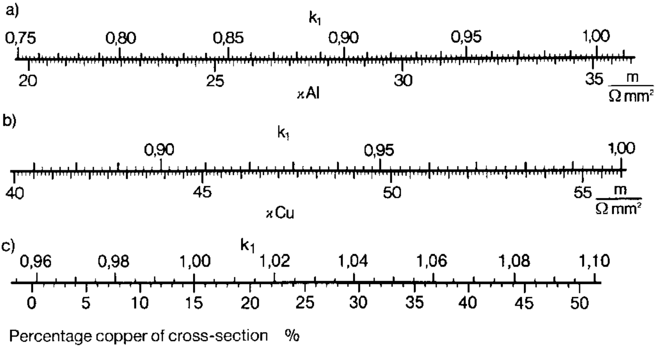

Fig. 13-3

Correction factor k_1 for variation of load capacity when conductivity differs a) from 35.1 m/Ωmm^2 for aluminium materials and b) from 56 m/Ωmm^2 for copper materials and c) factor k_1 for load capacity variation with copper-clad aluminium conductors having other than 15 % copper.

Correction factor k_2

for deviations in ambient and/or busbar temperature, see Fig. 13-4.

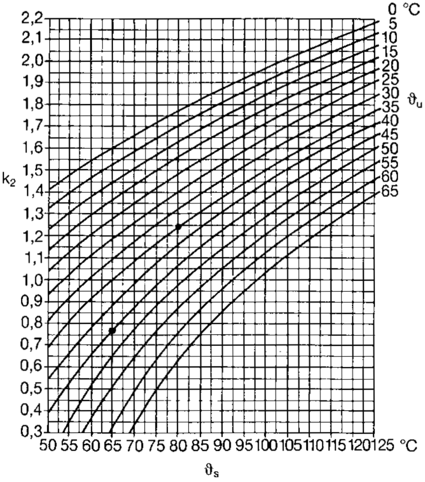

Fig. 13-4

Correction factor k_2 for load capacity variation at ambient temperatures other than 35 °C and/or busbar temperatures other than 65 °C; ϑ_s busbar temperature, ϑ_u mean ambient temperature over 24 hours, short-time maximum value 5 K above mean value.

When selecting the busbar cross-sections, attention must be paid to the maximum permissible operating temperature of the equipment and its connections, and also to heat-sensitive insulating materials. This applies in particular to metal-clad installations.

For example, at an ambient temperature of ϑ_u = 35 °C and an ultimate busbar temperature of ϑ_s = 80 °C (temperature rise 45 K), the factor $k_2 = 1.24$. With an ambient temperature of ϑ_u = 45 °C and an ultimate busbar temperature of ϑ_s = 65 °C (temperature rise 20 K), factor $k_2 = 0.77$.

Correction factor k_3

for thermal capacity load variations due to differences in layout, see Table 13-13.

Table 13-13

Correction factor k_3 for load capacity reduction with long side (width) of bus conductors in horizontal position or with busbars vertical for more than 2 m for Al = aluminium conductors DIN 43670, Al/Cu = copper-clad aluminium conductors DIN 43670 Part 2, Cu = copper conductors DIN 43671

Number of conductors		Width of busbar mm	Thickness of conductor and clearance mm	Factor k_3 when conductors					
				painted			bare		
				Al	Al/Cu	Cu	Al	Al/Cu	Cu
2		50…100	5…10	—	0.85	—	—	0.8	—
		50…200		0.85	—	0.85	0.8	—	0.8
3		50…80	5…10	0.85	0.85	0.85	0.8	0.8	0.8
		100		—	0.8	—	—	0.75	—
		100…200		0.8	—	0.8	0.75	—	0.75
4		up to 100		—	0.8	—	—	0.75	—
		160		0.75	—	0.75	0.7	—	0.7
		200		0.7	—	0.7	0.65	—	0.65
2		up to 200		0.95	—	—	0.9	—	—

Correction factor k_4

for electrical load capacity variations (with alternating current) due to different layout, Fig. 13-5 for copper conductors, Fig. 13-6 for aluminium conductors and 13-7 for copper-clad aluminium conductors. Factor k_4 need be considered only if there is no branching within a distance of at least 2 m.

Correction factor k_5

Influences specific to the location (altitude, exposure to sun, etc.) can be allowed for with factor k_5 as given in Table 13-14.

Table 13-14

Correction factor k_5 for reduction in load capacity at altitudes above 1000 m.

Height above sea-level m	Factor k_5 indoors	Factor k_5 outdoors[1)]
1 000	1.00	0.98
2 000	0.99	0.94
3 000	0.96	0.89
4 000	0.90	0.83

[1)] Reduction smaller at geogr. latitude above 60 ° and/or with heavily dust-laden air.

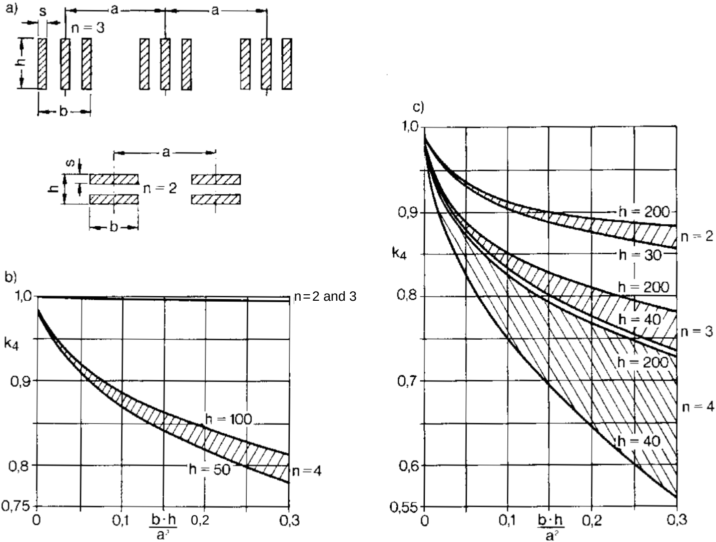

Fig. 13-5

Correction factor k_4 for reduction in load with alternating current up to 60 Hz due to additional skin effect in Cu conductors with small phase centre-line distance a:

a) Examples: Three-phase busbar with n = 3 conductors per phase and conductor thickness s in direction of phase centre-line distance a (above); AC single-phase busbar with n = 2 conductors per phase and conductor thickness s at right angles to phase centre-line distance a (below), b) Factor k_4 for conductors of s = 5 mm, and c) Factor k_4 for conductors of s = 10 mm as a function of $b \cdot h/a^2$; a, b and h in mm; parameter n = number of conductors per phase.

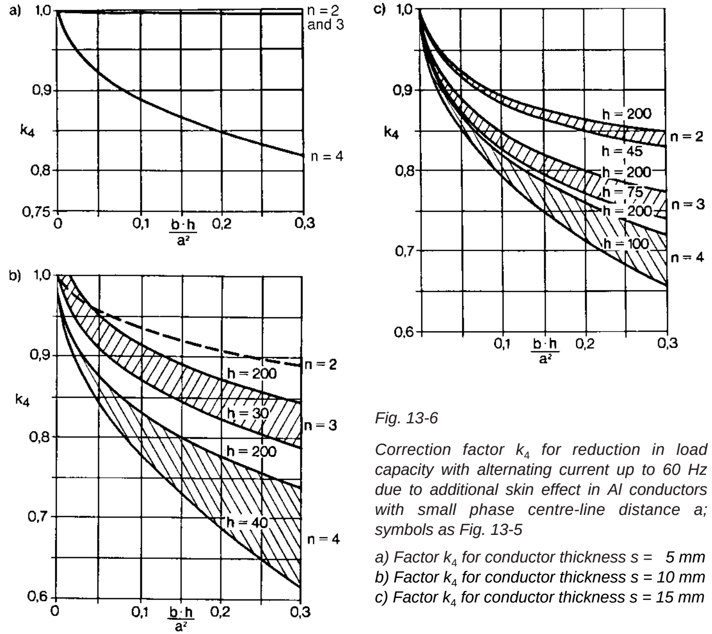

Fig. 13-6

Correction factor k_4 for reduction in load capacity with alternating current up to 60 Hz due to additional skin effect in Al conductors with small phase centre-line distance a; symbols as Fig. 13-5

a) Factor k_4 for conductor thickness s = 5 mm
b) Factor k_4 for conductor thickness s = 10 mm
c) Factor k_4 for conductor thickness s = 15 mm

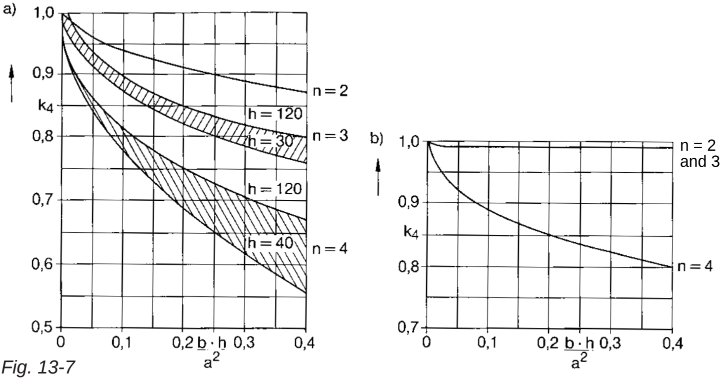

Fig. 13-7

Correction factor k_4 for reduction in load capacity with alternating current up to 60 Hz due to additional skin effect in copper-clad aluminium conductors with small phase centre-line distance a; symbols as Fig. 13-5

a) Factor k_4 for conductor thickness s = 10 mm
b) Factor k_4 for conductor thickness s = 5 mm

13.2 Cables, wires and flexible cords

13.2.1 Specifications, general

During the course of implementing the unified internal European market, there have been changes in the standardization of low and medium-voltage cables. The sections relevant after implementation of the corresponding European harmonization document (HD) for Germany have been collected in a new VDE regulation DIN VDE 0276:

Product group	Former standards DIN VDE ...	Voltage series (kV)	New VDE regulation DIN VDE ...
PVC cable	0271	1	0276 Part 603 (number of cores ≤ 4) 0276 Part 627 (number of cores > 4)
XLPE cable	0272	1	0276 Part 603
XLPE cable	0273	10, 20, 30	0276 Part 620
XLPE cable	0255	10, 20, 30	0276 Part 621

Cables, wires and flexible cords often have to satisfy very different requirements throughout the cable route. Before deciding the type and cross-section, therefore, one must examine their particular electrical function and also climatic and operational factors influencing system reliability and the expected life time of the equipment. Critical stresses at places along the route can endanger the entire link. Particularly important are the specified conditions for heat dissipation.

In the VDE specifications, the codes for the construction, properties and current-carrying capacity of power cables and wires are contained in Group 2 “Power guides”, and for cables and wires in telecommunications and information processing systems in Group 8 “Information technology”.

The identification codes for cables are obtained by adding the symbols in Table 13-43 to the initial letter “N” (types according to DIN VDE) in the sequence of their composition, starting from the conductor. Copper conductors are not identified in the type designation. With paper-insulated cables, the form of insulation is also not mentioned in the code.

Recommendations for the use, supply, transportation and installation and for the current-carrying capacity of cables can be found in the relevant sections of the VDE regulation DIN VDE 0276 and the VDE regulations for installation. Application information for flexible cords is given in DIN VDE 0298-3. The guidelines for up to 1000 V also contain notes on the selection of overload and short-circuit protection facilities.

Table 13-43

Code symbols for cables

Codes for plastic-insulated cables	
A	Aluminium conductor
I	House wiring cable
Y	Insulation of thermoplastic polyvinyl chloride (PVC)
2Y	Insulation of thermoplastic polyethylene (PE)
2X	Insulation of cross-linked polyethylene (XLPE)
HX	Insulation of cross-linked halogen-free polymer
C	Concentric copper conductor
CW	Concentric copper conductor, meander-shaped applied
S	Copper screen
SE	Copper screen, applied over each core of three-core cables
(F)	Screen area longitudinally watertight
Y	Protective PVC inner sheath
F	Armouring of galvanized flat steel wire
R	Armouring of galvanized round steel wire
G	Counter tape or binder of galvanized steel strip
Y	PVC outer sheath
2Y	PE outer sheath
H	Outer sheath of thermoplastic halogen-free polymer
HX	Outer sheath of cross-linked halogen-free polymer
–FE	Insulation maintained in case of fire
Codes for paper-insulated cables	
A	Aluminium conductor
H	Screening for Höchstädter cable
E	Metal sheath over each core (three-sheath cable)
K	Lead sheath
E	Protective cover with embedded layer of elastomer tape or plastic foil
Y	Protective PVC inner sheath
B	Armouring of steel strip
F	Armouring of galvanized flat steel wire
FO	Armouring of galvanized flat steel wire, open
G	Counter tape or binder of steel strip
A	Protective cover of fibrous material
Y	PVC outer sheath
YV	Reinforced PVC outer sheath
For cables U_0/U 0.6/1 kV without concentric conductor	
–J	Cable with core coded green/yellow
–O	Cable without core coded green/yellow
Codes for conductor shape and type	
RE	Solid round conductor
RM	Stranded round conductor
SE	Solid sector-shaped conductor
SM	Stranded sector-shaped conductor
RF	Flexible stranded round conductor

13.2.2 Current-carrying capacity

Specifications for the “rated currents” and the conversion factors in the case of deviations in operating conditions are to be found in the following VDE regulations:

DIN VDE 0276-603:	for PVC cables (number of cores ≤ 4) and XLPE cables 1 kV
DIN VDE 0276-604:	for cables with improved behaviour in case of fire for 1 kV
DIN VDE 0276-620:	for XLPE cables 10, 20 and 30 kV and for PVC cables 10 kV
DIN VDE 0276-621:	for paper-insulated cables 10, 20 and 30 kV
DIN VDE 0276-622:	for cables with improved behaviour in case of fire for power plants 10, 20 and 30 kV
DIN VDE 0276-627:	for PVC cables (number of cores > 4) 1 kV
DIN VDE 0271:	for PVC cables 1 kV (special designs) and PVC cables to 6 kV
DIN VDE 0276-1000:	conversion factors (current-carrying capacity)
DIN VDE 0298-4:	for lines

The values for the current capacity of cables laid underground can be found in Tables 13-44, and 13-46 to 13-49. They are applicable for a load factor of m = 0.7 (electrical utility load), for a specific ground thermal resistance of 1 K · m/W, for a ground temperature of 20 °C and for laying at a depth of 0.7 m to 1.2 m. The electrical utility load (load factor m = 0.7) is based on a load curve that is usual in power supply company networks; see Fig. 13-8. The load factor is calculated from the 24-hour load cycle and is a quotient of the “area under the load curve” to “total area of the rectangle (maximum load × 24 h)”.

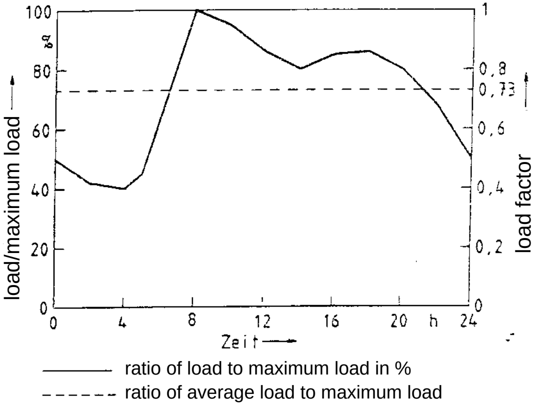

Fig. 13-8

24-hour load cycle and calculating of the load factor (example for a load factor of 0.73)

The values for the current capacity of cables laid in air can be found in Tables 13-45 to 13-49. They are applicable for three-phase continuous operation at an ambient temperature of 30 °C.

Different conditions must be taken into account by application of conversion factors to the above current rating values.

For multiconductor cables the conversion factors given in Table 13-50 apply.
The following apply for cables laid in air

- for different ambient temperatures, the conversion factors given in Table 13-51 and
- for the influence of laying and grouping the conversion factors from Tables 13-52 and 13-53.

The following applies for underground cables:

- for different ground temperatures, the conversion factor f_1 given in Tables 13-54 and 13-55 and
- for cables laying and grouping, the conversion factor f_2 given in Tables 13-56 to 13-59

Both factors also include the ground conditions and the configuration of the cables in the ground. Therefore, both conversion factors, f_1 and f_2, must be always used.

Additional conversion factors for laying cables underground may be:

- 0.85 when laying cables in conduits
- 0.9 when laying cables under covers with air space.

Examples for calculating the permissible current-carrying capacity:

Example 1

Current-carrying capacity of XLPE cable N2XSY 1 × 240 RM/25 6/10 kV:

Operating conditions: cables laid in trefoil formation in ground, covers containing air, load factor m = 0.7, specific soil thermal resistance 1.5 K · m/W, soil temperature 25 °C, 4 systems next to each other, spacing 7 cm.

1. Current rating from Table 13-47, column 10 — 526 A
2. Conversion factor f_1 for 25 °C ground temperature and a max. operating temperature of 90 °C, soil thermal resistance 1.5 K · m/W, load factor m = 0.7, from Table 13-54, column 5 — 0.87
3. Conversion factor for grouping f_2 for 4 parallel systems as in Table 13-56, column 5 (1.5/0.7) — 0.70
4. Reduction factor for protective shells — 0.90
5. Max. permitted capacity: 526 A × 0.87 × 0.70 × 0.9 = — 288 A

Example 2

Current rating for PVC cable NYY-J 3 × 120 SM/70 SM 0.6/1kV

Operating conditions: cables laid in air, ambient temperature 40 °C, 3 cables on a cable rack with unimpeded air circulation, spacing = cable outside diameter, two cable racks

1. Current rating from Table 13-45, column 3 — 285 A
2. Conversion factor for 40 °C from Table 13-51, column 10 — 0.87
3. Conversion factor for laying and grouping from Table 13-53, column 5 — 0.98
4. Reduced current rating: 285 A × 0.87 × 0.98 = — 243 A

Table 13-44

Rated current (three-phase operation) as per DIN VDE 0276-603 cables with U_0 / U = 0.6/1 kV laid underground

1	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*
Insulation material	PVC					VPE		
Permissible operating temperature	70 °C					90 °C		
Type designation	N(A)YY			N(A)YCWY3)		N(A)2XY; N(A)2X2Y		
Configuration	1) 					1) 		
Number of loaded conductors	1	3	3	3	3	1	3	3
Cross-section in mm²	Copper conductor: rated current in A							
1.5	41	27	30	27	31	48	31	33
2.5	55	36	39	36	40	63	40	42
4	71	47	50	47	51	82	52	54
6	90	59	62	59	63	102	64	57
10	124	79	83	79	84	136	86	89
16	160	102	107	102	108	176	112	115
25	208	133	138	133	139	229	145	148
35	250	159	164	160	166	275	174	177
50	296	188	195	190	196	326	206	209
70	365	232	238	234	238	400	254	256
95	438	280	286	280	281	480	305	307
120	501	318	325	319	315	548	348	349
150	563	359	365	357	347	616	392	393
185	639	406	413	402	385	698	444	445
240	746	473	479	463	432	815	517	517
300	848	535	541	518	473	927	585	583
400	975	613	614	579	521	1064	671	663
500	1125	687	693	624	574	1227	758	749
Cross-section in mm²	Aluminium conductor: rated current in A							
25	160	102	106	103	108	177	112	114
35	193	123	127	123	129	212	135	136
50	230	144	151	145	153	252	158	162
70	283	179	185	180	187	310	196	199
95	340	215	222	216	223	372	234	238
120	389	245	253	246	252	425	268	272
150	436	275	284	276	280	476	300	305
185	496	313	322	313	314	541	342	347
240	578	364	375	362	358	631	398	404
300	656	419	425	415	397	716	457	457
400	756	484	487	474	441	825	529	525
500	873	553	558	528	489	952	609	601
Conversion factors								
f_1 2) from tables	13-54	13-54	13-54	13-54	13-54	13-54	13-54	13-54
f_2 3) from tables	13-59	13-59	13-56 13-57	13-59	13-56 13-57	13-59	13-59	13-56 13-57

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1) Rated current in DC systems with remote return conductors
2) for ground temperature
3) for grouping

Table 13-45

Rated current (three-phase operation) as per DIN VDE 0276-603
cables with $U_0 / U = 0.6/1$ kV
laid in air

1	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*
Insulation material	PVC					VPE		
Permissible operating temperature	70°C					90°C		
Type designation	N(A)YY			N(A)YCWY3)		N(A)2XY; N(A)2X2Y		
Configuration	1) ⊙	⊛ ⊛	⊙⊙⊙	⊛ ⊛	⊙⊙⊙	1) ⊙	⊛ ⊛	⊙⊙⊙
Number of loaded conductors	1	3	3	3	3	1	3	3
Cross-section in mm²	Copper conductor: rated current in A							
1.5	27	19.5	21	19.5	22	33	24	26
2.5	35	25	28	26	29	43	32	34
4	47	34	37	34	39	57	42	44
6	59	43	47	44	49	72	53	56
10	81	59	64	60	67	99	74	77
16	107	79	84	80	89	131	98	102
25	144	106	114	108	119	177	133	138
35	176	129	139	132	146	217	162	170
50	214	157	169	160	177	265	197	207
70	270	199	213	202	221	336	250	263
95	334	246	264	249	270	415	308	325
120	389	285	307	289	310	485	359	380
150	446	326	352	329	350	557	412	437
185	516	374	406	377	399	646	475	507
240	618	445	483	443	462	774	564	604
300	717	511	557	504	519	901	649	697
400	843	597	646	577	583	1060	761	811
500	994	669	747	626	657	1252	866	940
Cross-section in mm²	Aluminium conductor: rated current in A							
25	110	82	87	83	91	136	102	106
35	135	100	107	101	112	166	126	130
50	166	119	131	121	137	205	149	161
70	210	152	166	155	173	260	191	204
95	259	186	205	189	212	321	234	252
120	302	216	239	220	247	376	273	295
150	345	246	273	249	280	431	311	339
185	401	285	317	287	321	501	360	395
240	479	338	378	339	374	600	427	472
300	555	400	437	401	426	696	507	547
400	653	472	513	468	488	821	600	643
500	772	539	600	524	556	971	695	754
Conversion factors								
f 2) from tables	13-51	13-51	13-51	13-51	13-51	13-51	13-51	13-51
f 3) from tables	13-53	13-53	13-52	13-53	13-52	13-53	13-53	13-52

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1) Rated current in DC systems with remote return conductors
2) for air temperature
3) for grouping

Table 13-46

Rated current (three-phase operation) as per DIN VDE 0271
cables with $U_0/U = 3.6/6$ kV
laid underground and in air

1	*2*	*3*
Insulation material	PVC	
Metal sheath	—	
Type designation Permissible operating temperature	NYFY[3]; NYSY 70 °C	
Configuration		
Laying	*in ground*	*in air*
Nominal cross-section of copper conductor mm^2	rated current in A	
25	129	105
35	155	128
50	184	155
70	227	196
95	272	242
120	309	280
150	346	319
185	390	366
240	449	430
300	502	489
400	562	560
Conversion factors		
f_1/f [1] from tables	13-54	13-51
f_2/f [2] from tables	13-59	13-53

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[1] for ground temperature/for air temperature

[2] for grouping in ground/in air

[3] three-core

13

Table 13-47

Rated current (three-phase operation) as per DIN VDE 0276-620 (PVC and XLPE cable) and DIN VDE 0276-621 (paper cable)
cable with U_0 / U = 6/10 kV
laid underground and in air

1	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	*11*	*12*	
Insulation mat.	Impreg. paper		PVC				XL PE					
Metal sheath	Lead		————						————			
Type designation	N(A)KBA		N(A)YSEY3) N(A)YSY4)				N(A)2XSEY, N(A)2XSE2Y3) N(A)2XSY, N(A)2XS2Y4)					
Permissible operating temp.	65 °C		70 °C				90 °C					
Configuration	⊛		⊛		⊙ ⊙⊙		⊛		⊙ ⊙⊙		⊙⊙⊙	
Installation	*Ground*	*Air*	*Ground*	*Air*	*Ground*	*Air*	*Ground*	*Air*	*Ground*	*Air*	*Ground*	*Air*
Nominal cross-section Copper	mm²				Rated current in A							
25	122	100	134	114	137	119	151	147	157	163	179	194
35	150	123	160	138	163	143	181	178	187	197	212	235
50	179	148	189	165	192	172	213	213	220	236	249	282
70	222	187	231	205	234	214	261	265	268	294	302	350
95	269	228	276	249	279	261	312	322	320	358	359	426
120	308	263	313	286	316	301	355	370	363	413	405	491
150	347	301	351	324	352	341	399	420	405	468	442	549
185	392	345	396	371	397	391	451	481	456	535	493	625
240	454	408	458	434	457	460	523	566	526	631	563	731
300	511	467	—	—	512	526	590	648	591	722	626	831
400	577	536	—	—	571	602	—	—	662	827	675	920
500	—	—	—	—	639	691	—	—	744	949	748	1043
Aluminium	mm²											
25	95	78	—	—	—	—	—	—	—	—	—	—
35	117	96	—	—	—	—	140	138	145	153	165	182
50	139	115	147	128	149	133	165	165	171	183	194	210
70	173	145	179	159	182	166	203	206	208	228	236	273
95	209	177	214	193	217	203	242	249	248	278	281	333
120	240	205	244	222	246	234	276	288	283	321	318	384
150	270	234	273	252	276	266	309	326	315	364	350	432
185	307	270	309	289	311	306	351	375	357	418	394	496
240	357	320	358	340	359	361	408	442	413	494	452	583
300	403	368	404	389	405	415	463	507	466	568	506	666
400	461	428	—	—	457	481	—	—	529	660	558	755
500	—	—	—	—	520	560	—	—	602	767	627	868
Conversion factors from tables												
f_1/f 1)	13-54	13-51	13-55	13-51	13-54	13-51	13-54	13-51	13-54	13-51	13-54	13-51
f_2/f 2)	13-59	13-53	13-59 13-57	13-53	13-56	13-52	13-59 13-57	13-53	13-56	13-52	13-58	13-52

1) for ground temperature/for air temperature

2) for grouping in ground/in air

3) three-core

4) single-core

Table 13-48

Rated current (three-phase operation) as per DIN VDE 0276-620 (XLPE cables) and DIN VDE 0276-621 (paper cable)
cable with $U_0 / U = 12/20$ kV
laid underground and in air

1	*2*	*3*	*4*	*5*	*6*	*7*
Insulation material	Impregnated paper		XLPE			
Metal sheath	Lead					
Type designation	N(A)EKBA		N(A)2XSY, N(A)2XS2Y N(A)2X(F)2Y			
Permissible operating temperature	65 °C		90 °C			
Configuration						
Installation	*Ground*	*Air*	*Ground*	*Air*	*Ground*	*Air*
Nominal cross-section Copper conductor mm²	Rated current in A					
25	129	111	—	—	—	—
35	155	134	189	200	213	235
50	185	161	222	239	250	282
70	229	200	271	297	303	351
95	274	243	323	361	360	426
120	314	279	367	416	407	491
150	354	317	409	470	445	549
185	402	363	461	538	498	625
240	468	426	532	634	568	731
300	530	488	599	724	633	830
400	600	560	671	829	685	923
500	674	641	754	953	760	1045
Aluminium conductor mm²						
25	100	86	—	—	—	—
35	121	104	—	—	—	—
50	144	125	172	185	195	219
70	178	156	210	231	237	273
95	213	189	251	280	282	332
120	244	218	285	323	319	384
150	275	247	319	366	352	432
185	314	284	361	420	396	494
240	367	334	417	496	455	581
300	417	384	471	569	510	663
400	478	445	535	660	564	753
500	545	516	609	766	634	866
Conversion factors						
f_1 / f [1] from tables	13-54	13-51	13-54	13-51	13-54	13-51
f_2 / f [2] from tables	13-59	13-53	13-56 13-57	13-52	13-58	13-52

[1] for ground temperature/for air temperature

[2] for grouping in ground/in air

Table 13-49

Rated current (three-phase operation) as per DIN VDE 0276-620 (XLPE cables) and DIN VDE 0276-621 (paper cable)
cable with U_0 / U = 18/30 kV
laid underground and in air

1	*2*	*3*	*4*	*5*	*6*	*7*
Insulation material	Impregnated paper		XLPE			
Metal sheath	Lead					
Type designation	N(A)EKEBA		N(A)2XSY, N(A)2XS2Y N(A)2XS(F)2Y			
Permissible operating temperature	60 °C		90 °C			
Configuration	⊛	⊛	⊙ ⊙⊙	⊙ ⊙⊙	⊙⊙⊙	⊙⊙⊙
Installation	*Ground*	*Air*	*Ground*	*Air*	*Ground*	*Air*
Nominal cross-section Copper conductor mm^2	Rated current in A					
35	146	126	—	—	—	—
50	174	150	225	241	251	282
70	215	187	274	299	304	350
95	259	227	327	363	362	425
120	297	261	371	418	409	488
150	334	295	414	472	449	548
185	379	338	466	539	502	624
240	442	397	539	635	574	728
300	501	453	606	725	640	828
400	569	519	680	831	695	922
500	644	594	765	953	773	1045
Aluminium conductor mm^2						
35	113	98	—	—	—	—
50	135	117	174	187	195	219
70	167	145	213	232	238	273
95	201	176	254	282	283	331
120	231	203	289	325	321	382
150	260	230	322	367	354	429
185	297	264	364	421	399	492
240	347	311	422	496	458	578
300	394	356	476	568	514	659
400	454	414	541	650	570	750
500	520	478	616	764	642	861
Conversion factors						
f_1/f 1) from tables	13-54	13-51	13-54	13-51	13-54	13-51
f_2/f 2) from tables	13-59	13-53	13-56 13-57	13-52	13-58	13-52

1) for ground temperature/for air temperature

2) for grouping in ground/in air

Table 13-50

Conversion factors[1)],
for multicore cables with conductor cross-sections of 1.5 to 10 mm^2
laid underground or in air (as per DIN VDE 0276-1000)

1	*2*	*3*
Number of loaded cores	Laid underground	 in air
5	0.70	0.75
7	0.60	0.65
10	0.50	0.55
14	0.45	0.50
19	0.40	0.45
24	0.35	0.40
40	0.30	0.35
61	0.25	0.30

1) The conversion factors must be used when
laid underground to the values in Table 13-44, column 3
laid in air to the values in Table 13-45, column 3

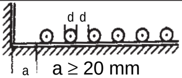
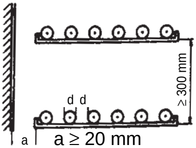
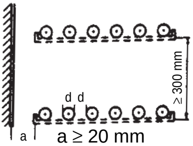
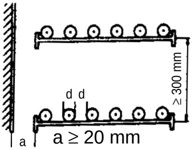
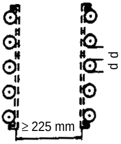
Table 13-51

Conversion factors for different air temperatures (as per DIN VDE 0276-1000)

1	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	*11*	*12*
Type	Permissible operating temperature	Permissible temperature rise		Conversion factors for the air temperature in °C							
			10	15	20	25	30	35	40	45	50
—	°C	K	—	—	—	—	—	—	—	—	—
XLPE cables	90	—	1.15	1.12	1.08	1.04	1.0	0.96	0.91	0.87	0.82
PVC cables	70	—	1.22	1.17	1.12	1.06	1.0	0.94	0.87	0.79	0.71
Mass-impreg. cables: Belted cables 6/10 kV	65	35	1.0	1.0	1.0	1.0	1.0	0.93	0.85	0.76	0.65
Single-core, three-core single lead sheathed and H-type cables 12/20 kV	65	35	1.0	1.0	1.0	1.0	1.0	0.93	0.85	0.76	0.65
18/30 kV	60	30	1.0	1.0	1.0	1.0	1.0	0.91	0.82	0.71	0.58

Table 13-52

Conversion factors for grouping in air[1], single-core cables in three-phase systems (as per DIN VDE 0276-1000)

1		*2*	*3*	*4*	*5*
Installation in flat formation Spacing = cable diameter *d*		Number of troughs/ racks vertical		Number of systems[2] horizontal	
			1	2	3
Laid on the floor		1	0.92	0.89	0.88
Unperforated cable troughs[3]		1	0.92	0.89	0.88
		2	0.87	0.84	0.83
		3	0.84	0.82	0.81
		6	0.82	0.80	0.79
Perforated cable troughs[3]		1	1.00	0.93	0.90
		2	0.97	0.89	0.85
		3	0.96	0.88	0.82
		6	0.94	0.85	0.80
Cable racks[4]		1	1.00	0.97	0.96
		2	0.97	0.94	0.93
		3	0.96	0.93	0.92
		6	0.94	0.91	0.90
On racks or on the wall or on perforated cable troughs in vertical configuration		Number of troughs horizontal		Number of systems vertical	
			1	2	3
		1	0.94	0.91	0.89
		2	0.94	0.90	0.86

[1] If the air temperature is increased by the heat loss of the cables in small buildings or because of high grouping, the conversion factors for different air temperatures in Table 13-51 must also be used.

[2] Factors as per DIN VDE 0255 (VDE 0255)

[3] A cable trough is a continuous surface with raised edges but no cover. A cable trough is considered perforated if it is perforated over at least 30 % of the entire surface area.

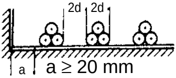
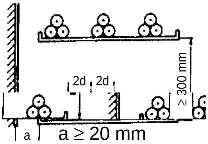
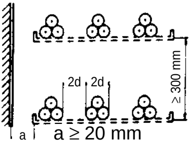
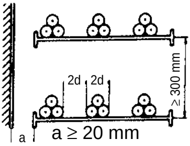
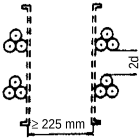
[4] A cable rack is a support structure in which the supporting area is no more than 10% of the total area of the structure.

When cables with metal sheathing or shielding are laid flat, the increased sheathing or shielding losses act against the reduced mutual heating when the spacing is increased. For this reason no information on reduction-free configurations can be given.

(continued)

Table 13-52 (continued)

Conversion factors for grouping in air[1], single-core cables in three-phase systems (as per DIN VDE 0276-1000)

6		*7*	*8*	*9*	*10*
Installation in trefoil formation Spacing = 2 · cable diameter *d*		Number of troughs/ racks vertical	Number of systems[2] horizontal 1	2	3
Laid on the floor		1	0.98	0.96	0.94
Unperforated cable troughs[3]		1	0.98	0.96	0.94
		2	0.95	0.91	0.87
		3	0.94	0.90	0.85
		6	0.93	0.88	0.82
Perforated cable troughs[3]		1	1.00	0.98	0.96
		2	0.97	0.93	0.89
		3	0.96	0.92	0.85
		6	0.95	0.90	0.83
Cable racks[4] (cable gratings)		1	1.00	0.97	0.96
		2	0.97	0.95	0.93
		3	0.96	0.94	0.90
		6	0.95	0.93	0.87
On racks or on the wall or on perforated cable troughs in vertical configuration		Number of troughs horizontal	Number of systems vertical 1	2	3
		1	1.00	0.91	0.89
		2	1.00	0.90	0.86

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[1] If the air temperature is increased by the heat loss of the cables in small buildings or because of high grouping, the conversion factors for different air temperatures in Table 13-51 must also be used.

[2] Factors as in CENELEC Report R064.001 re HD 384,5.523:1991.

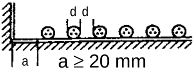
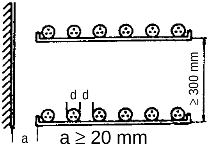
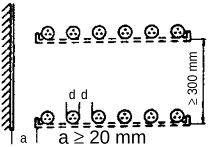
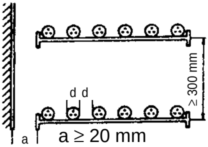
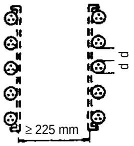
[3] A cable trough is a continuous surface with raised edges but no cover. A cable trough is considered perforated if the perforations cover at least 30 % of the entire surface area.

[4] A cable rack is a support structure in which the supporting area is no more than 10 % of the total area of the structure.

Load reduction is not required when laying in bundles where the spacing of adjacent systems is at least four times the cable diameter, as long as the ambient temperature is not increased by the heat loss (see footnote 1).

Table 13-53

Conversion factors for grouping in air[1], multicore cables and single-core DC cables (as per DIN VDE 0276-1000)

1	2	3	4	5	6	7
Installation Spacing = cable diameter *d*	Number of troughs/ racks vertical	Number of cables horizontal[4]				
		1	2	3	4	6
Laid on the floor 	1	0.97	0.96	0.94	0.93	0.90
Unperforated cable troughs[2] 	1	0.97	0.96	0.94	0.93	0.90
	2	0.97	0.95	0.92	0.90	0.86
	3	0.97	0.94	0.91	0.89	0.84
	6	0.97	0.93	0.90	0.88	0.83
Perforated cable troughs[2] 	1	1.00	1.00	0.98	0.95	0.91
	2	1.00	0.99	0.96	0.92	0.87
	3	1.00	0.98	0.95	0.91	0.85
	6	1.00	0.97	0.94	0.90	0.84
Cable racks[3] (cable gratings) 	1	1.00	1.00	1.00	1.00	1.00
	2	1.00	0.99	0.98	0.97	0.96
	3	1.00	0.98	0.97	0.96	0.93
	6	1.00	0.97	0.96	0.94	0.91
On racks or on the wall or on perforated cable troughs in vertical configuration 	Number of troughs horizontal	Number of systems vertical				
		1	2	3	4	6
	1	1.00	0.91	0.89	0.88	0.87
	2	1.00	0.91	0.88	0.87	0.85

[1] If the air temperature is increased by the heat loss of the cables in small buildings or because of high grouping, the conversion factors for different air temperatures in Table 13-51 must also be used.

[2] A cable trough is a continuous surface with raised edges but no cover. A cable trough is considered perforated if it is perforated over at least 30 % of the entire surface area.

[3] A cable rack is a support structure in which the supporting area is no more than 10 % of the total area of the structure.

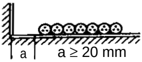
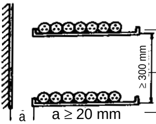
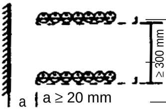
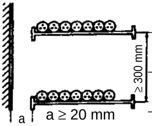
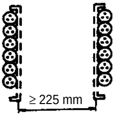
[4] Factors as in CENELEC Report R064.001 re HD 384.5.523:1991.

Load reduction is not required where the horizontal or vertical spacing of adjacent cables is at least twice the cable diameter, as long as the ambient temperature is not increased by the heat loss (see footnote 1).

(continued)

Table 13-53 (continued)

Conversion factors for grouping in air[1], multicore cables and single-core d.c. systems (as per DIN VDE 0276-1000)

8		*9*	*10*	*11*	*12*	*13*	*14*	*15*
Installation Mutual contact		Number of troughs/racks vertical	Number of cables horizontal[4] 1	2	3	4	6	9
Laid on the floor		1	0.97	0.85	0.78	0.75	0.71	0.68
Unperforated cable troughs[2]		1	0.97	0.85	0.78	0.75	0.71	0.68
		2	0.97	0.84	0.76	0.73	0.68	0.63
		3	0.97	0.83	0.75	0.72	0.66	0.63
		6	0.97	0.81	0.73	0.69	0.63	0.58
Perforated cable troughs[2]		1	1.00	0.88	0.82	0.79	0.76	0.73
		2	1.00	0.87	0.80	0.77	0.73	0.68
		3	1.00	0.86	0.79	0.76	0.71	0.66
		6	1.00	0.84	0.77	0.73	0.68	0.64
Cable racks[3] (cable gratings)		1	1.00	0.87	0.82	0.80	0.79	0.78
		2	1.00	0.86	0.80	0.78	0.76	0.73
		3	1.00	0.85	0.79	0.76	0.73	0.70
		6	1.00	0.83	0.76	0.73	0.69	0.66
Perforated cable troughs vertical configuration		Number of troughs horizontal	Number of cables vertical 1	2	3	4	6	9
		1	1.00	0.88	0.82	0.78	0.73	0.72
		2	1.00	0.88	0.81	0.76	0.71	0.70
On racks or on the wall in vertical configuration			Number of cables vertical 1	2	3	4	6	9
			0.95	0.78	0.73	0.72	0.68	0.66

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[1] If the air temperature is increased by the heat loss of the cables in small buildings or because of high grouping, the conversion factors for different air temperatures in Table 13-51 must also be used.

[2] A cable trough is a continuous surface with raised edges but no cover. A cable trough is considered perforated if it is perforated over at least 30 % of the entire surface area.

[3] A cable rack is a support structure in which the supporting area is no more than 10 % of the total area of the structure.

[4] Factors as in CENELEC Report R064.001 re HD 384,5.523:1991.

Load reduction is not required where the horizontal or vertical spacing of adjacent systems is at least twice the cable diameter, so long as the ambient temperatures are not increased by the heat loss (see footnote 1).

Table 13-54

Conversion factors f_1, cables laid in ground
All cables (except PVC cables for 6/10 kV) (as per DIN VDE 0276-1000)

1	*2*	*3*					*4*					*5*					*6*
Permissible operating temperature	Soil temperature	Specific thermal resistance of soil K · m/W															
		0.7					1.0					1.5					2.5
		Load factor					Load factor					Load factor					Load factor
°C	°C	0.50	0.60	0.70	0.85	1.00	0.50	0.60	0.70	0.85	1.00	0.50	0.60	0.70	0.85	1.00	0.5 to 1.00
90	5	1.24	1.21	1.18	1.13	1.07	1.11	1.09	1.07	1.03	1.00	0.99	0.98	0.97	0.96	0.94	0.89
	10	1.23	1.19	1.16	1.11	1.05	1.09	1.07	1.05	1.01	0.98	0.97	0.96	0.95	0.93	0.91	0.86
	15	1.21	1.17	1.14	1.08	1.03	1.07	1.05	1.02	0.99	0.95	0.95	0.93	0.92	0.91	0.89	0.84
	20	1.19	1.15	1.12	1.06	1.00	1.05	1.02	1.00	0.96	0.93	0.92	0.91	0.90	0.88	0.86	0.81
	25						1.02	1.00	0.98	0.94	0.90	0.90	0.88	0.87	0.85	0.84	0.78
	30								0.95	0.91	0.88	0.87	0.86	0.84	0.83	0.81	0.75
	35													0.82	0.80	0.78	0.72
	40																0.68
80	5	1.27	1.23	1.20	1.14	1.08	1.12	1.10	1.07	1.04	1.00	0.99	0.98	0.97	0.95	0.93	0.88
	10	1.25	1.21	1.17	1.12	1.06	1.10	1.07	1.05	1.01	0.97	0.97	0.95	0.94	0.92	0.91	0.85
	15	1.23	1.19	1.15	1.09	1.03	1.07	1.05	1.03	0.99	0.95	0.94	0.93	0.92	0.90	0.88	0.82
	20	1.20	1.17	1.13	1.07	1.01	1.05	1.03	1.00	0.96	0.92	0.91	0.90	0.89	0.87	0.85	0.78
	25						1.03	1.00	0.97	0.93	0.89	0.88	0.87	0.86	0.84	0.82	0.75
	30								0.95	0.91	0.86	0.85	0.84	0.83	0.81	0.78	0.72
	35													0.80	0.77	0.75	0.68
	40																0.64
70	5	1.29	1.26	1.22	1.15	1.09	1.13	1.11	1.08	1.04	1.00	0.99	0.98	0.97	0.95	0.93	0.86
	10	1.27	1.23	1.19	1.13	1.06	1.11	1.08	1.06	1.01	0.97	0.96	0.95	0.94	0.92	0.89	0.83
	15	1.25	1.21	1.17	1.10	1.03	1.08	1.06	1.03	0.99	0.94	0.93	0.92	0.91	0.88	0.86	0.79
	20	1.23	1.18	1.14	1.08	1.01	1.06	1.03	1.00	0.96	0.91	0.90	0.89	0.87	0.85	0.83	0.76
	25						1.03	1.00	0.97	0.93	0.88	0.87	0.85	0.84	0.82	0.79	0.72
	30								0.94	0.89	0.85	0.84	0.82	0.80	0.78	0.76	0.68
	35													0.77	0.74	0.72	0.63
	40																0.59

The conversion factor f_1 must always be used with the conversion factor f_2.
(continued)

Table 13-54 (continued)

1	*2*	*3*					*4*					*5*					*6*
Permissible operating temperature °C	Soil temperature °C	Specific thermal resistance of soil K · m/W															
		0.7					1.0					1.5					2.5
		Load factor					Load factor					Load factor					Load factor
		0.50	0.60	0.70	0.85	1.00	0.50	0.60	0.70	0.85	1.00	0.50	0.60	0.70	0.85	1.00	0.5 to 1.00
65	5	1.31	1.27	1.23	1.16	1.09	1.14	1.11	1.09	1.04	1.00	0.99	0.98	0.96	0.94	0.92	0 85
	10	1.29	1.24	1.20	1.14	1.06	1.11	1.09	1.06	1.02	0.97	0.96	0.95	0.93	0.91	0.89	0.82
	15	1.26	1.22	1.18	1.11	1.04	1.09	1.06	1.03	0.98	0.94	0.93	0.91	0.90	0.88	0.85	0.78
	20	1.24	1.20	1.15	1.08	1.01	1.06	1.03	1.00	0.95	0.90	0.90	0.88	0.86	0.84	0.82	0.74
	25						1.03	1.00	0.97	0.92	0.87	0.86	0.84	0.83	0.80	0.78	0.70
	30								0.94	0.89	0.83	0.82	0.81	0.79	0.77	0.74	0.65
	35													0.75	0.72	0.70	0.60
	40																0.55
60	5	1.33	1.28	1.24	1.17	1.10	1.15	1.12	1.09	1.05	1.00	0.99	0.98	0.96	0.94	0.92	0.84
	10	1.30	1.26	1.21	1.14	1.07	1.12	1.09	1.06	1.02	0.97	0.96	0.94	0.93	0.90	0.88	0.80
	15	1.28	1.23	1.19	1.12	1.04	1.09	1.06	1.03	0.98	0.93	0.92	0.91	0.89	0.87	0.84	0.76
	20	1.25	1.21	1.16	1.09	1.01	1.06	1.03	1.00	0.95	0.90	0.89	0.87	0.86	0.83	0.80	0.72
	25						1.03	1.00	0.97	0.92	0.86	0.85	0.83	0.82	0.79	0.76	0.67
	30								0.93	0.88	0.82	0.81	0.79	0.78	0.75	0.72	0.62
	35													0.73	0.70	0.67	0.57
	40																0.51

With mass-impregnated cables, increasing the current rating at temperatures below 20 °C is subject to conditions. The conversion factor f_1 must be applied only together with conversion factor f_2.

Table 13-55

Conversion factors f_1, cables laid in ground, PVC cables for 6/10 kV (as per DIN VDE 0276-1000)

1	*2*	*3*	*4*	*5*					*6*					*7*					*8*
Number of three-phase systems		Number of three-phase cables	Soil temperature ° C	Specific thermal resistance of soil K · m/W															
				0.7					1.0					1.5					2.5
				Load factor					Load factor					Load factor					Load factor
				0.50	0.60	0.70	0.85	1.00	0.50	0.60	0.70	0.85	1.00	0.50	0.60	0.70	0.85	1.00	0.5 to 1.0
1	1	1	5	1.31	1.27	1.23	1.16	1.09	1.14	1.12	1.09	1.05	1.00	0.99	0.98	0.96	0.94	0.92	0.85
			10	1.29	1.25	1.21	1.14	1.07	1.12	1.09	1.06	1.02	0.97	0.96	0.95	0.93	0.91	0.89	0.81
			15	1.27	1.22	1.18	1.11	1.04	1.09	1.06	1.03	0.98	0.94	0.93	0.91	0.90	0.87	0.85	0.77
			20	1.24	1.20	1.15	1.08	1.01	1.06	1.03	1.00	0.95	0.90	0.89	0.88	0.86	0.84	0.81	0.73
			25						1.03	1.00	0.97	0.92	0.87	0.86	0.84	0.83	0.80	0.77	0.69
			30								0.94	0.89	0.83	0.82	0.80	0.79	0.76	0.73	0.64
			35													0.75	0.72	0.70	0.59
			40																0.54
4	3	3	5	1.29	1.24	1.20	1.13	1.06	1.11	1.08	1.05	1.01	0.96	0.95	0.94	0.93	0.90	0.88	0.81
			10	1.26	1.22	1.17	1.11	1.03	1.08	1.05	1.03	0.98	0.93	0.92	0.91	0.89	0.87	0.84	0.77
			15	1.24	1.19	1.15	1.08	1.00	1.05	1.03	0.99	0.95	0.90	0.89	0.87	0.86	0.83	0.81	0.73
			20	1.21	1.17	1.12	1.05	0.97	1.03	0.99	0.96	0.91	0.86	0.85	0.84	0.82	0.79	0.77	0.68
			25						0.99	0.96	0.93	0.88	0.83	0.82	0.80	0.78	0.76	0.73	0.64
			30								0.90	0.84	0.79	0.78	0.76	0.74	0.71	0.68	0.59
			35													0.70	0.67	0.64	0.53
			40																0.47
10	5	6	5	1.26	1.21	1.17	1.10	1.03	1.08	1.05	1.02	0.97	0.93	0.92	0.90	0.89	0.86	0.84	0.76
			10	1.23	1.19	1.14	1.07	1.00	1.05	1.02	0.99	0.94	0.89	0.88	0.87	0.85	0.83	0.80	0.72
			15	1.21	1.16	1.12	1.04	0.96	1.02	0.99	0.96	0.91	0.86	0.85	0.83	0.81	0.79	0.76	0.68
			20	1.18	1.14	1.09	1.01	0.93	0.99	0.96	0.93	0.87	0.82	0.81	0.79	0.77	0.75	0.72	0.63
			25						0.96	0.93	0.89	0.84	0.78	0.77	0.75	0.73	0.70	0.68	0.58
			30								0.86	0.80	0.74	0.73	0.71	0.69	0.66	0.63	0.52
			35													0.64	0.61	0.58	0.46
			40																0.38

Conversion factor f_1 must be applied only together with conversion factor f_2.

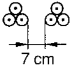
(continued)

Table 13-55 (continued)

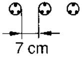
1	2	3	4	5					6					7					8
Number of three-phase systems		Number of three-phase cables	Soil temperature ° C	Specific thermal resistance of soil K · m/W 0.7					1.0					1.5					2.5
				Load factor					Load factor					Load factor					Load factor
				0.50	0.60	0.70	0.85	1.00	0.50	0.60	0.70	0.85	1.00	0.50	0.60	0.70	0.85	1.00	0.5 to 1.0
—	8	10	5	1.23	1.19	1.14	1.07	0.99	1.05	1.02	0.99	0.94	0.89	0.88	0.86	0.85	0.82	0.80	0.72
			10	1.21	1.16	1.11	1.04	0.96	1.02	0.99	0.96	0.91	0.85	0.84	0.83	0.81	0.78	0.76	0 67
			15	1.18	1.13	1.09	1.01	0.93	0.99	0.96	0.92	0.87	0.82	0.81	0.79	0.77	0.74	0.72	0.63
			20	1.15	1.11	1.06	0.98	0.90	0.96	0.92	0.89	0.84	0.78	0.77	0.75	0.73	0.70	0.67	0.57
			25						0.92	0.89	0.85	0.80	0.74	0.73	0.71	0.69	0.66	0.63	0.52
			30								0.82	0.76	0.70	0.68	0.66	0.64	0 61	0.57	0.45
			35													0.60	0.56	0.52	0.38
			40																0.29
—	10	—	5	1.22	1.17	1.13	1.05	0.98	1.03	1.00	0.97	0.92	0.87	0.86	0.84	0.83	0.80	0.78	0.69
			10	1.19	1.15	1.10	1.02	0.94	1.00	0.97	0.94	0.89	0.83	0.82	0.81	0.79	0.76	0.73	0.65
			15	1.17	1.12	1.07	0.99	0.91	0.97	0.94	0.90	0.85	0.79	0.78	0.77	0.75	0.72	0.69	0.60
			20	1.14	1.09	1.04	0.96	0.88	0.94	0.90	0.87	0.81	0.76	0.74	0.73	0.71	0.68	0.65	0.54
			25						0.90	0.87	0.83	0.78	0.71	0.70	0.68	0.66	0.63	0.60	0.48
			30								0.79	0.73	0.67	0.66	0.63	0.61	0.58	0.54	0.41
			35													0.56	0.52	0.48	0.33
			40																0.22

Arrangement of three-phase systems in column 1

Arrangement of three-phase systems in column 2

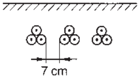


Arrangement of three-phase cables in column 3



Conversion factor f_1 must be applied only together with conversion factor f_2.

Table 13-56



Conversion factor f_2, cables laid in ground
Single-core cables in three phase systems, trefoil formation (as per DIN VDE 0276-1000)

1	2	3					4					5					6				
Type	Number of systems	Specific thermal resistance of soil in K · m/W																			
		0.7					1.0					1.5					2.5				
XLPE cables 0.6/1 kV 6/10 kV 12/20 kV 18/30 kV		load factor					load factor					load factor					load factor				
		0.5	0.6	0.7	0.85	1.00	0.5	0.6	0.7	0.85	1.00	0.5	0.6	0.7	0.85	1.00	0.5	0.6	0.7	0.85	1.00
	1	1.09	1.04	0.99	0.93	0.87	1.11	1.05	1.00	0.93	0.87	1.13	1.07	1.01	0.94	0.87	1.17	1.09	1.03	0.94	0.87
	2	0.97	0.90	0.84	0.77	0.71	0.98	0.91	0.85	0.77	0.71	1.00	0.92	0.86	0.77	0.71	1.02	0.94	0.87	0.78	0.71
	3	0.88	0.80	0.74	0.67	0.61	0.89	0.82	0.75	0.67	0.61	0.90	0.82	0.76	0.68	0.61	0.92	0.83	0.76	0.68	0.61
	4	0.83	0.75	0.69	0.62	0.56	0.84	0.76	0.70	0.62	0.56	0.85	0.77	0.70	0.62	0.56	0.86	0.78	0.71	0.63	0.56
	5	0.79	0.71	0.65	0.58	0.52	0.80	0.72	0.66	0.58	0.52	0.80	0.73	0.66	0.58	0.52	0.82	0.73	0.67	0.59	0.52
	6	0.76	0.68	0.62	0.55	0.50	0.77	0.69	0.63	0.55	0.50	0.77	0.70	0.63	0.56	0.50	0.78	0.70	0.64	0.56	0.50
	8	0.72	0.64	0.58	0.51	0.46	0.72	0.65	0.59	0.52	0.46	0.73	0.65	0.59	0.52	0.46	0.74	0.66	0.59	0.52	0.46
	10	0.69	0.61	0.56	0.49	0.44	0.69	0.62	0.56	0.49	0.44	0.70	0.62	0.56	0.49	0.44	0.70	0.63	0.57	0.49	0.44
PVC cables 0.6/1 kV 3.6/6 kV 6/10 kV		load factor					load factor					load factor					load factor				
		0.5	0.6	0.7	0.85	1.00	0.5	0.6	0.7	0.85	1.00	0.5	0.6	0.7	0.85	1.00	0.5	0.6	0.7	0.85	1.00
	1	1.01	1.02	0.99	0.93	0.87	1.04	1.05	1.00	0.93	0.87	1.07	1.06	1.01	0.94	0.87	1.11	1.08	1.01	0.94	0.87
	2	0.94	0.89	0.84	0.77	0.71	0.97	0.91	0.85	0.77	0.71	0.99	0.92	0.86	0.77	0.71	1.01	0.93	0.87	0.78	0.71
	3	0.86	0.79	0.74	0.67	0.61	0.89	0.81	0.75	0.67	0.61	0.90	0.83	0.76	0.68	0.61	0.91	0.83	0.77	0.68	0.61
	4	0.82	0.75	0.69	0.62	0.56	0.84	0.76	0.70	0.62	0.56	0.85	0.77	0.71	0.62	0.56	0.86	0.78	0.71	0.63	0.56
	5	0.78	0.71	0.65	0.58	0.52	0.80	0.72	0.66	0.58	0.52	0.80	0.73	0.66	0.58	0.52	0.81	0.73	0.67	0.59	0.52
	6	0.75	0.68	0.62	0.55	0.50	0.77	0.69	0.63	0.55	0.50	0.77	0.70	0.64	0.56	0.50	0.78	0.70	0.64	0.56	0.50
	8	0.71	0.64	0.58	0.51	0.46	0.72	0.65	0.59	0.52	0.46	0.73	0.65	0.59	0.52	0.46	0.73	0.66	0.60	0.52	0.46
	10	0.68	0.61	0.55	0.49	0.44	0.69	0.62	0.56	0.49	0.44	0.69	0.62	0.56	0.49	0.44	0.70	0.63	0.57	0.49	0.44

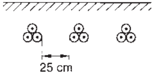
The conversion factor f_2 must be applied only together with conversion factor f_1.

Table 13-56 (continued)

1	2	3					4					5					6				
Type	Number of systems	Specific thermal resistance of soil in K · m/W																			
		0.7					1.0					1.5					2.5				
Mass-impregnated cables 0.6/1 kV 3.6/6 kV 6/10 kV 12/20 kV 18/30 kV		load factor					load factor					load factor					load factor				
		0.5	0.6	0.7	0.85	1.00	0.5	0.6	0.7	0.85	1.00	0.5	0.6	0.7	0.85	1.00	0.5	0.6	0.7	0.85	1.00
	1	0.94	0.95	0.97	0.93	0.87	0.99	0.99	1.00	0.93	0.87	1.06	1.04	1.01	0.94	0.87	1.15	1.08	1.02	0.94	0.87
	2	0.88	0.88	0.84	0.77	0.71	0.93	0.91	0.85	0.77	0.71	0.97	0.92	0.86	0.77	0.71	1.01	0.93	0.87	0.78	0.71
	3	0.84	0.79	0.74	0.67	0.61	0.87	0.81	0.75	0.67	0.61	0.90	0.82	0.76	0.68	0.61	0.91	0.83	0.76	0.68	0.61
	4	0.82	0.74	0.69	0.62	0.56	0.84	0.76	0.70	0.62	0.56	0.85	0.77	0.71	0.62	0.56	0.86	0.78	0.71	0.63	0.56
	5	0.78	0.70	0.65	0.58	0.52	0.79	0.72	0.65	0.58	0.52	0.80	0.73	0.66	0.58	0.52	0.81	0.73	0.67	0.59	0.52
	6	0.75	0.68	0.62	0.55	0.50	0.76	0.69	0.63	0.55	0.50	0.77	0.70	0.63	0.56	0.50	0.78	0.70	0.64	0.56	0.50
	8	0.71	0.64	0.58	0.51	0.46	0.72	0.64	0.58	0.52	0.46	0.72	0.65	0.59	0.52	0.46	0.73	0.66	0.59	0.52	0.46
	10	0.68	0.61	0.55	0.49	0.44	0.69	0.61	0.56	0.49	0.44	0.69	0.62	0.56	0.49	0.44	0.70	0.62	0.56	0.49	0.44

The conversion factor f_2 must be applied only together with conversion factor f_1.

Table 13-57



Conversion factor f_2, cables laid in ground
Single-core cables in three phase systems, trefoil formation (as per DIN VDE 0276-1000)

1	*2*	*3*					*4*					*5*					*6*				
Type	Number of systems	Specific thermal resistance of soil in K · m/W																			
		0.7					1.0					1.5					2.5				
XLPE cables 0.6/1 kV 6/10 kV 12/20 kV 18/30 kV		load factor					load factor					load factor					load factor				
		0.5	0.6	0.7	0.85	1.00	0.5	0.6	0.7	0.85	1.00	0.5	0.6	0.7	0.85	1.00	0.5	0.6	0.7	0.85	1.00
	1	1.09	1.04	0.99	0.93	0.87	1.11	1.05	1.00	0.93	0.87	1.13	1.07	1.01	0.94	0.87	1.17	1.09	1.03	0.94	0.87
	2	1.01	0.94	0.89	0.82	0.75	1.02	0.95	0.89	0.82	0.75	1.04	0.97	0.90	0.82	0.75	1.06	0.98	0.91	0.83	0.75
	3	0.94	0.87	0.81	0.74	0.67	0.95	0.88	0.82	0.74	0.67	0.97	0.89	0.82	0.74	0.67	0.99	0.90	0.83	0.74	0.67
	4	0.91	0.84	0.78	0.70	0.64	0.92	0.84	0.78	0.70	0.64	0.93	0.85	0.79	0.70	0.64	0.95	0.86	0.79	0.71	0.64
	5	0.88	0.80	0.74	0.67	0.60	0.89	0.81	0.75	0.67	0.60	0.90	0.82	0.75	0.67	0.60	0.91	0.83	0.76	0.67	0.60
	6	0.86	0.79	0.72	0.65	0.59	0.87	0.79	0.73	0.65	0.59	0.88	0.80	0.73	0.65	0.59	0.89	0.81	0.74	0.65	0.59
	8	0.83	0.76	0.70	0.62	0.56	0.84	0.76	0.70	0.62	0.56	0.85	0.77	0.70	0.62	0.56	0.86	0.78	0.71	0.62	0.56
	10	0.81	0.74	0.68	0.60	0.54	0.82	0.74	0.68	0.60	0.54	0.83	0.75	0.68	0.61	0.54	0.84	0.76	0.69	0.61	0.54
PVC cables 0.6/1 kV 3.6/6 kV 6/10 kV		load factor					load factor					load factor					load factor				
		0.5	0.6	0.7	0.85	1.00	0.5	0.6	0.7	0.85	1.00	0.5	0.6	0.7	0.85	1.00	0.5	0.6	0.7	0.85	1.00
	1	1.01	1.02	0.99	0.93	0.87	1.04	1.05	1.00	0.93	0.87	1.07	1.06	1.01	0.94	0.87	1.11	1.08	1.01	0.94	0.87
	2	0.97	0.95	0.89	0.82	0.75	1.00	0.96	0.90	0.82	0.75	1.03	0.97	0.91	0.82	0.75	1.06	0.98	0.92	0.83	0.75
	3	0.94	0.88	0.82	0.74	0.67	0.97	0.88	0.82	0.74	0.67	0.97	0.89	0.83	0.74	0.67	0.98	0.90	0.84	0.74	0.67
	4	0.91	0.84	0.78	0.70	0.64	0.92	0.85	0.79	0.70	0.64	0.93	0.86	0.79	0.70	0.64	0.95	0.87	0.80	0.71	0.64
	5	0.88	0.81	0.75	0.67	0.60	0.89	0.82	0.76	0.67	0.60	0.90	0.82	0.76	0.67	0.60	0.91	0.83	0.77	0.67	0.60
	6	0.86	0.79	0.73	0.65	0.59	0.87	0.80	0.74	0.65	0.59	0.88	0.81	0.74	0.65	0.59	0.89	0.81	0.75	0.65	0.59
	8	0.83	0.76	0.70	0.62	0.56	0.84	0.77	0.71	0.62	0.56	0.85	0.78	0.71	0.62	0.56	0.86	0.78	0.72	0.62	0.56
	10	0.82	0.75	0.69	0.60	0.54	0.82	0.75	0.69	0.60	0.54	0.83	0.76	0.69	0.61	0.54	0.84	0.76	0.70	0.61	0.54

The conversion factor f_2 must be applied only together with conversion factor f_1.

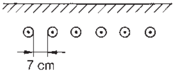
(continued)

Table 13-57 (continued)

1	2	3					4					5					6				
Type	Number of systems	Specific thermal resistance of soil in K · m/W																			
		0.7					1.0					1.5					2.5				
		load factor					load factor					load factor					load factor				
		0.5	0.6	0.7	0.85	1.00	0.5	0.6	0.7	0.85	1.00	0.5	0.6	0.7	0.85	1.00	0.5	0.6	0.7	0.85	1.00
Mass-impregnated cables 0.6/1 kV 3.6/6 kV 6/10 kV 12/10 kV 18/30 kV	1	0.94	0.95	0.97	0.93	0.87	0.99	0.99	1.00	0.93	0.87	1.06	1.04	1.01	0.94	0.87	1.15	1.08	1.02	0.94	0.87
	2	0.90	0.91	0.88	0.82	0.75	0.95	0.94	0.89	0.82	0.75	1.00	0.96	0.89	0.82	0.75	1.05	0.97	0.90	0.83	0.75
	3	0.87	0.86	0.80	0.74	0.67	0.91	0.87	0.81	0.74	0.67	0.95	0.88	0.81	0.74	0.67	0.97	0.89	0.82	0.74	0.67
	4	0.86	0.82	0.76	0.70	0.64	0.89	0.83	0.77	0.70	0.64	0.91	0.83	0.77	0.70	0.64	0.92	0.84	0.78	0.71	0.64
	5	0.84	0.79	0.73	0.67	0.60	0.86	0.79	0.73	0.67	0.60	0.87	0.80	0.73	0.67	0.60	0.89	0.81	0.74	0.67	0.60
	6	0.83	0.77	0.71	0.65	0.59	0.84	0.77	0.71	0.65	0.59	0.85	0.78	0.71	0.65	0.59	0.86	0.78	0.72	0.65	0.59
	8	0.80	0.73	0.67	0.62	0.56	0.81	0.74	0.68	0.62	0.56	0.82	0.74	0.68	0.62	0.56	0.83	0.75	0.68	0.62	0.56
	10	0.78	0.71	0.65	0.60	0.54	0.79	0.71	0.65	0.60	0.54	0.80	0.72	0.66	0.61	0.54	0.81	0.73	0.66	0.61	0.54

The conversion factor f_2 must be applied only together with conversion factor f_1.

Table 13-58



Conversion factor f_2, cables laid in ground
Single-core cables in three phase systems, flat formation (as per DIN VDE 0276-1000)

1	*2*	*3*					*4*					*5*					*6*				
Type	Number of systems	Specific thermal resistance of soil in K · m/W																			
		0.7					1.0					1.5					2.5				
XLPE cables 0.6/1 kV 6/10 kV 12/20 kV 18/30 kV		load factor					load factor					load factor					load factor				
		0.5	0.6	0.7	0.85	1.00	0.5	0.6	0.7	0.85	1.00	0.5	0.6	0.7	0.85	1.00	0.5	0.6	0.7	0.85	1.00
	1	1.08	1.05	0.99	0.91	0.85	1.13	1.07	1.00	0.92	0.85	1.18	1.09	1.01	0.92	0.85	1.19	1.11	1.03	0.93	0.85
	2	1.01	0.93	0.86	0.77	0.71	1.03	0.94	0.87	0.78	0.71	1.05	0.95	0.88	0.78	0.71	1.06	0.96	0.88	0.79	0.71
	3	0.92	0.84	0.77	0.69	0.62	0.93	0.85	0.77	0.69	0.62	0.95	0.86	0.78	0.69	0.62	0.96	0.86	0.79	0.69	0.62
	4	0.88	0.80	0.73	0.65	0.58	0.89	0.80	0.73	0.65	0.58	0.90	0.81	0.74	0.65	0.58	0.91	0.82	0.74	0.65	0.58
	5	0.84	0.76	0.69	0.61	0.55	0.85	0.77	0.70	0.61	0.55	0.87	0.78	0.70	0.62	0.55	0.87	0.78	0.71	0.62	0.55
	6	0.82	0.74	0.67	0.59	0.53	0.83	0.75	0.68	0.60	0.53	0.84	0.75	0.68	0.60	0.53	0.85	0.76	0.69	0.60	0.53
	8	0.79	0.71	0.64	0.57	0.51	0.80	0.71	0.65	0.57	0.51	0.81	0.72	0.65	0.57	0.51	0.81	0.72	0.65	0.57	0.51
	10	0.77	0.69	0.62	0.55	0.49	0.78	0.69	0.63	0.55	0.49	0.78	0.70	0.63	0.55	0.49	0.79	0.70	0.63	0.55	0.49
PVC cables 0.6/1 kV 3.6/6 kV 6/10 kV		load factor					load factor					load factor					load factor				
		0.5	0.6	0.7	0.85	1.00	0.5	0.6	0.7	0.85	1.00	0.5	0.6	0.7	0.85	1.00	0.5	0.6	0.7	0.85	1.00
	1	0.96	0.97	0.98	0.91	0.85	1.01	1.01	1.00	0.92	0.85	1.07	1.05	1.01	0.92	0.85	1.16	1.10	1.02	0.93	0.85
	2	0 92	0.89	0.86	0.77	0.71	0.96	0.94	0.87	0.78	0.71	1.00	0.95	0.88	0.78	0.71	1.05	0.97	0.89	0.79	0.71
	3	0.88	0.84	0.77	0.69	0.62	0.91	0.85	0.78	0.69	0.62	0.95	0.86	0.79	0.69	0.62	0.96	0.87	0.79	0.69	0.62
	4	0. 86	0.80	0.73	0.65	0.58	0.89	0.81	0.74	0.65	0.58	0.90	0.82	0.74	0.65	0.58	0.91	0.82	0.75	0.65	0.58
	5	0.84	0.76	0.70	0.61	0.55	0.85	0.77	0.70	0.61	0.55	0.87	0.78	0.71	0.62	0.55	0.87	0.79	0.71	0.62	0.55
	6	0.82	0.74	0.68	0.59	0.53	0.83	0.75	0.68	0.60	0.53	0.83	0.76	0.69	0.60	0.53	0.85	0.76	0.69	0.60	0.53
	8	0.79	0.71	0.65	0.57	0.51	0.80	0.72	0.65	0.57	0.51	0.81	0.72	0.65	0.57	0.51	0.81	0.73	0.66	0.57	0.51
	10	0.77	0.69	0.63	0.55	0.49	0.78	0.70	0.63	0.55	0.49	0.79	0.70	0.63	0.55	0.49	0.79	0.71	0.64	0.55	0.49

The conversion factor f_2 must be applied only together with conversion factor f_1.

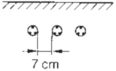
(continued)

Table 13-58 (continued)

1	2	3					4					5					6				
Type	Number of systems	Specific thermal resistance of soil in K · m/W 0.7					1.0					1.5					2.5				
		load factor					load factor					load factor					load factor				
		0.5	0.6	0.7	0.85	1.00	0.5	0.6	0.7	0.85	1.00	0.5	0.6	0.7	0.85	1.00	0.5	0.6	0.7	0.85	1.00
Mass-impregnated cables 0.6/1 kV 3.6/6 kV 6/10 kV 12/10 kV 18/30 kV	1	0.93	0.94	0.95	0.91	0.85	1.00	1.00	1.00	0.92	0.85	1.09	1.06	1.01	0.92	0.85	1.19	1.10	1.03	0.93	0.85
	2	0.89	0.89	0.86	0.77	0.71	0.95	0.93	0.87	0.78	0.71	1.01	0.95	0.88	0.78	0.71	1.05	0.97	0.89	0.79	0.71
	3	0.86	0.84	0.77	0.69	0.62	0.90	0.85	0.78	0.69	0.62	0.95	0.86	0.79	0.69	0.62	0.96	0.87	0.79	0.69	0.62
	4	0. 84	0.80	0.73	0.65	0.58	0.88	0.81	0.74	0.65	0.58	0.91	0.82	0.74	0.65	0.58	0.91	0.82	0.75	0.65	0.58
	5	0.82	0.77	0.70	0.61	0.55	0.86	0.77	0.70	0.61	0.55	0.87	0.78	0.71	0.62	0.55	0.87	0.79	0.71	0.62	0.55
	6	0.81	0.74	0.68	0.59	0.53	0.83	0.75	0.68	0.60	0.53	0.85	0.76	0.69	0.60	0.53	0.85	0.76	0.69	0.60	0.53
	8	0.78	0.71	0.65	0.57	0.51	0.80	0.72	0.65	0.57	0.51	0.81	0.73	0.66	0.57	0.51	0.82	0.73	0.66	0.57	0.51
	10	0.77	0.69	0.63	0.55	0.49	0.78	0.70	0.63	0.55	0.49	0.79	0.70	0.64	0.55	0.49	0.79	0.71	0.64	0.55	0.49

The conversion factor f_2 must be applied only together with conversion factor f_1.

Table 13-59



Conversion factor f_2, cables laid in ground
Three-core cables in three-phase systems (as per DIN VDE 0276-1000)

1	2	3					4					5					6				
Type	Number of systems	Specific thermal resistance of soil in K · m/W																			
		0.7					1.0					1.5					2.5				
VPE cables[1] 0.6/1 kV 6/10 kV PVC cables[1] 0.6/1 kV with $S_n \geq 35$ mm^2		load factor					load factor					load factor					load factor				
		0.5	0.6	0.7	0.85	1.00	0.5	0.6	0.7	0.85	1.00	0.5	0.6	0.7	0.85	1.00	0.5	0.6	0.7	0.85	1.00
	1	1.02	1.03	0.99	0.94	0.89	1.06	1.05	1.00	0.94	0.89	1.09	1.06	1.01	0.94	0.89	1.11	1.07	1.02	0.95	0.89
	2	0.95	0.89	0.84	0.77	0.72	0.98	0.91	0.85	0.78	0.72	0.99	0.92	0.86	0.78	0.72	1.01	0.94	0.87	0.79	0.72
	3	0.86	0.80	0.74	0.68	0.62	0.89	0.81	0.75	0.68	0.62	0.90	0.83	0.77	0.69	0.62	0.92	0.84	0.77	0.69	0.62
	4	0.82	0.75	0.69	0.63	0.57	0.84	0.76	0.70	0.63	0.57	0.85	0.78	0.71	0.63	0.57	0.86	0.78	0.72	0.64	0.57
	5	0.78	0.71	0.65	0.59	0.53	0.80	0.72	0.66	0.59	0.53	0.81	0.73	0.67	0.59	0.53	0.82	0.74	0.67	0.60	0.53
	6	0.75	0.68	0.63	0.56	0.51	0.77	0.69	0.63	0.56	0.51	0.78	0.70	0.64	0.57	0.51	0.79	0.71	0.65	0.57	0.51
	8	0.71	0.64	0.59	0.52	0.47	0.72	0.65	0.59	0.52	0.47	0.73	0.66	0.60	0.52	0.47	0.74	0.66	0.60	0.53	0.47
	10	0.68	0.61	0.56	0.49	0.44	0.69	0.62	0.56	0.50	0.44	0.70	0.63	0.57	0.50	0.44	0.71	0.63	0.57	0.50	0.44
PVC cables[1] 0.6/1 kV with $S_n < 35$ mm^2 3.6/6 kV		load factor					load factor					load factor					load factor				
		0.5	0.6	0.7	0.85	1.00	0.5	0.6	0.7	0.85	1.00	0.5	0.6	0.7	0.85	1.00	0.5	0.6	0.7	0.85	1.00
	1	0.91	0.92	0.94	0.94	0.89	0.98	0.99	1.00	0.94	0.89	1.04	1.03	1.01	0.94	0.89	1.13	1.07	1.02	0.95	0.89
	2	0.86	0.87	0.85	0.77	0.72	0.91	0.90	0.86	0.78	0.72	0.97	0.93	0.87	0.78	0.72	1.01	0.94	0.88	0.79	0.72
	3	0.82	0.80	0.75	0.68	0.62	0.86	0.82	0.76	0.68	0.62	0.91	0.84	0.77	0.69	0.62	0.92	0.84	0.78	0.69	0.62
	4	0.80	0.76	0.70	0.63	0.57	0.84	0.77	0.71	0.63	0.57	0.86	0.78	0.72	0.63	0.57	0.87	0.79	0.73	0.64	0.57
	5	0.78	0.72	0.66	0.59	0.53	0.81	0.73	0.67	0.59	0.53	0.81	0.74	0.68	0.59	0.53	0.82	0.75	0.68	0.60	0.53
	6	0.76	0.69	0.64	0.56	0.51	0.77	0.70	0.64	0.56	0.51	0.78	0.71	0.65	0.57	0.51	0.79	0.72	0.65	0.57	0.51
	8	0.72	0.65	0.59	0.52	0.47	0.73	0.66	0.60	0.52	0.47	0.74	0.67	0.61	0.52	0.47	0.75	0.67	0.61	0.53	0.47
	10	0.69	0.62	0.57	0.49	0.44	0.70	0.63	0.57	0.50	0.44	0.71	0.64	0.58	0.50	0.44	0.71	0.64	0.58	0.50	0.44

The conversion factor f_2 must be applied only together with conversion factor f_1.

(continued)

[1] In direct-current systems, these factors are also valid for single-core cables for 0.6/1 kV.

Table 13-59 (continued)

1	2	3					4					5					6				
Type	Number of systems	Specific thermal resistance of soil in K · m/W 0.7					1.0					1.5					2.5				
Mass-impregnated cables		load factor					load factor					load factor					load factor				
		0.5	0.6	0.7	0.85	1.00	0.5	0.6	0.7	0.85	1.00	0.5	0.6	0.7	0.85	1.00	0.5	0.6	0.7	0.85	1.00
Belted cables 0.6/1 kV 3.6/6 kv Single lead sheathed (SL) cables 3.6/6 kV 6/10 kV	1	0.94	0.95	0.97	0.94	0.89	1.00	1.00	1.00	0.94	0.89	1.06	1.05	1.01	0.94	0.89	1.13	1.07	1.02	0.95	0.89
	2	0.89	0.89	0.85	0.77	0.72	0.94	0.92	0.86	0.78	0.72	0.99	0.93	0.87	0.78	0.72	1.01	0.94	0.88	0.79	0.72
	3	0.84	0.81	0.76	0.68	0.62	0.89	0.83	0.77	0.68	0.62	0.91	0.84	0.78	0.69	0.62	0.92	0.85	0.79	0.69	0.62
	4	0.82	0.77	0.71	0.63	0.57	0.85	0.78	0.72	0.63	0.57	0.86	0.79	0.73	0.63	0.57	0.87	0.80	0.73	0.64	0.57
	5	0.80	0.73	0.67	0.59	0.53	0.81	0.74	0.68	0.59	0.53	0.82	0.75	0.69	0.59	0.53	0.83	0.76	0.69	0.60	0.53
	6	0.77	0.70	0.65	0.56	0.51	0.79	0.71	0.65	0.56	0.51	0.79	0.72	0.66	0.57	0.51	0.80	0.73	0.66	0.57	0.51
	8	0.73	0.66	0.61	0.52	0.47	0.74	0.67	0.61	0.52	0.47	0.75	0.68	0.62	0.52	0.47	0.75	0.68	0.62	0.53	0.47
	10	0.70	0.63	0.58	0.49	0.44	0.71	0.64	0.58	0.50	0.44	0.72	0.65	0.59	0.50	0.44	0.72	0.65	0.59	0.50	0.44
PVC cables 6/10 kV		load factor					load factor					load factor					load factor				
		0.5	0.6	0.7	0.85	1.00	0.5	0.6	0.7	0.85	1.00	0.5	0.6	0.7	0.85	1.00	0.5	0.6	0.7	0.85	1.00
Mass-impregnated cables Belted cables 6/10 kV H cables 6/10 kV 12/20 kV 18/30 kV Single lead sheathead (SL) cables 12/20 kV 18/30 kV	1	0.90	0.91	0.93	0.96	0.91	0.98	0.99	1.00	0.96	0.91	1.05	1.04	1.03	0.97	0.91	1.14	1.09	1.04	0.97	0.91
	2	0.85	0.85	0.85	0.81	0.76	0.93	0.92	0.89	0.82	0.76	0.98	0.95	0.90	0.82	0.76	1.03	0.96	0.90	0.82	0.76
	3	0.80	0.79	0.78	0.72	0.66	0.87	0.86	0.80	0.72	0.66	0.93	0.86	0.80	0. 73	0.66	0.95	0.87	0.81	0.73	0.66
	4	0.77	0.77	0.74	0.67	0.61	0.85	0.81	0.75	0.67	0.61	0.89	0.82	0.75	0.68	0.61	0.90	0.82	0.76	0.68	0.61
	5	0.75	0.75	0.70	0.63	0.57	0.84	0.77	0.71	0.63	0.57	0.85	0.77	0.71	0.63	0.57	0.86	0.78	0.72	0.64	0.57
	6	0.74	0.73	0.67	0.60	0.55	0.81	0.74	0.68	0.60	0.55	0.82	0.74	0.68	0.61	0.55	0.83	0.75	0.69	0.61	0.55
	8	0.73	0.69	0.63	0.56	0.51	0.77	0.70	0.64	0.56	0.51	0.77	0.70	0.64	0.57	0.51	0.78	0.71	0.64	0.57	0.51
	10	0.71	0.66	0.60	0.53	0.48	0.74	0.67	0.61	0.54	0.48	0.74	0.67	0.61	0.54	0.48	0.75	0.67	0.61	0.54	0.48

The conversion factor f_2 must be applied only together with conversion factor f_1.

13.3 Safe working equipment in switchgear installations

The following implements are required for safe working in indoor and outdoor switching stations:

- Earthing and short-circuiting devices to DIN VDE 0683 Part 1.
- Insertion plates (insulating guard plates) to DIN VDE 0681-8 (VDE 0681 Part 8).
- High-voltage detector to DIN VDE 0681-4 (VDE 0681 Tel 4).
- Fuse tongs for voltages from 1 to 30 kV to DIN VDE 0681-3 (VDE 0681 Part 3).
- Warning signs to DIN 40008 Part 2; they must conform to DIN VDE 0105-100 (VDE 0105 Part 100).

As per DIN EN 50 110-1 (VDE 0105 Part 1), the dead status allowing safe access to any part of the switching installation should be established and secured with the following measures (“5 Safety Rules”):

- Disconnecting
- Securing against reclosing
- Testing for absence of voltage
- Earthing and short-circuiting
- Covering or fencing off adjacent live parts

In general, the above sequence should be followed. Reasonable non-conformances can be specified in plant manuals. The following information applies to the measures:

Disconnecting

The equipment used for disconnecting must conform to the isolating distance requirements specified in DIN EN 60129 (VDE 0670 Tel 2). Such equipment can be in the form of

- disconnectors,
- switch disconnectors,
- fuse disconnectors,
- fuse-bases,
- draw-out switching devices whose isolating contact configurations meet the isolating distance requirements

The specifications for isolating distances are also met by equipment having air gaps of at least 1.2 times the minimum clearances in Table 1 of DIN VDE 0101, e.g. isolating links or wire loops.

A segregation may be used in place of an isolating distance.

Securing against reclosing

Warning or prohibition signs must be displayed to guard against reclosing. In addition, switchgear mechanisms must be blocked or tripping disabled.

Testing for absence of voltage

The voltage detector specified in DIN VDE 0681-4 (VDE 0681 Part 4) is used to detect non-hazardous absence of voltage in air-insulated switchgear installations.

The voltage testers (voltage detectors) to DIN VDE 0681-4 (VDE 0681 Part 4) show a clear indication “voltage present” when the line-to-earth voltage of the station component being tested has at least 40% of the nominal voltage of the voltage detector. To ensure that interference fields do not influence the indication, minimum lengths for the extension part are defined in the above standard.

The detectors fall into three categories:

Voltage detector “for indoors only”
For use indoors with lighting levels of up to 1000 lux.

Voltage detector “not for use in rain, snow, etc.”
Can be used indoors and outdoors, but not in rain, snow, etc.

Voltage detector “for use in rain, snow, etc.”
Can be used indoors and outdoors in all weathers.

The instructions of operating these devices must be strictly followed.

In gas-insulated switch disconnector panels, the test for absence of voltage can be conducted directly at the T-shaped plug-in end seals with voltage detectors.

As per VDE 0105 Part 1 Section 9, the test for absence of voltage of a switchbay can also be indicated with signal lamps if the change in the indication is visible during the disconnection process. The use of a make-proof earthing switch as an option for testing for absence of voltage should not be adopted as the general operational practice.

In gas-insulated switchgear and increasingly also with metal-clad air-insulated switchgear, the absence of voltage is tested with a capacitively coupled low-voltage display device. The coupling capacitors are continuously connected to the high-voltage conductor and are generally integrated into current transformers, resin insulators or bushings. The display devices may be permanently fixed to the installation or connected to the coupling capacitor with plug connectors. With appropriate subcapacitors, this forms a voltage divider connected to earth, to the tap of which the low-voltage display device – measuring against earth – is connected. Depending on the design of the display device, high-resistance, low-resistance and more recently medium-resistance systems are distinguished. VDE 0682 Part 415 (currently in draft form) is applicable to this type of testing for absence of voltage.

Earthing and short-circuiting

The earthed and short-circuited condition must be visible from the working position. The ground connection can be made either with an earthing switch incorporated in the switching bay, or with an earthing and short-circuiting device. An earthing truck is a possibility for metal-clad switchgear with draw-out switching devices.

Fig. 13-18 illustrates the earthing of a busbar with earthing truck and earthing cable in a metal-clad panel after the circuit-breaker has been withdrawn.

The lower isolating contact and the cable are earthed and shorted over the permanently installed earthing switch.

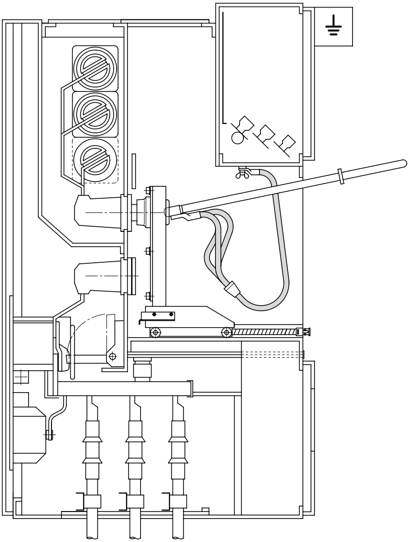


Fig. 13-18

Earthing the busbar system in a metal-clad panel of draw-out design, e.g. Type ZS1, with earthing truck and earthing cable.

In gas-insulated switchgear, the feeder circuits are preferably earthed over the circuit-breaker (in closed position) connected to an earthing switch, which does not have a short-circuit current-making capacity.

The cable can in addition be separately earthed with the cable plug in disconnected position by means of a portable earthing device.

Using the earthing device

Observing the 5 safety rules (DIN EN 50110-1 (VDE 0105 Part 1), the earthing cable (Fig. 13-19) is first screwed to the specially marked fixed earthing point. To be safe, the 3 phase conductors are then checked for voltage with the voltage detector. The individual phase conductors are then discharged by touching the feeder lines with the earthing cable. Finally, the earthing cable is placed on the earthing pin of the respective phase conductor, and firmly screwed in place.

The earthing device must be removed again in the reverse order before the earthed feeder is put back in operation.

Earthing devices fittings are also available for direct connecting to the disconnector bolts of switchgear installations with draw-out circuit-breakers.

The earthing and short-circuiting devices are designed to withstand one exposure to the maximum permissible short-circuit stress. Having been fully subjected to this stress, they must be discarded.

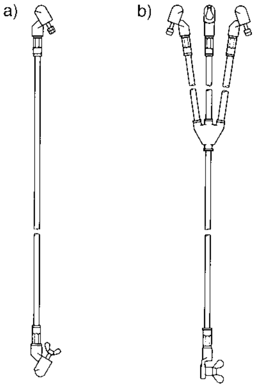


Fig. 13-19

Earthing devices to DIN 57683

a) Earthing and short-circuiting device for 20 and 25 mm dia. spherical fixed points, single-phase, cable cross-section 16 to 150 mm

b) Earthing and short-circuiting device for 20 and 25 mm dia. spherical fixed points, three-phase model, cable cross-section 16 to 150 mm

Covering or fencing off adjacent live parts

Work may be carried out in the vicinity of live parts only if precautions against direct contact (DIN EN 50110-1 (VDE 0105 Part 1) have been taken in the form of

- protection by cover or barrier, or
- protection by distance.

Before working on an outgoing feeder with fixed apparatus, a plate is inserted in the open busbar disconnector. This guards against contact with live parts on the busbar side. Provided the cable side is dead (beware of dangerous reverse voltages), work can proceed on the feeder apparatus after attaching the earthing device. Special care is called for in the case of transformers connected in parallel on the low-voltage side.

14 Protection and Control in Substations and Power Networks

14.1 Introduction

Contained under the heading of protection and control in substations and power networks are all the technical aids and facilities necessary for the optimum supervision, protection, control and management of all system components and equipment in high- and medium-voltage networks. The task of the control system begins with the position message at the HV circuit-breaker and ends in complex control systems and substations for network and load management.

Fig. 14-1 gives an indication of the functions and subsystems that go to make up control technology in the context of electricity transmission and distribution.

The purpose of the secondary systems is to gather information directly at the high- and medium-voltage apparatus in the substations and to effect their on-site operation, including the maintenance of secure power supplies. Additional contacts or integral sensors establish the interface with the telecontrol system and hence with the network control facility.

Modern automation techniques can provide all the means necessary for processing and compressing information at the actual switchgear locations in order to simplify and secure normal routine operation, make more efficient use of existing equipment and quickly localize and disconnect faults in the event of trouble, thereby also relieving the burden on the communication paths and the network control centres.

Protective devices are required to safeguard the expensive equipment and transmission lines against overloads and damage by very quickly and selectively isolating defective parts of the supply network, e.g. in the event of short circuit or earth faults. They are thus a major factor in ensuring consistent operation of the network.

The purpose of network management as a subdivision of power system control is to secure the transmission and distribution of power in ever more complex supply networks by providing each control centre with a continually up-to-date and user-friendly general picture of the entire network. All essential information is sent via telecontrol links from the substations to the control centre, where it is instantly evaluated and corrective actions are taken. The growing flood of information has meant that the conventional control rooms with mimic displays as used in the past for controlling the processes directly have been virtually superseded by management systems with computers and video terminals, and are employed only to depict the network's geographical layout or for emergencies.

Load management consists in directly influencing the system load, possibly with the aid of ripple control which, acting via the normal power network, can selectively disconnect and re-connect consumers or consumer categories. On the basis of current figures and forecasts, it is possible to even out the generating plant's load curves and make better use of available power reserves.

It would be beyond the scope of this book to consider in detail all the subsystems and components relating to network control. This chapter can therefore serve only as an introduction to the complex tasks, fundamentals, problems and solutions encountered in power network control and its systems. Closer attention is paid, however, to all components and interfaces which directly concern the switching installation and the switchgear engineer, and which must be considered in the planning, erection and operation of substations.

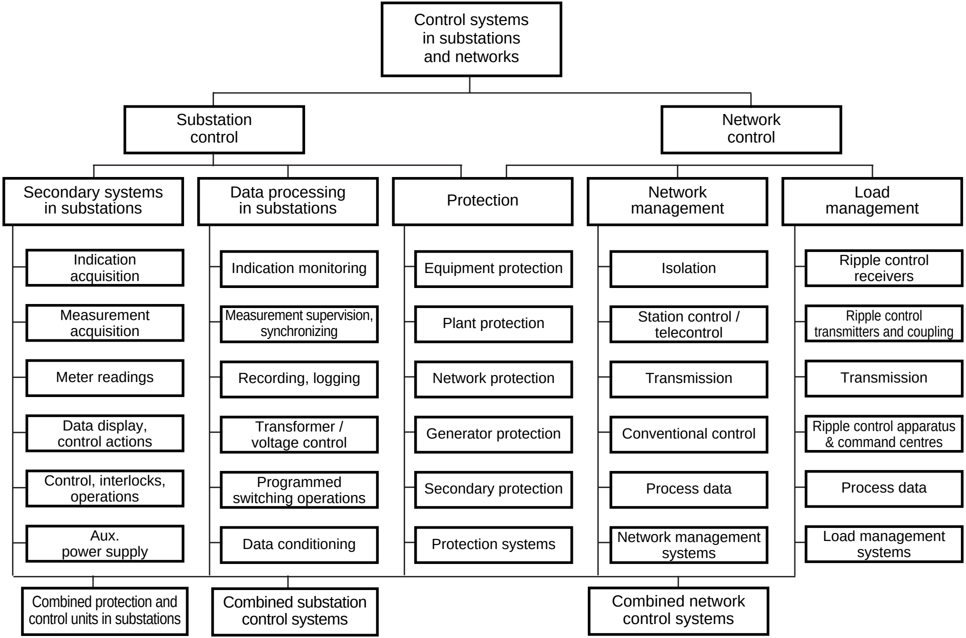


Fig. 41-1

Functions and subsystems of controls in substations and networks

14.2 Protection

Various protection devices – in systems with rated voltages > 1kV – are available to protect generators, transformers, cables, busbars and consumers. The purpose of these devices is to detect faults and isolate them selectively and quickly from the network as a whole so that the consequences of the fault are limited as much as possible. With today's high fault levels and highly integrated networks, faults have far-reaching consequences, both direct (damaged equipment) and indirect (loss of production). Protection relays must therefore act very fast with the greatest possible reliability and availability.

Relays can be divided into various categories.

A basic distinction is made with respect to function between contactor relays and measuring relays.

Other distinguishing characteristics are
- the relay's construction
  (e.g. circuit-board relays, reed relays, miniature relays, mercury-wetted relays);
- the relay's operating principle
  (e.g. attracted-armature relays, immersed-armature relays, moving-coil relays);
- the relay's location
  (e.g. telephone relays, antenna relays, generator protection relays, network protection relays);
- the relay's specific function
  (e.g. signalling relays, time-delay relays, control relays, momentary-contact relays, auxiliary relays);
- the relay's required performance
  (e.g. heavy-current relays, high/low temperature relays, d.c. relays).

The relays used for protection purposes, together with supervisory relays, fall into the category of measuring relays, and as electronic relays become more widespread, of solid-state measuring relays. All the types of relays mentioned are used to transmit clearly defined, fast and carefully isolated indication and control signals from low-energy electronic circuits to external circuits.

14.2.1 Protection relays and protection systems

Today's standard protection relays and protection systems are in some cases still preferably static but are designed to be numerically controlled (with microprocessors). Electromechanical relays are practically never specified in new systems. They have to meet the following international specifications:

– IEC 60 255

– DIN VDE 0435-303 Electrical Relays – Static Measuring Relays (SMR)

– and the new VDE standards DIN EN 60255 – ... derived from IEC in all parts

Please also observe the
– VDEW – "Directives for static protective equipment".

Overcurrent relays/time-overcurrent relays

Currents above an adjustable threshold value are detected in one or more phases, and interrupted after a presettable time. The release time is the same, no matter how much the threshold has been exceeded by.

(*D*efinite *T*ime *L*ag *R*elay = DTL relay)

The preference in English-speaking countries is for Inverse Definite Minimum Time Lag (IDMT) relays which respond faster to heavier currents.

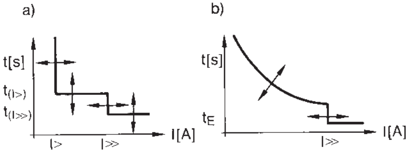


Fig. 14-2

Characteristics of overcurrent relays

a) *DTL relays, two-stage*
b) *IDMT relays with high-current stage*
I > *Overcurrent stage*
1 ≫ *High-current stage*
t_E *Opening time*

Overcurrent relays are used in radial networks with single infeed.

The relays are connected via a current transformer (secondary relay).

With a direction-sensing element that measures current and voltage, the relay can be made to provide directional time-overcurrent protection. They are preferably implemented with parallel lines and on the transformer undervoltage side with parallel transformer operation.

Overload relays

The temperature conditions at the protected object are simulated with the same time constant in the relays. Any load bias is taken into account by the thermal replica in the relay in accordance with the heating and cooling curves. Alarm signals or tripping commands are given if a set temperature is exceeded. The relays are built as primary or secondary relays. Secondary relays usually operate in two or more stages. Overload relays are used on machines that can overheat, such as transformers and motors, but occasionally on cables, too.

Differential relays

The currents measured at the beginning and end of the protected object are matched in phase angle and magnitude and compared in a measuring element. If a set ratio of difference current to through current is exceeded, the relay emits a tripping command.

Modern relays contain all the components needed for differential protection:
- matching transformers,
- signalling devices,
- tripping devices,
- inrush stabilization.

Differential relays are available for transformers or generators.

Differential relays for lines have a measuring element (relay) at each end. The relays must be linked to transmit protection data. Fibre-optic cables or pilot wires are available as connections. The connection must be monitored to ensure proper functioning of the protection system.

Comparative protection

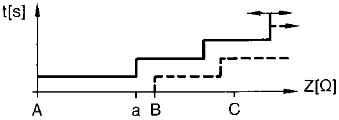
The variables measured at beginning and end of the protected item are checked to see if they are coincident (phase comparison) or of the same kind (signal comparison). These protection devices require only a few communication channels and are unaffected by interference.

Distance relays

The distance of a fault from the relay is assigned to a tripping range by measuring the impedance with reference to the fault current and voltage. In accordance with an adjustable distance/time characteristic set on the relay, the relay trips the appropriate circuit-breaker or serves as back-up protection. Distance relays operate selectively and extremely quickly in meshed networks with multiple infeed, and need no auxiliary link.

Fig. 14-3

Characteristic of a distance relay
A, B, C Stations
Station A location of relay
a = approx. 85 – 90 % of distance A–B



Auto-reclose relays

In networks with overhead lines, the auto-reclose relay interrupts 1 or 3 phases of the power feed to the faults detected by the time-overcurrent relay or distance relay and then reconnects it after an adjustable interval of about 300 ms. The arc across the fault is able to de-ionize during this time, and operation can resume without interruption. If the autoreclosure is not successful, the result will be a 3-phase definite trip.

Busbar protection

The quantities from a number of measuring points which respond in different ways to faults on the branch lines or in the busbar system are evaluated in a measuring circuit. Owing to the difficulty of obtaining measurements (transformer saturation) and the high speed needed to limit damage in the case of high short-circuit powers, electronic protection systems are used. (Measuring time approx. 2 ms, system command time approx. 10–20 ms). In static busbar protection, a breaker backup protection is frequently installed as backup protection. Additional functions are integrated into numeric busbar protection, such as overcurrent, undervoltage protection, (circuit-breaker) synchronization monitoring and, as an advantage of numeric technology, event lists, fault records, comprehensive hardware and software monitoring, test procedures (manual or automatic) etc.

Directional earth-fault relays

An indication of direction is obtained from the relative vectorial position of neutral current and neutral voltage. The side of the fault is identified by comparing the values measured in the network. Other methods of measurement are possible.

Frequency relays

If the frequency goes above or below set limits or fluctuates at an unacceptable rate (df/dt), this is detected, resulting in disconnection or load rejection.

Voltage relays

Voltage deviations are indicated, allowing the system load to be reduced as necessary.

Other protective devices used specifically with certain system components include interturn-fault relays, negative sequence relays, reverse-power relays for generators, Buchholz relays, temperature monitors, oil level indicators, oil and air flow indicators for transformers, and insulation monitoring for conductors.

14.2.2 Advantages of numeric relays

Static protection relays with discrete components have now been joined by digital relays equipped with microprocessors (µP). Digital devices of the same kind can perform control functions as well as protection duties. Users are coming to insist on their use.

Features of these relays include:

– Analogue variables are digitalized in the relay’s input circuit and calculated in the processor.

– The entered settings act on the relay’s built-in program.

– Several protective functions can be combined and executed in a single unit. All newly developed numeric protection relays are multifunction relays.

– The relays incorporate constant self-monitorlng and diagnosis.

– They can be controlled from a personal computer (PC) with menu guidance in a variety of languages.

– Logic functions allow links to external signals by way of optocoupler inputs.

– Memories for recording events and disturbances enable faults to be analysed afterwards in detail from the stored data.

Serial interfaces make them easy to integrate into control and instrumentation systems.

14.2.3 Protection of substations, lines and transformers

The basic scheme for protecting switchgear installations, lines and transformers is shown in Fig. 14-4.

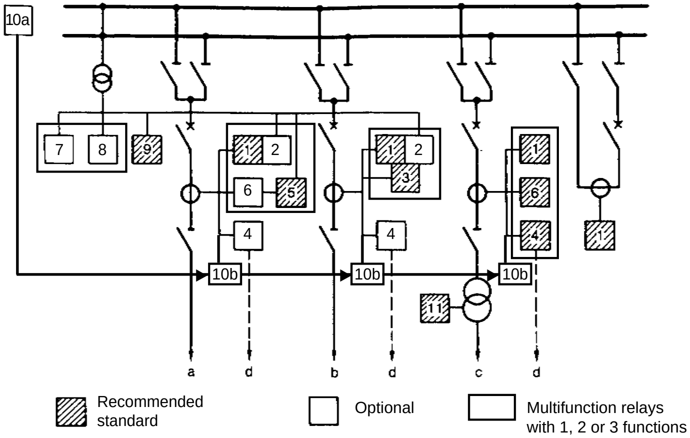


Fig. 14-4

Basic scheme of protection system for switchgear, lines and transformers:
a) Cable, b) Overhead line, c) Transformer, d) Auxiliary line
1 Overcurrent time protection, 2 Distance protection, 3 Autoreclose function, 4 Differential protection, 5 Directional ground-fault protection, 6 Overload protection, 7 Frequency monitoring, 8 Voltage monitoring, 9 Ground-fault indicator monitoring, 10 Busbar protection, 10a Central processor, 10b Bay unit, 11 Buchholz protection, temperature monitoring

14.2.4 Generator unit protection

The term generator unit protection is used when the means of protecting the generator, the main transformer and the station services transformer are combined with those for protecting the generator circuit-breaker or load disconnector.

Numerical relays are used almost exclusively with modern generator unit protection. Important factors influencing the form of the protection system within the overall electrical design concept include:

- whether the generator is switched by a circuit-breaker or a load switch,
- whether the station services transformer has two or three windings,
- the number of station services transformers,
- the method of excitation (solid-state thyristors or rotating rectifiers).

The general layout is drawn up accordingly for each individual project. As an example, Fig. 14-5 shows the single-line diagram for a unit-type arrangement with generator circuit-breaker in a large thermal power plant.

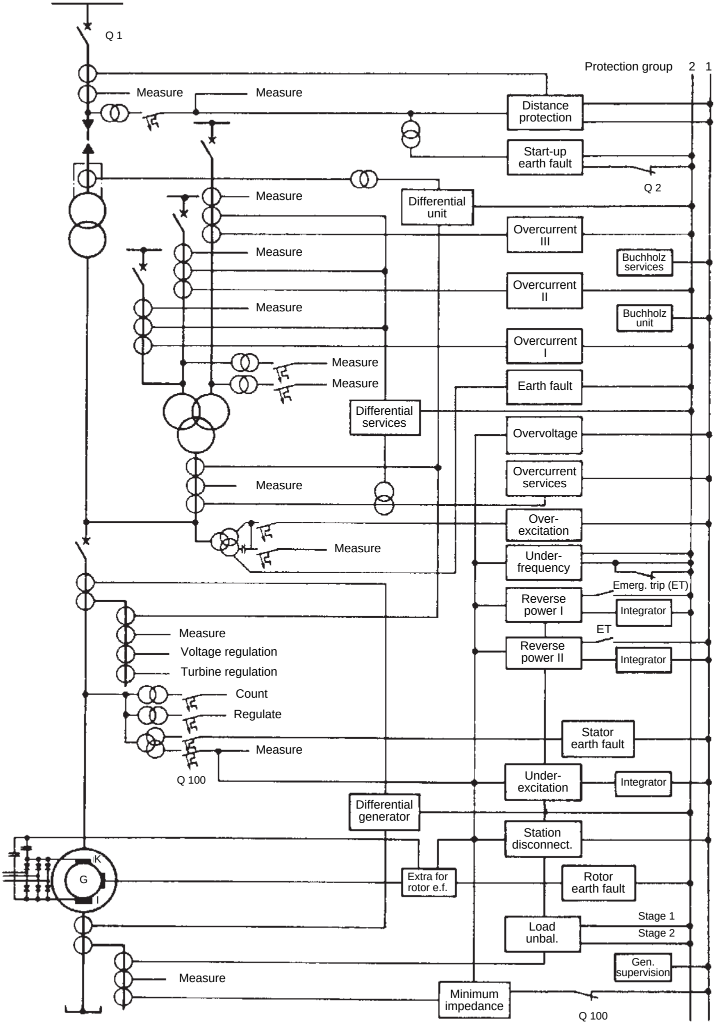


Fig. 14-5

Single-line diagram of generator unit protection system, unit connection wlth generator circuit-breaker

A function diagram shows how the individual protective devices are linked to the operating circuits. The protection device OFF commands are configured on the switching devices (for example, generator circuit-breaker, magnetic field switch, etc.) and switching systems (for example, automatic internal transfer gear) with a software matrix (component of the relays) or, in the case of larger systems, with a tripping matrix (diode matrix).The tripping schedule can then easily be modified later.

To maximize availability, the protection facilities are split into two separate and largely independent groups and installed in different cubicles. Protection systems that complement or at times may step in for each other can be assigned to both groups.

14.3 Control, measurement and regulation (secondary systems)

Secondary systems are all those facilities needed to ensure reliable operation of the primary system, e.g. a high-voltage substation. They cover the functions of controlling, interlocking, signalling and monitoring, measuring, counting, recording and protecting (see also Fig. 14-6). The power for these auxiliary functions is taken from batteries so that they continue in the event of network faults. Whereas in the past conventional techniques were used for decentralized control, e.g. from a local panel, this can now be done using substation control techniques such as ABB's PYRAMID system. Today, overall network management is undertaken by computer-assisted systems based at regional or supraregional control centres and load-dispatching stations. The interface that this necessitates, however, is moving ever closer to the process, i.e. to the primary system. How near this interface can be brought to the process depends, for example, on how practical and reliable it is to convert from electromechanical methods to electronic techniques, or whether the information to be transmitted can be provided by the process in a form which can be directly processed by the electronics.

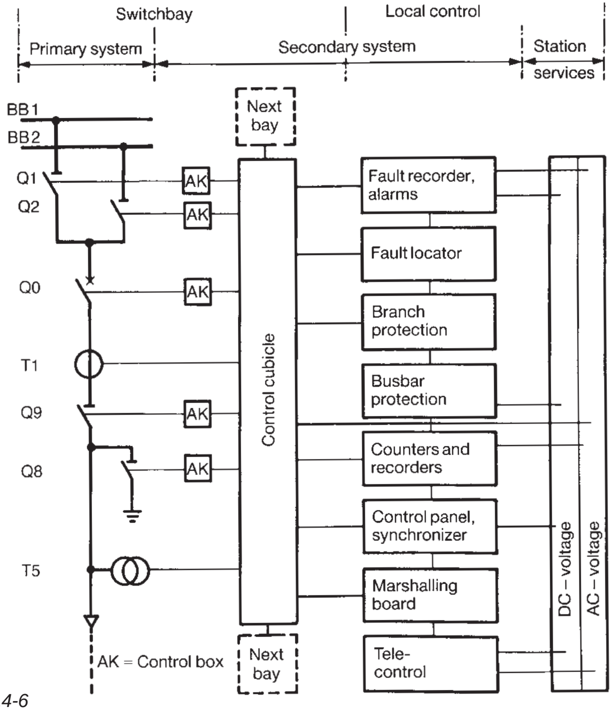


Fig. 14-6
AK = Control box
The functions of secondary systems in high-voltage switchgear installations, for coding of apparatus in primary systems see Tables 6-12 and 6-13

14.3.1 D.C. voltage supply

It is essential that the components of the secondary systems have a secure DC power supply. For HV and EHV installations, this means that the DC power supply must include redundancy (see also Fig. 14-7) so as not to be rendered inoperative by a single fault. Indeed it is advisable to provide two separate infeeds for the low-voltage three-phase network. If these infeeds are not very dependable, a diesel generator should also be provided for emergencies. The three-phase loads are connected as symmetrically as possible to the two three-phase busbars thus formed; the battery rectifiers are also connected here, one to each busbar.

If the battery equipment is suitable, the DC output from the rectifier and also the battery can be connected independently to the DC busbars, so giving greater flexibility. It is best to use 220 V and 110 V for direct control, with 60 V, 48 V and 24 V for remote control and signal circuits. With the aid of inverters, a secure AC busbar can then be created from the DC busbar if necessary.

The DC network must be carefully planned. The auxiliary circuits must be assigned to each function and branch so that only one function or one bay is affected by a fault. Faults in the signal circuit, for example, do not then influence the control circuit, and vice versa.

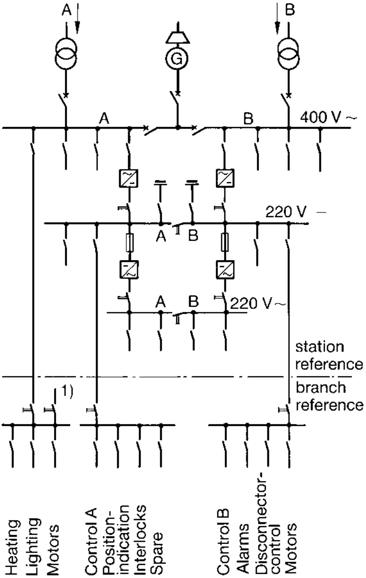


Fig. 14-7

Single-line diagram of station services power supply, A and B Independent infeeds or bus sections, 1) Connection to adjacent bay

14.3.2 Interlocking

To ensure reliable control, the high voltage switching devices within each bay, and at a higher level within the entire installation, are interlocked with respect to each other. The interlock conditions depend on the circuit configuration and status of the installation at any given time. The interlocks must in particular prevent an isolator from operating while under load. The interlock conditions must be defined according to the station layout, such as in the following example for a double busbar with branch, coupling and bus earthing switch, see Fig. 14-8.

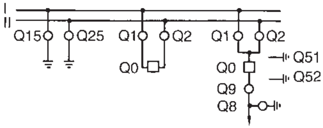


Fig. 14-8

Mimic diagram of a double busbar substation with branch, coupling and bus earthing switch

The following conditions must be satisfied in this case:

1. Disconnectors Q1, Q2 and Q9 can be operated only when breaker Q0 is open (protection against switching under load).
2. Breaker Q0 cannot be closed with disconnectors Q1, Q2 and Q9 in the intermediate position (intermediate position indication).
3. Disconnectors Q1 and Q2 are mutually interlocked so that only one can be closed at a time.
4. When the bus-tie is closed, a second bus disconnector (Q1 or Q2) belonging to the tied system can be closed. One of the two closed disconnectors can then be opened (change of bus under load).
5. Disconnectors Q1 and Q2 can be operated only if the related bus earthing switch Q15 or Q25 is open.
6. Disconnector Q9 can be operated only when earthing switch Q8 is open (taking account of other end if necessary).
7. Earthing switch Q8 can be operated only when disconnector Q9 is open (taking account of other end of outgoing line if necessary).
8. Disconnectors Q1, Q2 and Q9 can be operated only when maintenance earthing switches Q51/Q52 are open.
9. Maintenance earthing switches Q51/Q52 can be operated only when disconnectors Q1, Q2 and Q9 are open.
10. The tie-breaker Q0 can be opened only if not more than one bus isolator in each branch is closed (tie-breaker lock-in).
11. One bus earthing switch Q15 or Q25 can be operated if in the respective bus section all bus disconnectors of the corresponding bus system are open.
12. All interlocks remain active if the auxiliary power fails.
13. An interlock release switch cancels the interlock conditions. Switching operations are then the responsibility of the person authorized.

14.3.3 Control

The purpose of a control device in a switchgear installation is to change a defined actual condition into a specified desired condition.

The operating sequences of controlling, interlocking and signalling can be performed either by simple contact-type electromechanical and electromagnetic devices such as discrepancy switches, auxiliary contactors and auxiliary relays or by contact-less electronic components. Both methods allow single switching operations and programmed switching sequences up to fully automated switching routines.

With conventional control techniques, there are limits to the scope for automation. These methods are becoming less popular because of the space required, the equipment's high power consumption, wear due to constant operation, and the fixed wiring. Today they are used mainly for local control within the switching installation.

Here, the devices can be divided into those relating to:

- switching apparatus,
- branch and
- station.

The apparatus-related devices are contained in a box on the circuit-breaker or isolator. The branch-related devices are usually in a control cubicle or local relay kiosk. Station-related devices are located in central relay kiosks or in the station control building.

Because of the increasing reliability of electronic components, and also the question of interference, the tendency is for contact-type systems to be employed only for apparatus-related devices, and electronic components to be used very extensively for branch-related and station-related devices.

When drawing up the control system concept, it must be considered whether the substation is to be largely manned or unmanned, or remotely monitored and controlled. The kinds of control system can be broadly defined as follows.

Local control

Here, the controls are close to the switchgear. They are used mainly during commissioning and maintenance, often for emergencies as well. They are located on the apparatus itself or in a branch cubicle, and work independently of higher-level control systems.

Direct control

In this case, the switchgear is controlled locally from the on-site control point, where each piece of apparatus has its own control switch, etc. It may utilize the switchgear’s control voltage or light-duty relays. Control from the station panel always includes indication of the switchgear’s respective operating positions.

Selective control

This method is used both for on-site control and in central control rooms. It is arranged in a number of levels, so that from an operator’s position one can, for instance, pick first the station, then the branch and finally the item of switchgear before initiating the actual switching operation with the "execute" button.

Both station-level and central control systems nowadays have two mutually interlocked operator positions for this purpose. Each consists of a control panel and a VDU. The interlock prevents commands being sent simultaneously from both positions to a station or branch. Certain control sequences can be pre-programmed where necessary. Light current is used for the control circuits. Feedback signals and switchgear settings are shown on the monitor. A mosaic-type display panel is sometimes provided in addition to the video screen.

Remote control

In this case, the substation is controlled from regional and central control centres, predominantly via telecontrol lines. The general trend is increasingly away from local control to remote control, so the latter warrants particular attention. For details on telecontrol, see Sections 14.5.4 and 14.5.6.

Control functions include a wide variety of different applications; representative examples are the monitoring of tripping circuits, Fig. 14-9, and the duplication of tripping circuits, Fig. 14-10.

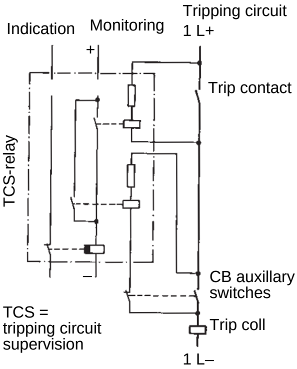


Fig. 14-9

Tripping circuit supervision for a circuit-breaker in closed and open position

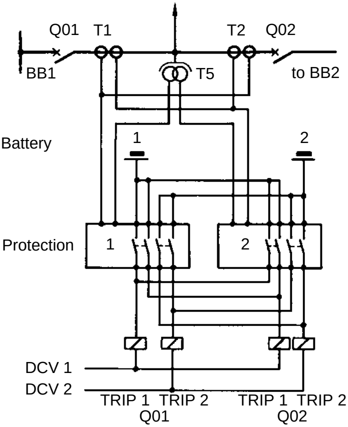


Fig. 14-10

Duplication of tripping circuits with 1½- and 2-breaker arrangement

14.3.4 Indication

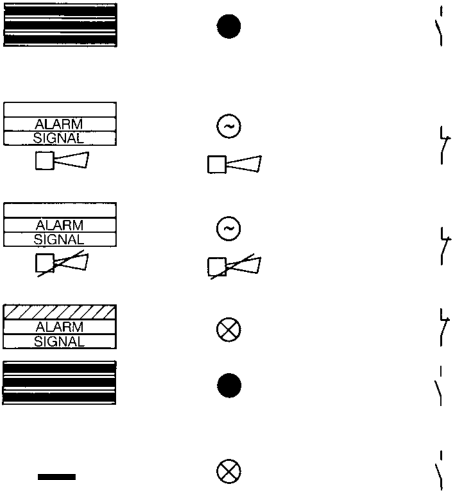
Operating personnel must be informed of faults, circuit conditions and the settings of switchgear.

Switchgear contact settings are indicated by means of position transmitters, light-emitting diodes or on a screen. The signal must not be sent until the apparatus has reached or is certain to reach its final CLOSED or OPEN position; otherwise an intermediate position must be indicated.

Incoming fault and status signals are indicated by optical and acoustic means, and often recorded, see Section 14.3.8 Recording and logging. The signals are gathered or passed on by signalling relays with floating auxiliary contacts. The relays can be electromechanical or electronic. Table 14-3 shows the standard signal sequence of drop indicator relays and light indicators.

Table 14-1

Standard signal sequence for drop indicators and light indicators



Signal sequence	Drop indicator	Light indicator	Alarm contact
Initial status	▤	●	
Alarm contact closes	ALARM SIGNAL 📢	(~) 📢	
Acoustic signal reset	ALARM SIGNAL 🔇	(~) 🔇	
Optical signal reset a) Alarm condition persists b) Alarm condition cleared	▨ ALARM SIGNAL ▤	⊗ ●	
Lamp test	▬	⊗	

Lamp	is out	●	Acoustic signal	
	is on	⊗	on	📢
	flashes	(~)	off	🔇

14.3.5 Measurement

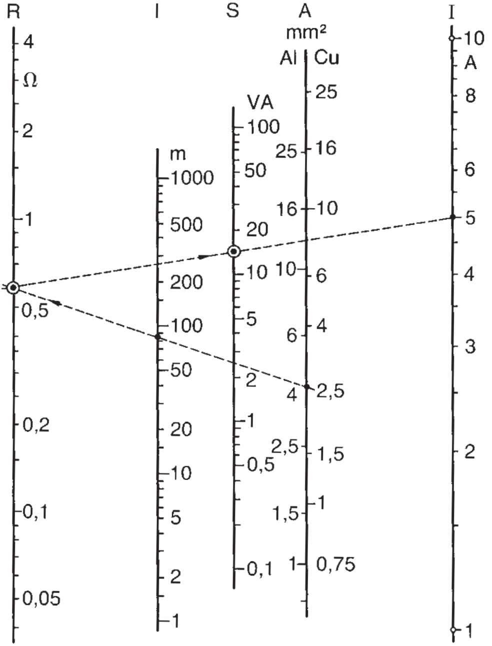
Operating a substation involves measuring, recording and evaluating a number of quantities such as currents, voltages, powers, etc. To do this, the primary system requires current and voltage transformers, which can be incorporated in the busbars or branches. What instrument transformers are necessary will depend on operating requirements, see Sections 10.5.2 to 10.5.5 on transformer selection.

Voltage transformers are useful in the branches for measurement and protection. Voltage transformers on the busbar as well are convenient for synchronizing and measurement purposes; there is then no need for simulation.

The secondary sides of current and voltage transformers must be earthed so as to avoid any risk to equipment and personnel from unacceptably high voltages.

Current transformers must not be operated with open secondary windings as the high voltages occurring at the secondary terminals are dangerous and may damage the transformer.

Current transformer circuits must be earthed at only one point. In high-voltage installations, this should be the branch control cubicle wherever possible. The standards applicable at the particular location must be observed. One must make sure that the transformer power rating is at least equal to the power consumption of the measuring devices, including the connecting lines. The dimensions of these can be determined with the aid of Fig. 14-11.



Example:

A = 2.5 mm^2,l_r = 85 m:
then R ≈ 0.6 Ω
I = 5 A, R ≈ 0.6 Ω:
then S ≈ 15 VA

Fig. 14-11

Current transformer secondary lines; To determine resistance and power consumption, R = line resistance Ω, l_r = resultant line length m, S = power VA, A = line cross section mm^2 for Cu and Al, I = sec. transformer current A

The readings of the measurements are displayed in the control cubicles, in the on-site control room and /or at the command centre. Attention must be paid to the positioning of the instruments. With modern control systems, the readings are shown on the screen in the central control room.

The shapes, sizes and coding of switchboard instruments are summarized in Fig.14-12. See DIN 43700 and 43701 for detailed information on standardized designs and dimensions of control panel instrumentation and measurement ranges.

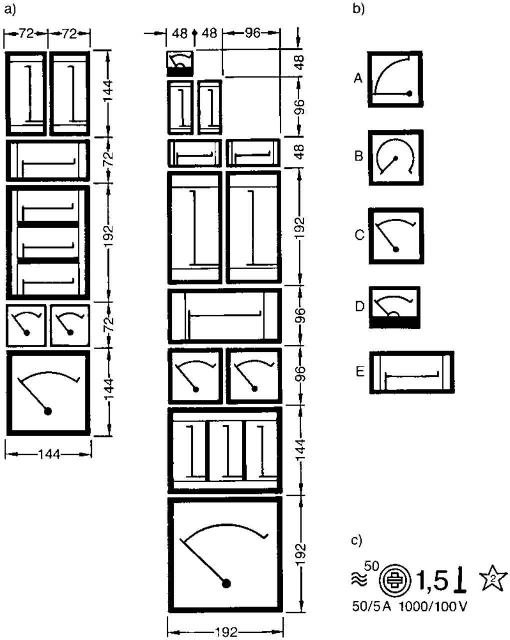


Fig. 14-12

a) Shapes, sizes, b) Scales and c) Coding of switchboard instruments (dimensions in mm):

A Quadrant scale, B Circular scale, C Sector scale, D Sector scale for tubular instruments, E Linear scale; Example of coding: c) Instrument for 3-ph. 50 Hz with 2 iron-cored el.-dyn. elements Cl. 1.5; vert. posn.; test voltage 2 kV, transf. connection: prim. current 50 A, sec. current 5 A, prim. volt. 1000 V, sec. volt. 100 V

Measuring elements and their principal applications

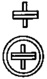
Electrical measuring instruments have a class coding. The classes are: 0.1; 0.2; 0.5; 1; 1.5; 2.5 and 5. These denote the measurement or reading error in percent, both positive and negative. They always relate to the top of the measuring range. Instruments of classes 0.1 to 0.5 are precision instruments, those above are industrial instruments.

The choice of measuring elements for the instruments is summarized in Table 14-2.

DIN EN 61010-1 (VDE 0411 Part 1), DIN EN 61010-1/A2 (VDE 0411 Part 1/A1) and DIN EN 60051; plus DIN 43781 (for recorders) are applicable for electrical instrumentation and recorders. These standards contain the most important definitions, classifications, safety and test requirements and forms of identification.

Table 14-2

Measuring elements for measuring instruments

Element	Symbol	Operating principle	Input	Application and characteristics
Moving-iron element		Two iron cores in a ring coil are magnetized with the same polarity and repel each other.	*I* –, *U* – *I* ~, *U* ~	For DC and AC currents and voltages. Greater overload capacity than other measuring elements. Much higher consumption than moving-coil elements. Scale almost linear, but can be extensively influenced. Robust.
Moving-coil element		Coils able to rotate in the homogeneous field of a permanent magnet; variants with magnet outside or as core magnet element with permanent magnet inside the coil.	*I* –, *U* – Thermocouple, Resistance thermometer, *I* ~, *U* ~ Active power, Reactive power, Power factor	Chiefly a DC instrument. Together with rectifiers also suitable for AC; with adapters also for power measurement. Greater accuracy than all other electrical measuring elements. Low consumption. Scale almost linear. Moving-coil galvanometers are highly sensitive.[1]
Moving-iron ratiometer (cross-coil element)				
Electro-dynamic element		A voltage coil is able to rotate in the homogeneous magnetic field of a fixed current winding.	Active power, Reactive power, Power factor	For power measurement with AC and DC, as quotient meter also for measuring power factor. Scale almost linear. Largely independent of frequency and curve shape. Core-less types for precision instruments, iron-cored types for industrial instruments and recorders.
Electronic element		Two electrodes in an electrostatic field move relative to each other owing to potential differences.	*U* – *U* ~	For DC and AC voltages, also high-frequency voltage.
Vibrating-reed element (reed-type frequency meter)		A row of steel reeds is induced to vibrate in the force field of an electromagnet.	Frequency	For frequencies from 7 – 1500 Hz. High, consistent measuring accuracy. Robust.
Bimetal element		A bimetal spiral indicates the mean value of prolonged loads.	*I* ~	For monitoring thermal loading of transformers and power cables. With resettable slave pointer. Scales calibrated in percent or amps. Compensated for changes in room temperature.

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[1] Sensitivity and accuracy must not be confused. If an indicating instrument is required to be sensitive, this means it has to respond to small changes in the measuring variable with large scale deflections, but it does not have to be accurate.

Measuring transducers

Transducers in the field of power engineering convert input variables such as current, voltage, power and system frequency into analogue electrical output quantities, usually in the form of impressed direct current but sometimes also impressed d.c. voltage. These output quantities are then particularly suitable for subsequent measured-value processing and transmission systems.

The most important parameters, device properties, designations and tests of transducers for quantities in electrical engineering can be found in the VDE 0411 Part 1 and VDE 0411 Part 1/A1 standards mentioned above in the “Instrumentation” section. The DIN EN 50178 (VDE 0160) and the VDE/VDI Directive 2192 must also be observed.

Fig. 14-13 shows various measuring arrangements. The transducers can be single or multiple. Table 14-3 shows an overview of the typical consumption values of the most important instrumentation.

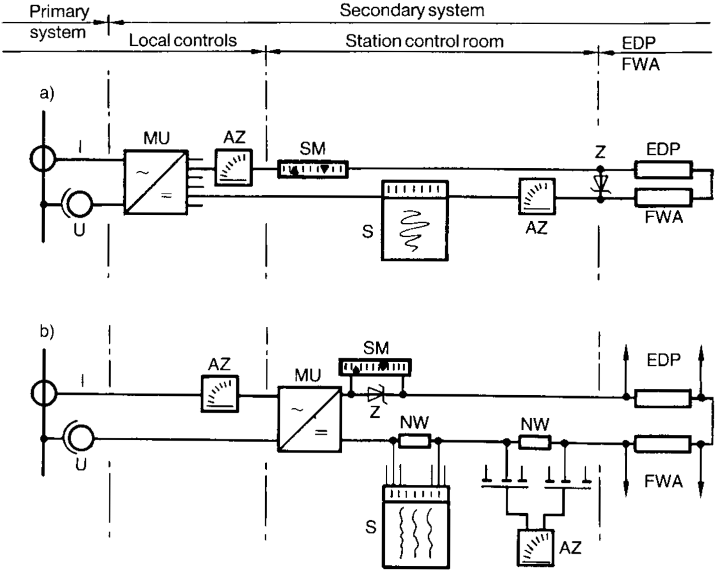


Fig. 14-13

Common measuring circuits with transducers:

a) Connection to indicating and recording instruments in the transducer output circuit for indoor stations, b) Connection to selectable instruments via shunt resistors in the transducer output circuit for outdoor stations, AZ Indicating instrument, EDP Data processing, FWA Telecontrol system, I Current, MU Transducer, NW Shunt resistor, S Recorder, SM Signal meter with maximum contact, U Voltage, Z Zener diode

Table 14-3

Typical1) power consumption of measuring instruments, recorders, meters, transducers and lines

Instrument	Power consumption per	
	Current path VA	Voltage path VA
Ammeter	0.3…3	—
Current recorder	5…10	—
Voltmeter	—	1.5…7
Voltage recorder	—	10…20
Voltage range recorder	—	18
Wattmeter	1…3	0.5…2
Power recorder	1.5…10	1.3…12
P.f. meter	1.5…6	0.5…3.5
P.f. meter with alternating energy direction	5…15	3.3…8
P.f. recorder	6…14	10…12
Frequency meter	—	1…3
Frequency recorder	—	10…13
Time recorder	—	0.6…3.4
Electric drive for paper feed	—	3…25
Zero-voltage indicator	—	15
Synchroscope	—	15…22
Meter (counter)	0.17…3	0.85…5
Voltage transducer	—	1…3
Current transducer	0.5…3	—
Power transducer	0.5…1	1…1.5
P.f. transducer	0.5	2.5
Multi-transducer	0.1…0.5	0.02

Power consumption of copper measuring lines for length 1 m and 5 A

1.5 mm^2	0.29 VA	6 mm^2	0.07 VA
2.5 mm^2	0.18 VA	10 mm^2	0.044 VA
4 mm^2	0.11 VA	16 mm^2	0.0011 VA

1) Instrument power consumption vary according to manufacturer. Exact values are to be found in the manufacturer’s literature.

14.3.6 Synchronizing

Synchronizing is also a kind of measurement. System components cannot be connected in parallel unless their voltage curves coincide, otherwise the electrical stresses on the equipment become too high. While with direct current it is sufficient for the system components' voltage and polarity to be the same, with a.c. voltages the frequency, voltage and phase angle must match; with three-phase current so must the phase sequence.

The standard synchronizing instruments are double frequency meter, double voltmeter and synchronoscope. Digital control technology now offers the option of feeding the input signals of these instruments directly to an automatic synchronization device, which independently trips the closing operation at the right time.

When parallel switching system parts, it is sufficient to use an automatic synchronization test instrument, e.g. the Synchrocheck design of the SYNCHROTACT range from ABB, which prevents switching in asynchronous mode with non-permitted high phase difference angles or excessively high voltage differences.

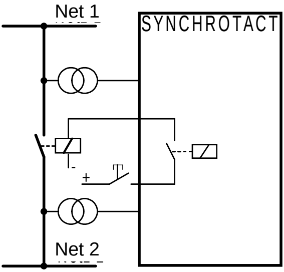


Fig. 14-14

Automatic synchronization test instrument
When paralleling conditions have been met, the contact is closed, the networks can be synchronized.

An automatic synchronization device is always recommended for parallel switching of generators with power supply units. This automatically brings the speed and voltage of the generator into a preset tolerance range using higher and lower commands. The voltage, phase angle, frequency and switch mechanical delay are taken into account to set the paralleling command to ensure that the switch contacts touch at precisely the instant the phases are the same.

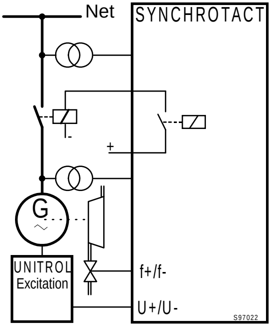


Fig. 14-15

Automatic synchronizer unit
The synchronizer device issues higher and lower commands to turbine controllers and voltage controllers. When paralleling conditions are met, the circuit-breaker is closed at the exact moment when the phases are the same.

The SYNCHROTACT automatic synchronization device in its simplest form is one single channel, which takes care of measurement, voltage, frequency balancing, monitoring and command formation with high security against faulty operation. Depending on system size and safety design, dual channel solutions are also available. Measuring, microprocessor and command relays in both channels are separate in the SYNCHROTACT dual-channel synchronization units. This independence significantly increases security against faulty operation in comparison to the single channel system.

14.3.7 Metering

General

Meters are used for determining the amounts of power supplied from the power source or distribution system to the consumer. The selection criteria are shown in Table 14-4.

In a special category are meters for billing electricity consumption. In the Federal Republic of Germany, for instance, they have to meet the requirements of the Physikalisch-Technische Bundesanstalt (PTB) and of the Deutsches Amt für Maße und Gewichte (DAMG), i.e. certified and approved. The voltage drop on the instrument transformer line of billing meters must not exceed 0.05 %.

Table 14-4

Selection criteria and alternatives for electricity meters (counters)

Criterion	Alternatives
Connection	direct or to instrument transformer
Type	electromechanical or electronic
Mounting	surface-mounted housing, live parts fixed flush-mounted housing, live parts fixed flush-mounted housing, live parts removable subrack, live parts on circuit boards
Current	alternating current three-phase in 3- and 4-wire systems loaded symmetrically and asymmetrically
Power	active and reactive consumption, incoming and outgoing[1]
Tariff	single or two-rate tariff[2]
Accuracy class	0.2, 0.5, 1, 2, 3
Metering system	primary system[3] semi-primary system[4] secondary system[5]
Special meters	maximum-demand meters[6] pulse meters[7] remote meters

[1] Reversal prevention is necessary where the power flow direction changes.

[2] Tariff changed with separate timer or ripple control receiver.

[3] The ratio of preceding transformers is accounted for in the meter reading.

[4] This takes account only of the ratio of preceding voltage or instrument transformers, the readings must be multiplied by a constant.

[5] This does not take account of the ratio of preceding transformers, the readings must be multiplied by a constant.

[6] The maximum rate is calculated from the price per kilowatt-hour (kWh) and per kilowatt (kW).

[7] These measure the power throughput and according to the units counted, emit pulses to the connected remote meters, remote summation meters or telecontrol devices.

14.4 Substation control with microprocessors

14.4.1 Outline

Substation control facilities using microprocessors and serial data transfer perform all the established functions of the secondary systems in transformer and substations, i.e. on / off control, interlocking, measurement, feedback control, indication, signalling, protection (feeders and busbar) and metering etc..

But computer-aided systems offer more: process diagnostics, the creation and automation of decentralized substations, together with preliminary on-site data processing, so easing the general task of network management.

A radical feature of this new technology is its diagnostic capability, which alone has operational benefits for the user, even if he decides against the other new possibilities available.

Overall, the new technology offers

- fast fault recognition
- simple system structure
- error-free operation,

so significantly improving station availability.

14.4.2 Microprocessor and conventional secondary systems compared

With conventional secondary systems, the various functions considered in Section 14.3 are performed by separate devices (discrete components) which mostly work on the analogue principle and as a rule are of varying sophistication.

The resulting situation is as follows:

- Each task is performed by devices employing different technologies (electromechanical, electronic, solid-state or microprocessor-based).
- These discrete devices may require many different auxiliary voltages and power supply concepts.
- The links between the devices and with the switchgear require a great deal of wiring or cabling and means of matching.
- The information from the switching apparatus has to be applied separately to numerous inputs for protection, control, interlocks etc., so monitoring the interfaces is complicated.
- Checking the performance of the individual devices is accompanied by more difficult verification of overall performance.

With the new control technology for switching installations, the emphasis is on the system and its function as a whole.

Digital methods are employed for the respective functions, using programmable modules based on microprocessors.

The distinguishing features of the new technology are:

- Use of identical device components or combined devices based on microprocessors for the various tasks or functions.
- Standardized power supply and supply concept.

- Serial data transfer minimizes wiring (bus technique).
- Fibre optic cables are used near the process to reduce the cost of established adequate electromagnetic compatibility.
- Composite use made of data from the switchgear.
- Self-diagnosis with continuous function check-up, hence simpler testing of overall system and subsystem.
- Simple correct-sequence signal acquisition with a resolution of about 1 ms.
- Reduced space requirements.
- Records of station functions.

Another major innovation of the new approach is the man-machine interface (MMI). While the access interface to conventional secondary technology is switch panel- or mimic control panel-oriented with the elements of switches, buttons, lamps and analogue instrumentation, access to the new control systems is usually through a display at bay level and through monitors and keyboards at substation and system control centre level. Operation is mostly menu-guided, so no programming or computer skills are necessary.

14.4.3 Structure of computerized control systems

A substation can be divided broadly into a sector comprising the switchbays (feeders, ties, sectionalizers and earthing system) with their functions:

- Control, supervision, interlocking
- Transformer control and voltage regulation
- Bay-level automatic functions
- Indication acquisition and processing
- Measurement acquisition and processing
- Local (bay) control
- Autonomous bay protection

and a sector with higher-level, i. e. station-related, tasks such as:

- Local (station) control
- Communication link
- Connection to station auxiliaries
- Station functions
- Busbar protection.

The logic structure of the control system consequently has two hierarchical levels: the switchbay level with the bay units (BU) and the station level with the station unit (SU), see Fig. 14-26.

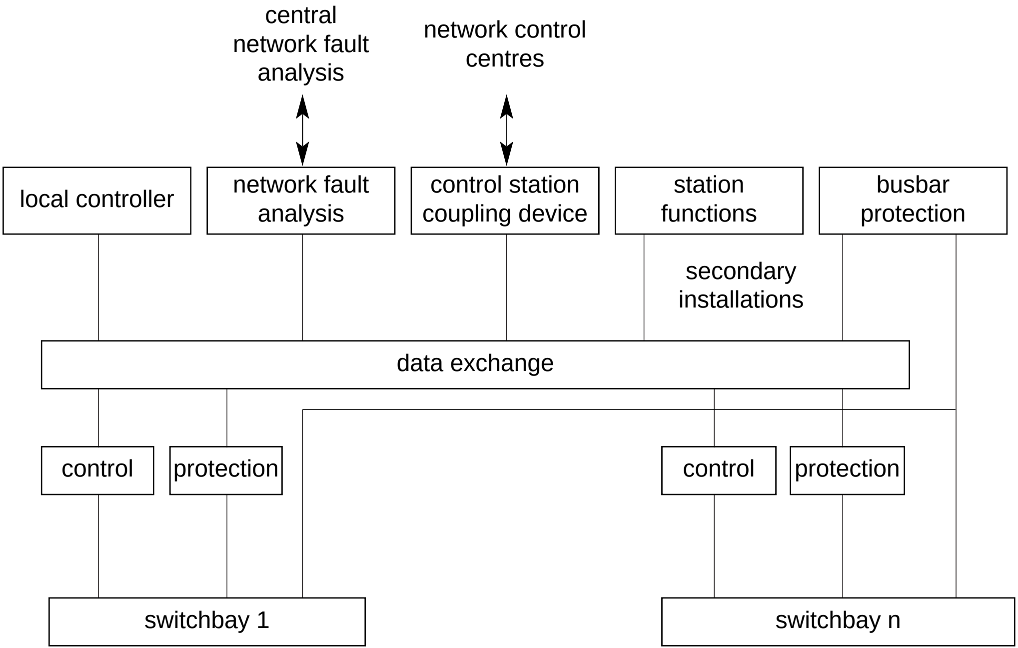


Fig. 14-26
Logic structure of computerized substation control

On the process side of the control system, the bay units are assigned accordingly to the process (switchbays). The result is that between every switchbay and the associated bay unit either a parallel connection, i.e. a direct connection between switchbay and bay unit is established for every datapoint such as position indicators and encoders for analogue values, or the data are linked to the bay unit by actuators and sensors over a process bus.

The functions performed in the bay units are basically those which require data from their associated switchbay (e.g. line protection, bay interlocks) and for which short functional loops are preferable.

The functions in the station unit, on the other hand, are those which need data from the whole station (e.g. busbar protection, priority treatment of alarms, indication of busbar voltage) or have a central function (connection to network control centre, radio time mark receiver, central operating position).

Serial links are used throughout for transferring data between bay and station units. The serial links are arranged radially. With a radial configuration serial links pass radially from the station unit to all bay units, and via these links the station unit can exchange data simultaneously with the bay units.

The ABB PYRAMID substation automation system uses a bus system for this data transmission. The radial (star) network consists of fibre-optic cables which are brought together at a star coupler (see also Section 14.4.4).

The bay and substation units are built up from modular components, or as a combined bay control and protection unit. The number of modules used depends on the required quantity of functions, the desired structure and specified aspects of system quality, such as availability. However, for safety reasons, in the high-voltage area beyond 72 kV the protection components are generally designed to operate independently of the other components of that bay unit.

Components of this new technology are also used for the self-contained protection circuits prevalent today, which provide additional information such as fault recording and fault location.

The self-contained protection devices can be of traditional or digital design, even from different manufacturers or different generations of protection equipment. In the case of conventional protection gear, parallel wiring continues to be used for the signal lines between bay and station units. Modern digital devices, on the other hand, offer the possibility of serial data transmission. To enable this, the interface is defined as per IEC 60 870-5-103 as a standard interface for serial connection of protection devices. Fig. 14-27 shows the general structure of the ABB PYRAMID control system with its decentralized function components. The star coupler ensures data communications between the autonomous subsystems.

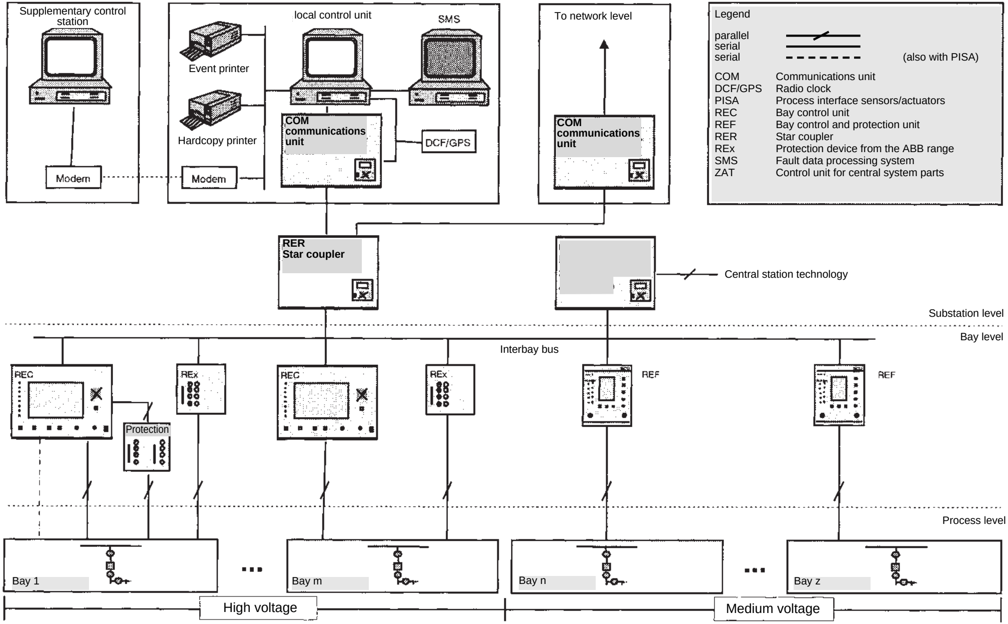
The functions are decentralized, irrespective of the bay unit’s locations and distribution.

A recommendation on “Digital Station Control Systems” by the VDEW working group for “Integrated Station Control Systems” has been in force since 1994, and a revised version is currently in preparation.

Sections 7.2.5 and 8.2.5 contain further information on computer-aided control for low-voltage and medium-voltage systems.

Fig. 14-27

Basic structure of the ABB PYRAMID control system



14.4.4 Fibre-optic cables

In modern station control systems, the links between the individual components usually carry information serially. Fibre-optic cables are used for these serial connections.

Properties and principle

Fibre-optic cables (FOC) are composed of glass or manmade filaments which by utilizing the property of total reflection are able to transmit light over long distances. They have a core with a high refractive index surrounded by cladding with a low refractive index and a mechanical protective coating (primary coating). The light is conducted by the core (subject to certain boundary conditions). Light-emitting diodes (LEDs) generally serve as the light source, but laser diodes are also used in special cases. Fig. 14-28 shows an optical transmission link.

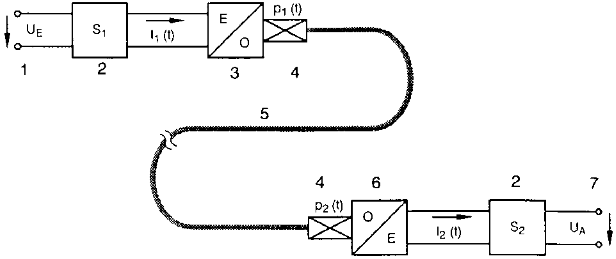


Fig. 14-28

Optical transmission technology with fibre optic cable, 1 Input, 2 Signal conditioning, 3 Electro-optical converter, 4 Connector, 5 Fibre optic cable, 6 Opto-electrical transducer, 7 Output

Their most important features regarding application in switchgear control systems are their complete immunity to electromagnetic interference and the absence of any problems with earthing and potential bonding.

Other major advantages are their large transmission bandwidth, low signal attenuation (regardless of transmission speed) and ease of handling. Fibre-optic cables are thin and flexible, and can be bent to relatively small radii.

Glass fibres differ from synthetic fibres mainly in that their attenuation is significantly lower, so the cables can be longer. On the other hand, they are not quite so convenient in practice.

Applications

The German VDEW recommendation “Integrated control and instrumentation in stations” includes many possible forms of serial links between the components of a station control system, all of which can in principle consist of fibre-optic cables. Because of their distinctive properties, however, especially their noise immunity, the main applications tend to be focused near the process itself. These are the communication links at the bay level, and the links joining components at the bay level with those at the station level.

One typical application is to connect the bay units with the higher-order star coupler at substation level.

As described earlier in Section 14.4.3 Structure of computerized control systems, the bay units of the ABB station control system communicate with each other and with the units at station level by means of a bus configuration that in physical terms comprises a star arrangement of fibre optic cables. This is an ideal combination, bringing together the advantages of the bus system, in particular the ability of all components to communicate quickly with each other, and the benefits of fibre optics. Furthermore, with this star structure, the failure of one component or its communication link has no effect on the performance of the other components.

VDEW ‘’Interface No. 6''

Applicable in Germany since 1991 is the “VDEW/ZVEI recommendation on serial interfaces for protection devices in integrated station control systems of electricity supply utilities”. This is also called “Interface No. 6”, since it bears the number 6 in the VDEW recommendation “Integrated control and instrumentation in stations”. The interface has also been included in international standards as the basis for IEC 60870-5-103.

Compliance with IEC 60870-5-103 ensures that digital bay protection equipment from different manufacturers retains connector compatibility. The specified connector corresponds to the F-SMA design in accordance with the IEC 60874-2 standard “Fibre-optic connector type F-SMA”. It has been chosen because it allows the use of both glass and synthetic fibres. The technical details of the compatible FOC transmission system can be seen in Table 14-6.

Table 14-6

Specification for the compatible fibre optic transmission system in the VDEW “6”

Characteristic	Synthetic fibre	Glass fibre 62.5/125 µm
Connector	F-SMA	F-SMA
Distance, typical	to 40 m	to 1000 m
Optical wavelength	660 nm	820 – 860 nm
Temperature range	– 5 to + 55 °C	– 5 to + 55 °C
Inserted power	min –7 dBm	min – 16 dBm
Received power	min – 20 dBm	min – 24 dBm
System reserve	min + 3 dBm	min + 3 dBm

Source: VDEW / ZVEI recommendation on serial interfaces for protection devices in integrated station control systems of electricity supply utilities. 1st edn. 1991.

14.5 Network control and telecontrol

14.5.1 Functions of network control systems

The purpose of network control systems is to operate transmission and distribution networks economically and reliably with the aid of data processing and information technology. The principal aim under normal conditions is to minimize overheads and capital costs by optimizing the utilization of the equipment, and under fault conditions to secure the supply of power at all points of the network and restore the situation to normal with interruption times kept to a minimum.

In order to achieve this, the status of the (usually extensive and closely intermeshed) network as regards topology, voltage and load must be known at all times, abnormal values must be instantly detected and signaled, and countermeasures taken. As supply systems become ever more complex, this is done at control centres which are fed by way of telecontrol links with all the information from the switchgear necessary for appraising the network's status and controlling it.

Initially, all functions were centralized in the control station. However, the increasing volume of information soon resulted in a shortage of processing capacity. The current trend is to decentralize most individual tasks at the point where they occur by implementing intelligent telecontrol stations or more powerful substation automation systems and to forward only the compressed information essential for centralized control of the overall network to the central control station for processing.

The exact duties to be performed by the network management system depend on the type and size of the network, on the nature of its main equipment and on the operational strategy adopted by the network operator.

In the supraregional network, the electricity is transported in bulk from the power stations to the load centres at voltages of 380 kV and 220 kV, or sometimes higher. This transmission network in turn supplies the distribution systems, operating at 110 kV, 60 kV, 20 kV, 10 kV and also other voltages, which carry the electricity at regional level from the interconnected network to the consumers.

The entire control and supervision of the machinery and equipment in the power plant itself, such as turbines and generators, is the province of power plant control, and so is not considered further here.

The tasks of network control begin with transmission of the electricity. For this, a *load-dispatching centre* controls the output of the power stations and the flow of power in the grid to meet the demand at any moment, aided by equivalent load curves from previous periods and according to mutual agreements with other electrical utilities, supplying the grid and large customers, together with various other parameters, in order to provide the most economical and secure service.

Network control centres monitor and control circuit status and the loading on switchgear and lines in the bulk transmission and distribution systems. When faults occur, it is possible with the aid of the high-speed data processing to obtain immediately an up-to-date picture of the network's general status and the situation at the site of the fault, then select and execute the required switching operations.

At the urban and municipal level, the supply of all forms of energy, i.e. gas, water, district heat, etc. as well as electricity, is controlled from one central multi-purpose centre.

The exact performance required from such a management system determines the equipment in the control centre. Today this consists almost exclusively of computer systems with separately assigned functions, together with colour monitors for displaylng the network and its parts. Because of the continuous increase in the scope and interconnection of the information processed in the control stations, it would no longer be possible for the control room staff to monitor and control the system without the aid of information technology. Process computers take over routine tasks from operators and quickly and safely prepare the data for processing. Central control rooms with computers and colour monitors for standard control operation and with an additional mimic diagram or large display with cumulative information for emergency operation or geographical overview are also encountered.

The internal data processing and information systems in many utilities are now networked with company data networks. This offers the option of deriving information from the system control technology for planning tasks, e.g. for network and maintenance planning, and for management information.

Practical experience shows that the designing of a new network management system calls for close cooperation between operator and supplier so that the individual parts of the system, such as data acquisition, transmission and processing, can be ideally matched to each other and to what they are required to do.

The general concept is often arrived at with the aid of joint preliminary studies, including the use of simulators, in order to make full use of today’s technology and optimize the control system to the specific requirements.

The Federation of German Electricity Companies VDEW has published a manual of recommendations1) on the design, construction and operation of network control centres, telecontrol and process computer systems, ripple-control systems, control rooms, auxiliary services, station control and network management. The different subjects are thoroughly dealt with in separate volumes.

These are:

0. General (overview, project management, non-technical requirements, awarding contracts)
1. Telecontrol systems (general, functions, technical requirements)
2. Ripple-control systems (basic planning, frequency planning, interactions, ripple-control receivers)
3. Process computer systems (task division in control and subcontrol rooms, functions, design of process computing systems, network database, interfaces)
4. Control engineering (task division and analysis, information input and output, control design, control room, ergonomic requirements)
5. Auxiliary equipment (backup power supply, rooms, signalling equipment, communications, equipment protection)
6. Integrated control systems in substations (design, requirements, information for the operator)

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1) Manual “Netzleitsysteme in Elektrizitätsversorgungsunternehmen (EVU) – Empfehlungen” (Network control systems in electrical utilities – Recommendations), VDEW-Verlag, 4/1994

7. NN
8. Network control systems
9. Standards, directives and recommendations

The latest supplement to this publication appeared in April 1994 as a ring binder. Some designs have in the meantime been superseded by technical progress. However, additional revisions are not proposed at present because the publisher is planning to replace the publication by various internationally coordinated documents.

The international standard on process data communication in network control systems is IEC/TC 57 “Power system control and associated communications”. The K 952 “System control technology” of the DKE is the responsible technical committee for Germany.

The results of the standardization are published internationally as parts of the IEC 60870 publication “Telecontrol equipment and systems”. In Europe, the publications are appearing from IEC 60870 as EN 60870 with the corresponding part number of the IEC document, in Germany as DIN EN 60870.

14.5.2 Control centres with process computers for central network management

With the growing trend towards centralized management of power networks and the accompanying large volume of incoming information, operating staff were subjected to an ever heavier work load until eventually they were unable to cope even under normal conditions owing to the limits on their ability to assimilate data within a given time span. In the interests of clarity and security, the information therefore has to be conditioned and condensed. The operators must be relieved of routine duties so as to be free for important tasks and decisions.

These demands can be met only by using programmable process computers. Table 14-7 lists a number of tasks that can be performed with the aid of process computers in network control centres and outstations. Although the technology has made rapid progress since this part of the recommendation (1981) was published and new solutions such as the integrated control system in the outstations have been implemented, in principle the task assignments are still generally current.

Table 14-7

Tasks for process computers in control centres and substations[1]

1	2	3
Display and supervision of network status	**Control of switchgear and auxiliaries**	**Load management**
● Alphanumeric display of incoming data tabulated in clear text – group signals – derived single signals	● Command input via keyboards – all kinds of control command – uniform operation – independent of existing control systems	● System load measurement and monitoring – measurement of energy at supply points – transmission as meter reading or pulse string – acquisition and storage in computer – calculation of total system load over accounting period – determination of free capacity – generation of substitute values for missing values – output via VDU or digital display – printouts of individual values
● Graphic display of network and station diagrams – networks by voltage level – subnets – block diagrams of transformer and substations – station segments – station allocation lists – list of available pictures	● Multiple-step commands – operator guidance functions – stepwise checking of completeness and correct sequence – command output, storage and reporting	● Load management – calculation of load trends – short-range load forecasts – time-related load control
● Additional information in selected pictures – measurements (digital or bar diag.) – setpoints and limit values – updates of switchgear settings – identification of earthed and unavailable apparatus – identification of messages to be reset locally – indication of work in progress on switchgear		● Operation of ripple-control systems – manual commands to control unit, bypassing computer – manual commands through computer – automatic commands through computer based on calculation
● Use of colour display units – separate colour per voltage level or network section having same earthing condition		
● Mimic panel as general display – geographical layout – linked node-point signals – limited additional information		

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[1] Summary from manual "Netzleitsysteme in Elektrizitätsversorgungsunternehmen (EVU) – Empfehlungen" (Network control systems in electrical utilities – Recommendations), Section 3.1, 4/81

(continued)

Table 14-7 (continued)

Tasks for process computers in control centres and substations[1)]

4	5
Load shedding	**Documentation of events – printouts and off-line storage**
● Determination of loads to disconnect according to – time of year – day of week – time of day – system load immediately before fault – available generating capacity – network circuit status ● High-speed detection of fault criteria and measurements – system frequency – unassisted power available – total system load – load of separately switchable subnets – measurements to determine transfer lines ● Shedding of load – determination of optimum reduction with computer – disconnection with minimum delay – assumption of load frequency control in subnet	● Printouts required for – recording events in network – later analysis of disturbances – statistical purposes – future planning ● Clear text printouts – text summaries – clearly organized typefaces ● Computer tasks – essential information in most effective form – data conditioning and compression – collation of data – production of sorted reports ● Off-line storage required for – examination and analysis of past events or operating conditions – network planning – forecasting ● Selection of storage media – disk – tape, cassette – punched tape, cards – diskette, CD-ROM ● Preparation for storage – conversion to most suitable form – savings of memory space

(continued)

Table 14-7 (continued)

Tasks for process computers in control centres and substations[1)]

6	7
Data acquisition and processing in substations	**Other tasks for process computers**
● Telecontrol functions ● Indication processing – collection of fault signals in real time – collection of fault signals with follow-up faults – preprocessing of data – transmission after initial sorting ● Processing of measurements and meter readings – transmission only when value alters – totals generated at substation – readings transmitted in different time cycles – supervision of limit values – generation of operating values from performance values or as pulse strings ● Commands – verification of interlock conditions – execution of programmed control actions – construction of a switching matrix ● Simplified reports – for indications and measurements – for executing switching commands ● Station control system – takes over partial tasks – complete control and monitoring	● In network operation – data reduction, e.g. earth-fault location – programmed switching operations – temperature-rise calculations for cables and transformers ● In network planning – power flow calculation – short-circuit calculation ● In load dispatching – state estimation – network security calculation – restoration of supply – load forecasting – optimization of generator output ● In statistics – measurement statistics – apparatus statistics – maintenance planning

Which of the many functions are to be incorporated in a control centre depends very much on the performance specification and financial resources at the user's disposal. Deciding the exact details must form part of the planning phase.

PC-based computer systems with fully graphic colour monitors for process control are primarily used in small and medium municipal and regional control stations, and also in station control systems. In selecting computers, great emphasis is placed on commercially available industry standards for the hardware, the operating systems and the basic software (e.g. OS/2, RMX, Windows). Networking over local area networks (LAN, Ethernet) is also important.

In addition to straight electricity control rooms for medium-voltage networks, sometimes linked to load management, this category also includes multi-purpose centres for several different types of energy, e.g. electricity, gas, district heat and water, which run in parallel on the same or multiple networked computer systems and are monitored from the same workstation.

Very exacting demands are made on the computer systems for large and complex network management facilities and for load-dispatching centres. In addition to standard system control (SCADA basic functions), more advanced tasks for network operation, load distribution, system planning and for statistical purposes must be handled here. These functions are designated as higher decision and optimization functions (HEO) or as energy management functions (EMS).

The computer hardware used consists of 32-bit computers, increasingly also 64-bit computers, with the associated storage media, teletypes, printers, graphic monitors, keyboards, etc. Front-end computers or remote terminals are used to link local substations and telecontrol lines

Multiple computer configurations with redundancy are used in medium and larger network management systems in order to increase availability and spread the work load. With the hierarchical system structure which used to be customary, computers connected in series performed different tasks such as time-critical scheduling of telecontrol lines, network management and statistical calculations. If a computer went out, others connected in parallel took over operation without interruption and with no loss of data. Now "distributed computer systems" are primarily used for this purpose. The overall system tasks are distributed over smaller computer units, which are connected in parallel to a duplicate or segmented LAN (Local Area Network) and can also operate independently of one another.

Besides the hardware, the network management system's capabilities are determined above all by the software. Preferred operating systems are the widespread and proven standards, e.g. UNIX operating systems such as ULTRIX, POSIX, HP-UX, or the industry standard operating system OSF/1. An important requirement of the application software, apart from performing all its allotted functions, is that it should be easy to use. The user must be able to manage the system without any programming skills, and with dialogue guidance easily be capable of adjustments and changes to the data and network configurations.

Control centres equipped with process computers require a number of other facilities as well. Besides air-conditioning for the computer rooms to maintain a constant atmosphere, an uninterruptible power supply is necessary to prevent data from being garbled or lost.

Chapter 3 of the VDEW manual “Netzleitsysteme in Elektrizitätsversorgungsunternehmen (EVU)” (Network control systems in electrical utilities) contains a series of recommendations for task allocation and design of process computer systems in control stations and outstations. An important part of this chapter is also the “process for development of a network database”.

ABB provides an integrated series of network control systems for economical and reliable management of power supply networks with the S.P.I.D.E.R. system family under the Panorama integrated system solution to cover all task areas from the smallest introductory version to the largest load distributor.

The S.P.I.D.E.R. MicroSCADA system, a PC-based control system, is designed for small and medium tasks in system control and also for load management and station control systems. The S.P.I.D.E.R. SCADA system is the basis for larger network control systems. Depending on the actual application, it can be scaled up for high-performance network control systems, e.g. for higher optimization tasks to the S.P.I.D.E.R. EMS system, as a distributor network management system to S.P.I.D.E.R. DMS or in pipeline monitoring to S.P.I.D.E.R. PMS. All these systems are equipped with high-performance computers of the DEC-VAX family.

The hardware and software of all S.P.I.D.E.R. systems are made up of self-contained modules which are compatible with each other and can easily be combined to form complex, distributed network management systems. In addition, S.P.I.D.E.R. network control systems are completely separate from the switchgear itself and the telecontrol facilities. They can be adapted without difficulty to any set of requirements.

14.5.3 Control centres, design and equipment

The aim of control room design is to create the best possible man-machine interface (MMI). All the facilities must be provided for controlling and supervising technical processes and equipment from a central point located at a distance from the various installations.

The essential requirements to be met by a control room are a clear presentation of the supervised network or network segment, indication of the circuit conditions, voltages and loadings of the apparatus and linking conductors, the immediate and unambiguous signalling of abnormal circumstances and the keeping of records regularly and in response to events.

To arrive at the best possible solution for performing all the control and supervisory tasks, many different aspects have to be considered in equipping and arranging the control room. Included among these is the field of ergonomics, which is the scientific study of optimizing and standardizing the communication interface between man and process to accord with human cognitive capabilities and reactions.

An important point when designing a control room is that the equipment must be suited to its particular task, and must also take into account the limited capacity of a person to absorb information within a given length of time. All important information must be presented within the operator’s primary field of view. Here, attention must be paid to the correct arrangement of the individual functional units, such as VDU, operator’s console and signal display, and also to an appropriate and easily understood representation of the state of the system and the various controls.

These technical considerations have also given rise to recommendations on the control room's interior design. These aim to create physiological comfort by means of glare-free lighting, acoustic treatment and indoor climate, but at the same time make sure that the operating staff stay alert. Although their duties are not very demanding under normal circumstances, they must react quickly and correctly if trouble occurs. The relevant DIN, EN and IEC provisions must be observed with respect to these environmental conditions.

Further recommendations and hints on control room design are to be found in the VDEW manual "Netzleitsysteme in Elektrizitätsversorgungsunternehmen (EVU)" (Network control systems in electrical utilities). Volume 4 "Control room design" (as of 08/92) contains guidelines on all major aspects of planning and designing network control centres, including the essential considerations of

- human physiology and sensory perception,
- codification of information (e.g. as symbols),
- presentation and interrelation of information, taking into account disturbing influences such as glare, noise, etc.

The individual subsections describe the general task allocation of the control engineering, the task analysis including task assignment and functional overview for the specific application case, provide details of input of information (commands, control and display) and information output (information quantities, processing and display), provide suggestions for control procedures, on the spatial configuration of the subsystems inside the control room, on control room equipment and air-conditioning and also on the ergonomic requirements. At the end, a series of provisions and directives that must be considered in control engineering is listed.

As the control room is often seen as reflecting the image of the supply utility, this is another significant aspect to be considered in deciding the furnishings and fittings.

Up to the seventies, a large mimic panel was the principal and often also the only means of displaying a replica of the network. Owing to increasing centralization and automation together with the growing complexity of power supply systems, the mosaic-type mimic panel has lost its former importance. It certainly provides a quick overall view of the network, but limits are imposed by sheer size and the ease of recognizing details. The mosaic-type mimic panel has hence become restricted to local or other small control rooms where system layout and status can still be shown using simple systems on a manageable area and modifications to network configuration and apparatus can be made without difficulty. The mosaic panel with reset controls continues to be used as well as VDUs in larger control centres, serving to provide a less detailed overall picture, a stylized map of the network, and also back-up for the main system. More and more often batteries of projectors are found in control rooms, which are arranged in a pattern and project a seamless overview of the entire system in one large image. The active network images are taken from the computer, and video images (e.g. door monitoring) can also be incorporated into the general view. In addition to the usual means of signalling and control, the panels are also fitted with other intelligent devices for indicating faults, large-scale displays and recording.

In all medium-sized and larger control centres with process computers, the details of the network are shown on fully-graphic colour VDU terminals. With these, it is possible to prepare and display the specific up-to-date information necessary for a given switching operation or for fault analysis. All unneeded information, such as healthy branches, can be omitted. Important details can be emphasized by colour, e.g. Iine loadings, earth lines, etc. Signals and measurements arriving spontaneously can be presented on the screen as they occur. The video terminal thus offers a greater density of information than the same area of a mosaic panel, and at the same time more clearly, i.e. perceived faster and more reliably by the operator. Different parts of a picture can be shown on a number of adjacent screens. In another form of presentation, the picture shown on one screen sweeps across the entire network (rolling map method). Additional functions offered by the graphics monitors are image zooming, decluttering with automatic changes of the degree of detail when zooming, the windowing technique with temporary display of windows for control or help and softkeys (virtual keys) that can be shown on the edges of the display for frequently occurring functions. The image section and the equipment that is to be controlled during switching operations and input of the switching command are selected on screen, primarily using keyboards on the control panel as the input device but also “virtual keyboards” on the display or cursor positioning on the screen with a joystick, arrow keys, roller ball or mouse. Light pens and digitizing tablets with stylus are not recommended because that would require the monitors to be installed within reach of the operators. However, this does enable the change service to design images and symbols particularly quickly.

In both conventional and computerized control rooms, the process is usually controlled from a desk or console. It is important that the monitors used to depict and control the network are simple to operate and show the network in a uniform manner, especially when an extensive management system has several computers sited at various places in the network, e.g. at the control centre and at the substation. The previously process-orientated operating staff must be able to do their work easily, without the need for skilled computer specialists. In many cases, therefore, the operator receives guidance from the screen in the form of a menu showing instructions on forthcoming control actions, either in clear text or by means of icons, in much the same way as with modern personal computers.

Fig. 14-29 shows an example of a control room in a computerized regional control centre. As well as the technical facilities with 2 workstations, 4 colour terminals, mosaic-type mimic display and other input and output devices in the control room itself, one can also see some of the other amenities forming part of a large network control centre.

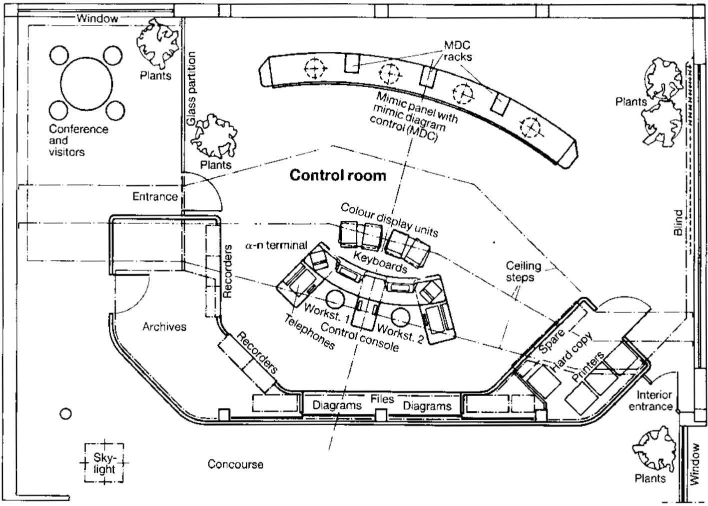

Fig.14-29

Layout of a regional network control room

14.5.4 Telecontrol and telecontrol systems

Along with data processing, telecontrol plays a vital role in central network management. It is communications technology applied to technical processes. Its purpose is the economical and reliable transmission of data (such as switching and adjustment commands, signals and measurements) between the decentralized substations and the central control room.

At the transmitting end of a telecontrol system, the relevant information is prepared for transmission, i.e. it is coded and secured with additional redundancy so that errors due to disturbances along the transmission path can be detected at once, and spurious output data prevented. At the receiving end, the incoming information is decoded, checked and, if free from errors, sent as a command, signal or measured value to the process modules or passed to the master computer.

The IEC's TC 57 has drawn up a number of standards on telecontrol and published them as IEC 870. The results have been published in the European standard EN 60870, i.e. in the German DIN 19244. The terminology of telecontrol is defined in the "International Electrotechnical Dictionary, Part 371: Telecontrol", available in Germany under the number IEC 50, part 371.

The most important telecontrol terms can be found in the "Internationales Elektrotechnisches Wörterbuch Kapitel 371: Fernwirken" (International electrotechnical dictionary – Chapter 371: Telecontrol) as IEC publication IEC 50 (371) (1984), incorporated nationally as IEV 371 (1989), and in the associated change 1 as supplement IEC 60050 (371) dated 1997.

Also on this subject, "Begriffe der Fernwirktechnik", published as ntz-report No. 26 by VDE-Verlag GmbH, Berlin-Offenbach 1991, has been brought up to date and contains all definitions in English and German.

The growing size and complexity of power supply networks and the increased volume of information has necessitated telecontrol systems of different structures. In the case of small control centres with few substations, all the stations can still be connected directly to the control centre by their own telecontrol links, either point-to-point (the control centre communicates only with one substation) or on the multi-point principle (the control centre interrogates a number of substations one after the other for new information). For medium or large network management systems with many or distant substations, however, a hierarchically structured telecontrol network is unavoidable owing to the usually limited number of available communications channels, and also to relieve the control centre. In this case, the information from several substations, for instance, can be collected and compressed at so-called router stations or passed to telecontrol substations via additional telecontrol feeder lines.

Choosing the most suitable telecontrol system depends on its required performance. The main criteria are the volume of information and how up-to-date it needs to be, but equally important is its incorporation into the hierarchy of the control system as a whole.

Today time-division multiplex (TDM) telecontrol systems are used almost exclusively. With the TDM system the data are transmitted one after the other in the form of telegrams, a succession of pulses. Each piece of information is assigned to a certain place in the telegram. Besides the information itself, the telegram also includes address and test characters, the purpose of the latter being to prevent incorrect information from being sent.

The IEC TC 57 "Power Systems Control" and the DKE committee K.952 "Netzleittechnik" (system control technology) have been working on standardizing transmission protocols for a long time. These standards are or will be published in IEC 60870-5 (international), EN 60870-5 (European) or the DIN EN 60870-5 (German) standards series under the subject of "Telecontrol equipment and systems, Part 5 – Transmission protocols". The individual parts describe and define the following subjects:

Part -5-1:	Transmission frame formats
Part -5-2:	Link transmission procedures
Part -5-3:	Structure of application data
Part -5-4:	Definition/coding of elements
Part -5-5:	Basic application functions

The main section IEC 60870-5-101 “Companion standard for basic telecontrol tasks” (1993) or EN 60870-5-101 “Application-based standard for fundamental telecontrol tasks” (1996) is particularly interesting and important for telecontrol. This standard is intended to lead to a unification of the transmission protocols of various manufacturers of telecontrol systems and to make it easier to combine different telecontrol systems in the same network control system. The protocol as per IEC 60870-5-101 is in the process of being integrated into existing or new telecontrol systems.

The December 1997 main section IEC 60870-5-103 “Companion standard for the informative interface of protection equipment” marks an important milestone for the serial connection of protection relays in substation control systems and telecontrol stations. The standard is derived from the earlier VDEW “no. 6” interface (see Section 14.4.4).

The usual transmission speeds employed for telecontrol are between 50 and 1200 Bd (baud)1). In large network control systems and in special application cases, e.g. where system protection information with very short reaction time is transmitted, transmission speeds of 2400, 4800, 9600 and even 19200 Bd are also standard if permitted by the available transmission channels.

The manual “Netzleitsysteme in Elektrizitätsversorgungsunternehmen (EVU)”(Network control systems in electrical utilities) covers the subject of telecontrol in volume 1. The fundamentals of telecontrol and its different functions are defined and described, and the section “Technical conditions” contains information on environmental factors, on conditions for interfacing with switchgear and the transmission facility, on operating behaviour, power supply and general questions of design. Under “Non-technical conditions” are notes on documentation, identity coding, training, performance certification and warranties.

With the introduction of programmable central processors, telecontrol stations have been assigned not only the usual functions (input and output of information, preparation and transmission of telegrams, securing of information) but also additional decentralized processing tasks to ease the load on the control centre. The trend has since been towards incorporating the telecontrol station as an integral component of the station control system or setting it to completely and independently control all the control tasks in the substation.

Examples of functions in the outstations can be seen in column 6 of Table 14-7. A new function is the serial linking of digital protection relays to telecontrol substations and to control centres.

Additional functions at router stations are:

- compression of information,
- correlation of data to reduce volume,
- evaluation, processing and interconnection of information from underlying substations,
- information distribution to more than one control station and substation control system,
- execution of emergency action.

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1) 1 baud = 1 digital pulse per second

Other possibilities with modern telecontrol systems are:

- interlinking of telecontrol systems of different types and makes,
- serial linking of digital protection relays and bay or substation units,
- standardization of telegrams,
- different transmission protocols to higher-order control systems,
- pre-processing of data.

The ABB Panorama design with the RTU system family has a range of modern telecontrol systems suitable for all tasks. The range extends from small systems for simple telecontrol tasks up to very large TDM systems with many additional functions at all hierarchical levels for use in complex network control systems.

The various ABB systems can be combined with each other, and also expanded from the smallest up to the very largest. For network management systems of any size, therefore, there is ABB telecontrol system suitable for every point in the communications network.

With the aid of intelligent coupling devices, it is also easy to incorporate ABB telecontrol systems in network control facilities from other suppliers, or connect ‘foreign’ feeder stations to the S.P.I.D.E.R. substation. The implementation of standard protocols as per IEC 60870-5-101 will make this task even easier in the future. The same applies for interconnection with station control systems in the substations, e.g. with the ABB PYRAMID control system. As an example, interfaces as per the ABB SPA bus protocol or as per the international IEC 60870-5-103 standard are offered for serial linking of protection relays or control modules.

14.5.5 Transmission techniques

Communications links are required for transmitting the telecontrol signals between the control centres and the various stations of the telecontrol network. The nature and capacity of these links also determine the maximum speed of transmission.

Audio-frequency (AF) transmission by means of voice-frequency telegraphy (VFT) or modem over the following paths is generally preferred:

Telecommunication lines or cables with copper wire or fibre-optic conductors, PLC links (power-line carrier transmission over high-voltage lines), VHF and radio relay links. Direct-current data transmission is also used for short distances (≤ 10 km), in this case usually with only low transmission speeds.

The communication channels can either be owned by the system operator or rented from the postal authority. Typical examples of transmission links belonging to the utility are telecommunication cables in the form of buried or aerial lines run along the same route in parallel with high-voltage cables or overhead power lines. Aerial cables are divided into autonomous cables, earth-conductor cables and phase cables. Other examples are multichannel radio relay links, chiefly at grid level, and PLC communication by way of the power lines themselves.

If no telecontrol transmission paths are available, current paths or data connections can be leased from Telekom. However, note that Telekom current paths must not be switched together with private telecommunication paths.

The terminal devices must be approved for this purpose[1]. Telekom guarantees a sufficient receive level for transmission on leased lines. With private lines, it may be necessary to provide repeaters, amplifiers and matching elements.

The most important provisions and recommendations for the transmission paths are presented together in Volume 1, Chap. 1.1 of the VDEW recommendations. This includes the provisions of VDE 0800 (telecommunications), VDE 0228 (influence by power systems), VDE 0816 and DIN VDE 0818 (for cables), VDE 0850 or EN 60495 and VDE 0851 (for TFH (power line telephony) and VDE 0888 or EN 187000 (fibre optics for telecommunications).

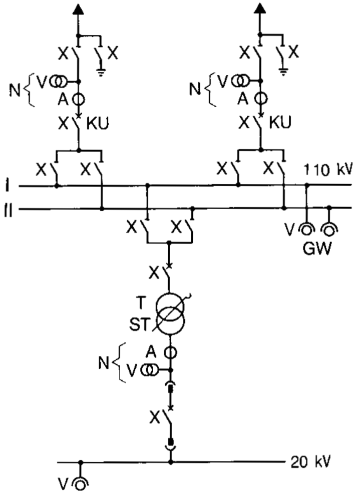
14.5.6 Technical conditions for telecontrol systems and interfaces with substations

Volume 1 of the manual “Netzleitsysteme in Elektrizitätsversorgungsunternehmen (EVU)” (Network control systems in electrical utilities) contains recommendations regarding the technical conditions that telecontrol systems have to satisfy. Described here, too, are the different interfaces, including those to the substations, and the question of power supply. In the meantime, there are various standards that are also concerned with this subject as per E DIN IEC 57(CO)21 (international IEC 60870-1-1) and E DIN IEC 57(CO)49 (international IEC 60870-1-3). The following principal conditions for interfacing with the switchgear are also taken from these source documents.

The centralized management of a network requires a variety of information from the substations relating to closed and open-loop control, measurements etc. The nature and quantity of signals, commands and measurements that need to be made available and transmitted depends among other things on the kind of supply network, its voltage level and scope of the network management system. Fig. 14-30 shows an example of the telecontrol information transmitted from a 110 / 20 kV substation[2].

Fig. 14-30

Example of the telecontrol information transmitted from a 110 / 20 kV substation, X Control action and indication, GW Limit value, A Measurement: current, V Measurement: voltage, N Power, ST Tapping, T Temperature, KU Auto-reclosure



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[1] The Zentralamt für Zulassungen im Fernmeldewesen (FZZ) (central office for telecommunications approvals), Saarbrücken, is responsible for this in Germany.

[2] Taken slightly revised from the manual "Netzleitsysteme in Elektrizitätsversorgungs-unternehmen (EVU)" (Network control systems in electrical utilities), P. 1.1.2-1.

Interface telecontrol unit/substation

This interface carries information passing between the telecontrol equipment and the control devices in the substation. For the telecontrol equipment, there are the following 4 kinds of data input/output:

- digital inputs,
- analogue inputs,
- digital outputs,
- analogue outputs.

The classes of noise-voltage limit values and insulation requirements are shown in Tables 14-8 and 14-9. The choice of class depends on the characteristics of the switchgear.

Table 14-8

Noise-voltage limit values and insulation requirements for binary signals

	Transverse voltage	Longitudinal voltage
Operating limits	10 % power frequency volt. peak / peak referred to U_N 0.2 kV H.F. (1) 0.3 kV IMP (1)	 25 V AC 65 V DC 0.3 kV H.F. (1) 0.5 kV IMP (1)
Destruction limits class 1	+ 200 % U_N DC (2) – 125 % U_N DC (2) 200 % U_N A. (2) 0.3 kV H.F. (1) 0.5 kV IMP (1)	 0.5 kV N.F. (1) 0.5 kV H.F. (1) 1.0 kV IMP (1)
Destruction limits class 2 for telecontrol equipment with series EMI barrier	+ 200 % U_N DC (2) – 125 % U_N DC (2) 200 % U_N AC (2) 0.5 kV H.F. (1) 1.0 kV IMP (1)	 0.5 kV N.F. (1) 1.0 kV H.F. (1) 2.5 kV IMP (1)
Destruction limits class 3 for telecontrol equipment connected direct to the switchgear	+ 200 % U_N DC (2) – 125 % U_N DC (2) 200 % U_N AC (2) 1.0 kV H.F. (1) 25 kV IMP (1)	 2.5 kV N.F. (1) 2.5 kV H.F. (1) 5.0 kV IMP (1)
Insulation between inputs and/or outputs and/or earths		(a) min 1 MΩ at 500 V AC (3) (b) min 10 MΩ at 500 V AC (3) (c) min 100 MΩ at 500 V AC (3)

Notes:

(1) N.F. = System frequency (usually 50/60 Hz)
H.F. = Damped high-frequency oscillation, see IEC 60255-4
IMP = High-voltage pulse

(2) The equipment must withstand this voltage for 1 min without harm.

(3) Insulation class (a) is for normal applications. Insulation classes (b) and (c) may be used in special cases.

Table 14-9

Noise-voltage limit values and insulation requirements for analogue signals

	Transverse voltage	Longitudinal voltage
Destruction limits class 1	± 50 mA DC (2) ± 24 V DC (2) 0.2 kV H.F. (1) 0.3 kV IMP (1)	25 V AC 65 V DC 1.0 kV H.F. (1) 2.0 kV IMP (1)
Destruction limits class 2 for telecontrol equipment with series EMI barrier (4)	± 50 mA DC (2) ± 24 V DC (2) 0.5 kV H.F. (1) 1.0 kV IMP (1)	± 0.5 kV DC 0.5 kV N.F. (1) 1.0 kV H.F. (1) 2.0 kV IMP (1)
Insulation between inputs and/or outputs and/or earth		(a) min 1 MΩ at 500 V AC (3) (b) min 10 MΩ at 500 V AC (3) (c) min 100 MΩ at 500 V AC (3)

Notes:

(1) N.F. = System frequency (usually 50/60 Hz)
H.F. = Damped high-frequency oscillation, see IEC 60255-4
IMP = High-voltage pulse

(2) The equipment must withstand this voltage for 1 min without harm.

(3) Insulation class (a) is for normal applications. Insulation classes (b) and (c) may be used in special cases.

(4) The values for class 3 in Table 14-8 apply here if telecontrol equipment is connected direct to control devices at the switchgear.

General conditions for substations

In the substations, all the circuit-breakers and disconnectors to be remotely controlled must have a power operating mechanism and a floating-potential make and break contact for indicating status. Transformers, arc-suppression and charging-current shunt coils must be provided with additional floating contacts to indicate grading level and on-status. All enunciator relays working together with telecontrol devices must have a floating NO contact, and so that new changes of state can be detected the enunciator contacts must be closed only while the coil is energized. Relays for isolating against external interference must be mounted close to the telecontrol equipment. Measuring sensors are required for remote measurement.

As part of the power equipment, all these interface devices must conform to the relevant IEC standards, for instance IEC 364, and if electronic to IEC 1010.

Commands

Commands to switching devices and transformers or graded arc-suppression coils are transmitted by the telecontrol system via digital outputs as two-phase pulsed commands of ≤ 60 V DC lasting 100 to 500 ms. Single-phase and one-and-a-half-phase output arrangements should be fitted with a switching monitor in the process-side circuit. Disconnectors with longer operating times (10 – 15 sec) must be provided with additional means of automatic control or additional timing elements. Plunger-type arc suppression coils can be activated continuously or converted locally to step control. With a switching device such as a local/remote selector switch it must be possible to inhibit individual groups of commands or all commands from the telecontrol substation.

Indications

Indications are passed individually via digital inputs to the telecontrol device, although the enunciator contacts can be grouped to feed common return lines. Signals indicating switchgear settings must identify both positions. These two signals are usually obtained from a changeover contact or an NC and NO contact. With isolators that move slowly, transmission of the intermediate position is suppressed by the telecontrol system during the isolator’s usual operating time. Signals in response to tripping should, wherever possible, be generated locally in each switchbay.

The signals can be continuous, of short duration or fleeting signals with times of ≥ 10 ms, the last two categories being stored by the telecontrol system until they are acknowledged. A DC signal voltage of 60 V should be used (48 or 24 V are also possible) so that even with considerable distances between switchyard and telecontrol station any noise voltages remain below the signal-tripping value.

Measured values

The remote measuring sensors employed to convert the process data into standardized values must have floating-potential outputs. The voltage at the output of open-circuit sensors must not exceed 100 V. They must not be damaged by short-circuits or open circuits on the output side, nor in such cases have any unacceptable effects on the primary transformers.

Buffer amplifier or lightning arresters should be provided to guard against overvoltages, particularly in high-voltage installations.

The expected input quantity for the analogue inputs of the telecontrol device is preferably an injected unipolar or bipolar direct current, also if applicable an injected DC voltage (1 mA, 2.5 mA, 5 mA, 10 mA, 20 mA, 1V, 10V). The entire measurement and transmission chain, from switchyard to control centre, should conform to accuracy class 1.

Meter readings

Metered values are fed to the telecontrol system as counting pulses or coded counter totals. The counting devices (primary coders) usually have 6 decades and BCD coding at the output. A floating input is required for the digital inputs to the telecontrol equipment.

Connecting conductors

Only insulated wires and cables may be used to connect the telecontrol equipment to the respective devices and plant components. Cables with conductors whose insulation is not moisture-proof must be suitably sealed at the ends if necessary. The wires and cables are best laid in underfloor gulleys or on trays or racks. If no gulley is available, the wiring to the apparatus must be protected with ducting, conduit, or similar. Earth wires and shielding must be connected by low-impedance joints to rails linked to the protective earth conductor. Signal lines must be routed away from power and control lines.

Power supply, premises

The telecontrol devices are usually connected to a secure power supply so that data can still be sent if the power in the switching installation should fail. This is generally a 60 V or 24 V battery (also 48 V in other countries), and occasionally a secure 220 V AC supply. The requirements for power supply for telecontrol devices are summarized in Main Section 1 of IEC 60870-2-1 or in DIN EN 60870-2-1, also in VDEW Manual Volume 1, Chap. 1.3.4. In addition, all of Chap. 5.1 “Secured power supply” of Volume 5 “Auxiliary Equipment” covers the recommendations.

In addition to electrical requirements, the premises in which telecontrol systems are installed and operated must also satisfy certain conditions.

The premises must be dry with a room temperature between 0 °C and + 55 °C, in large substations + 5 °C to + 40 °C. Generally the telecontrol equipment shall be able to operate without air-conditioning.

14.6 Load management, ripple control

14.6.1 Purpose of ripple control and load management

Ripple-control techniques enable power suppliers to control their widely dispersed consumers from a central point. The principal object of this is load management, i.e. the supply utility can influence the consumption of electricity by connecting and disconnecting suitable items such as storage heaters, hot water heaters, heat pumps etc.

Fig. 14-31 shows the uncontrolled load pattern between midnight and 3 p.m., the lines representing quarter-hourly averages.

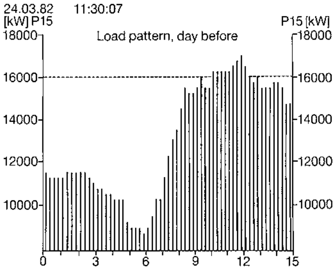

Fig. 14-31

Load pattern between midnight and 3 p.m., shown as quarter-hourly averages

Electricity consumption throughout the day can be made more even by connecting consumers when load is low- afternoons and at night – and disconnecting them at peak times – mornings, evenings. Power stations and transmission/distribution networks are loaded more uniformly. Depending on the network management policy, the system, comprising load management centre, ripple-control equipment (transmitter and coupling) and ripple-control receiver, can be operated on either the open- or closed-loop principle.

In the first case, the consumers are switched on and off according to a fixed timetable. In the second instance, the computer also measures the effective network load, calculates the trend in order to establish, in relation to a set value, the necessity for connection or disconnection, and chooses the consumers to be affected by any correction required. The system thus functions like a digital feedback circuit.

Although the principal aim is load management, the power utilities also use ripple control for other purposes, e.g. tariff control (peak rate, off-peak, special rates, etc.), controlling street lighting, neon signs or building illumination, and in special cases also fire and other alarms, and for operating switchgear where there are no telecontrol links.

14.6.2 Principle and components for ripple-control systems

Under the principle of ripple-control technology, signal voltages with frequencies of 150 to 1350 Hz must be injected briefly at a few places in the power supply system (50 or 60 Hz), in general in the substations of the distribution network, for the duration of the information transmission. The signals consist of a train of pulses in telegram form with an injection level of 1 to 5% of the system voltage. They can be received throughout the supply network, decoded by ripple-control receivers and converted into switching commands.

The telegrams have a distinctive pulse sequence for each kind of signal and are preceded by a starting pulse, while modern systems also have an interrupt pulse (Fig. 14-32).

The ripple control frequencies are determined in relation to the harmonics of the network frequency, which can assume values up to 8 %, and of neighbouring control frequencies. The middle frequencies of broad-band systems are arranged symmetrically at 33⅓ Hz intervals, for example, between the odd-numbered harmonics of the network frequency (e.g. 150 Hz, 250 Hz etc.), while those of narrow-band systems are inserted accordingly (Fig. 14-33).

Where electricity networks are inductively linked with each other through a higher order voltage level, certain regulations must be observed when operating a ripple-control system so that the ripple control facilities of adjacent supply utilities do not interfere with each other. In Germany, the Federation of German Electricity Companies (VDEW) in collaboration with the manufacturing companies has issued “Recommendations for frequency planning in ripple control installations”1). These stipulate the audio frequencies and limit the residual audio frequency level in the higher-order network to a maximum of 0.3 % U_n.

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1) Source: Ringbuch der Energiewirtschaft, Abschnitt 234, 3 bis 5

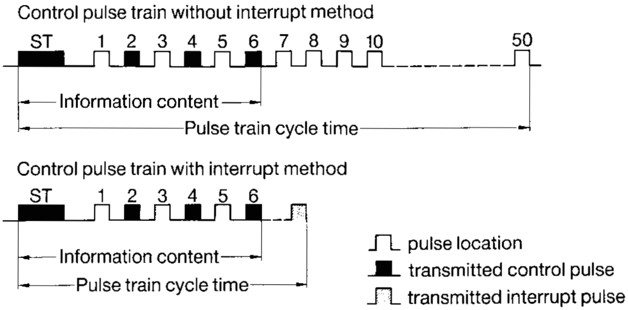


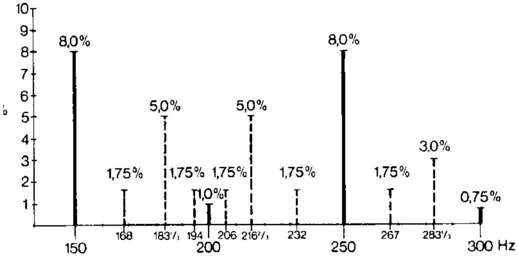
Fig. 14-32

Trains of control pulses with and without interrupt pulses
ST= starting pulse

Fig. 14-33

The harmonics of a 50 Hz network ————

Preferred ripple control frequencies ---------



With new installations, frequencies of 150 to 450 Hz (the bottom part of the permitted frequency band) are preferred because of better propagation conditions and a more uniform distribution of levels, i.e. reduced resonance effects due to the power transformers and compensating capacitors being connected in series. In older systems or in special cases, higher ripple-control frequencies (up to approx. 1600 Hz) may also occur.

The requisite audio frequency voltages and currents are injected into the supply network by static inverters followed by either series or parallel couplings.

Filtering out the audio frequency voltages, decoding the telegrams and then converting them into switching commands is done by ripple control receivers, which can be connected to the consumer's network (e.g. 220 V) wherever desired. Switching operations are generally controlled with the aid of ripple-control technology in low-voltage networks. If switching operations also need to be controlled in the distribution network in special cases, the ripple-control receiver is connected via voltage transformers.

The transmitter units are connected to the central load management computers by dedicated telecommunication channels, e.g. VFT channels.

New ways of operating ripple-control systems have become possible as the result of a new technique which allows the receivers to function as “remote-controlled timers”.

With this method, changeover times can be stored in the switching program or schedule, and then activated by the internal clock. The timetable can also be modified, adjusted according to temperature for instance, from the central command point.

It is then only necessary to send synchronizing signals from the command centre to the receivers, perhaps once a day, so that the receivers can continue to function independently.

The control system is thus unaffected by outside influences. In consequence, the central ripple control equipment and the power distribution network serving as the communication channel must no longer be 100 % available in order to be certain that the appropriate control action always takes place. A protocol for transmission with secured data now exists to accommodate this new approach.

The equipment of control centre, transmission equipment and receivers must therefore conform to the protocols both of conventional ripple control techniques and of data-protected transmission.

14.6.3 Ripple-control command centre

The process is controlled and monitored centrally from the load management unit.

Its main duties are:

- Execution of time- and event-based control actions according to defined time schedules.
- Display of receiver status.
- Continuous measurement of system load and calculation of load trends within a billing interval (e. g. 15 minutes).
- Determining power corrections and scheduling consumers for connection / disconnection.
- Control and monitoring of transmission equipment and of transmitted pulse trains by exchanging data with the substation controllers.
- Displaying tables and curves on video terminals.
- Printing out reports.
- The new technology also requires means of registering the time schedules stored in the decentralized receivers, supporting the second secured transmission protocol, etc.

14.6.4 Equipment for ripple control

Ripple-control systems are the equipment required for injecting the audiofrequency signals into the distribution network.

The entire system comprises an audiofrequency transmitter, which generates a constant output voltage of a defined frequency, the connection for injecting the audiofrequency voltages or currents into the distribution network at the required level values, e.g. 1.5 % of the rated system voltage, and the substation control devices. These controllers continually exchange data with the command centre, generate conventional or secured-data control telegrams, control and monitor the transmitter, keep check of the signal level and detect fault conditions. The station’s status is regularly transmitted to the command centre.

Ripple-control transmitters

Ripple-control transmitters are static converters which rectify the network voltage (e. g. 50 Hz/380 V), and by triggering power semiconductors (thyristors or transistors) convert the DC voltage into audiofrequency voltages which are passed as a three-phase signal to the transmitter output.

Depending on the injection level, network structure and losses at the couplings, roughly 0.1 % of the network power is needed for the transmitters. When injecting into 12 kV and 24 kV networks, this means that outputs of 15 to 150 kVA are required and for injection into the 110 kV network outputs of 400 to 1500 kVA.

ABB RTS 400 transmitters of the S.P.I.D.E.R. LMS family have electronic current limitation and can be matched to the transient behaviour of different kinds of coupling. The same transmitters can be used for parallel and series couplings.

Coupling

The audio frequency generated by the ripple control transmitter must be superimposed over the distribution network at the required injection level and must be as loss-free as possible, and in reverse the system voltage and its harmonics must be dampened enough to prevent the transmitter from negatively influencing the process. This is the task of the coupling. A distinction is made between inductive (series) coupling and capacitive (parallel) coupling.

The choice of coupling technique depends on the impedance ratios due to the selected ripple control frequency, as these influence the signal and crosstalk levels. But important too, is the design of the station being fed with the injected signal, together with installation aspects (presence of high-voltage switchbays for parallel coupling) and operational considerations.

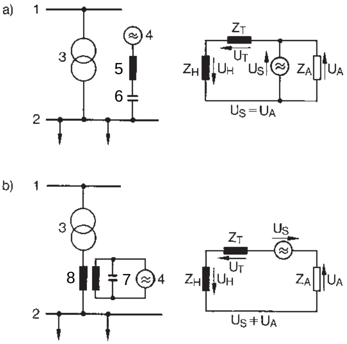


Fig. 14-34

Principle and equivalent diagrams of parallel and series coupling of ripple-control transmitters:
1 Higher-order network, 2 System being controlled, 3 Power transformer, 4 Ripple-control transmitter,

a) Parallel coupling
5 Coupling transformer
6 Coupling capacitor

b) Series coupling
7 Series capacitor
8 Instrument transformer / power transformer (for coupling)

Parallel coupling, Fig. 14-34a

Parallel coupling is preferred for higher audio frequencies. The voltage source is in this case in parallel with the ripple-control network Z_A (see equivalent diagram). The audio frequency current across the shunt of transformer Z_T and high-voltage network Z_H must however be provided in addition to the current from the ripple-controlled network.

Coupling to the 50 Hz network is effected by a series resonant circuit matched to the audio frequency. The capacitor is on the network side and almost the entire network voltage drop occurs here. The ratings of high-voltage capacitor and coupling transformer are governed by the audio frequency and the total network impedance (Z_A parallel to Z_T and Z_H) and the signal level.

Series coupling, Fig. 14-34b

Series coupling is used mainly with low frequencies where, as the equivalent diagram shows, the inductive voltage drop across transformer Z_T and high-voltage network Z_H is small compared to the network Z_A with ripple control .

The coupling is inductive, injection being via an instrument transformer or power transformer. The audio frequency transmitter output voltage is transformed to the required network injection level, e.g. 1.5 % of the system voltage, or 173 V with 20 kV/$\sqrt{3}$.

The 50 Hz network currents (instrument transformer) or 50 Hz network voltages (power transformer) are reflected back to the transmitter side. With instrument transformer injection, the transformed 50 Hz current is passed through a 50 Hz series circuit (see Fig. 14-34b), while with power transformer injection the 50 Hz reverse voltage is blocked capacitively. The instrument transformer method has the advantage over the power transformer of smaller network voltage drops, but is less suitable for higher throughput ratings.

14.6.5 Ripple control receivers

Most of the ripple control receivers installed at the consumer's end evaluate the pulse trains of a defined frequency superposed on the 50 Hz supply, and convert them into switching commands. According to IEC 1037, which covers ripple control receivers, the guaranteed functional voltage must be 0.5 % and the guaranteed non-functional voltage 0.3 %. This means that all receivers in the network must be sure to respond to audiofrequency voltages equal to or greater than 0.5 % of the network voltage, and refuse to respond to values equal to or less than 0.3 %.

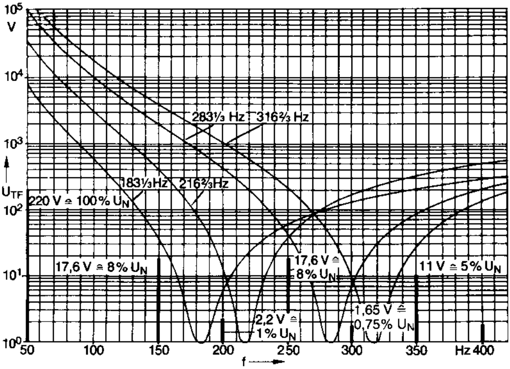


Fig. 14-35

Broad-band response characteristics of ripple-control receivers for common transmission frequencies, ─── Response characteristics of receivers, ━━━ Harmonic voltage level of network, U_N Network voltage, f Audio frequency, U_{TF} Audio-frequency voltage

The principal components of a conventional ripple control receiver are the filter module, the telegram decoding unit and the output relay stages.

The filter unit has a pass band optimized to the chosen control frequency, and must adequately suppress the unwanted frequencies, e.g. system harmonics or neighbouring control frequencies. A distinction is made between narrow-band and broad-band systems, see Fig. 14-35, i. e. filters with greater or lesser selectivity, corresponding to longer and shorter settling times, or telegrams of longer or shorter duration.

Receivers with digital filters show particularly good characteristics, suppressing system harmonics and frequencies very effectively at defined intervals of 8⅓ Hz for example, see Fig. 14-36.

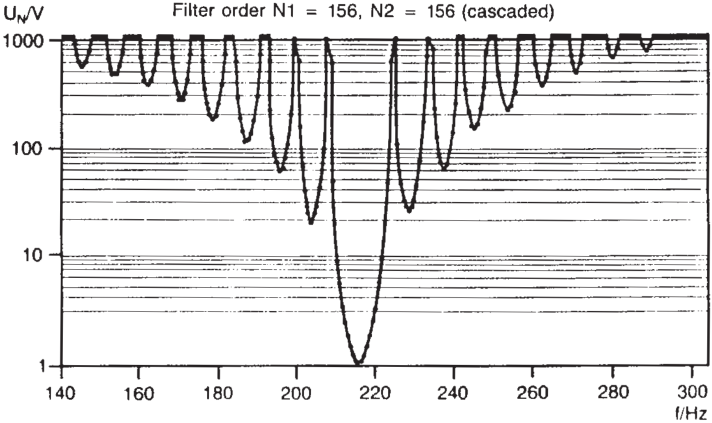


Fig. 14-36

Filter curve of a digital filter with optimum suppression of system harmonics and defined neighbouring frequencies at 8 ⅓ Hz intervals

The decoding units can evaluate telegrams generated by different ripple-control methods, e.g. Semagyr, Decabit, Ricontic, etc. Identification is by means of so-called system parameters. The telegrams are usually encoded in m-out-of-n or m-times-n codes.

New types of ripple control receiver are able to process in parallel both conventional telegrams and telegrams with data protection. This protocol is defined by a statement of block length, CRC of the block length, statements of function specification and address specification, CRC of the complete data block and an active end bit. The protocol is used for all kinds of purposes, such as transmission of switching commands, remote assignment of parameters (switching times, enabling/disabling of switching schedules, and so on) and sending synchronizing signals, etc.

Modern receivers can thus operate on the “distributed intelligence” principle and perform functions independently.

The devices are generally installed on meter panels or directly on the meter terminal cover with the use of a special terminal cover (see DIN 43861).

Technical requirements and test procedures are described in the VDE 0420 standard and must be observed.

15 Secondary Installations

15.1 Stand-by power systems

15.1.1 Overview

Stand-by power systems supply power to electrical equipment if the supply from the public distribution system is interrupted by faults or if a direct supply does not seem feasible for technical or business reasons.

The following grouping is based in the different requirements:
- emergency power systems,
- auxiliary power systems,
- frequency converters.

Table 15-1
Application for stand-by power systems

User group		Equipment with secure supply
public and commercial buildings	public assembly areas, shop and office buildings, banks, insurance companies, control centres.	emergency lighting as per DIN VDE0108
	high-rise buildings, hotels, government and administration buildings, conference centres, institutions, laboratories.	security, monitoring and power supply systems.
	hospitals	as per DIN VDE 0107 and 0108, special regulations, AV SV and ZSV network for security, monitoring and power supply systems, operating room lighting.
	warehouses and refrigerated storage	cooling units, security systems.
	communications centres, data processing centres.	data processing systems, air-conditioning systems.
traffic	airports, air traffic control	control centres, runway, tower and emergency lighting, radio and radar systems, data processing systems, aircraft on-board systems (400 Hz) for ground power.
	railway stations	control centres, emergency lighting, monitoring and signalling systems.
	road tunnels, highway intersections	lighting, ventilation, monitoring and signalling systems

(continued)

Table 15-1 (continued)

Applications of stand-by power systems

User group		Equipment with secure supply
telecommunications and energy transmission	radio systems and telecommunications exchanges, relay stations, energy auxiliary equipment supply substations	telecommunications devices and installations, telecontrol systems, monitoring and power equipment
industry	manufacturing and functional processes	safety, monitoring and power supply installations, process computers, automation.

15.1.2 Stand-by power with generator systems

Generators with diesel engines are preferred for providing stand-by power to consumers for which there is sufficient time for starting a power generator; see DIN 6280 Parts 1 to 15.

The generator sets are used to generate power for

- emergency power supply installations that supply the regular consumers in the event of failure of the regular power supply,
- peak load operation to cover daily demand peaks,
- auxiliary supply of cogenerating systems with heat or current-controlled operation,
- installations in continuous operation without an adequate power supply system.

Diesel engines are most frequently used for emergency power systems. Units with an output above 100 kW are normally supplied with turbo charger only. High-speed machines with a rated speed of 1500 min^{-1} are mostly used. As well as better power-to-weight ratio, this allows better adaptation to synchronous generators of the standard type (4-pole design). However,diesel engines with turbo charger do have the disadvantage that they cannot produce their rated output in one stage.

The power generators used may be asynchronous generators (economical) or for installations of higher output, they can be alternators. The most common alternators have a brushless design. A built-in self-excited three-phase stationary-pole exciter with rotating diodes supplies the rotor current. The voltage is regulated in the three-phase exciter field. If fast compensation of the generator voltage is required, self-excited compound generators (constant-voltage generators) are to be preferred. Electronic voltage controllers are equivalent to the compound regulators.

The demands on the power supply of the consumers depend on the application. The operational response of the generator set must be able to meet the consumer's requirements. The following types are classified according to the application:

Type 1, low demands on the voltage and frequency response

Type 2, voltage response generally conforming to that of the public system

Type 3, increased demands on the voltage and frequency response

Type 4, maximum demands on the voltage and frequency response

The sets must be selected depending on the type. When rating the power of the generator, the connected loads of all power consumers must be determined, taking into account the simultaneity factor and the largest consumer that is to be connected. The connected load should be 60%-70% of the rated generator set output to ensure sufficient reserve power for reactive power requirements and switching operations. If 6-pulse three-phase rectifiers are connected as consumers, the output of the set must be adequately rated because of the resulting harmonics (overdimensional). In addition to the intrinsic response of the diesel engine and generator caused by design characteristics, the size and type of the connected consumers have a decisive influence on the required generator power. So with turbocharged diesel engines, a base load already provides better frequency response (turbine pre-acceleration). Rotor damping, type of excitation and overexcitation capacity are the main influences on the maximum voltage dip for the generator.

Typical values for the speed and voltage response are specified in DIN 6280 Parts 1 to 13 and the standard ISO 8528 Parts 1 to 6. Small generators (<10 kVA) are subject to the standard ISO 8528 Part 8.

The machine room should be sufficiently large. Rooms that are too small make operation and maintenance difficult and the ventilation problem is often difficult to solve satisfactorily. The questions regarding setup with proper noise isolation and fuel storage (observe TÜV regulations) are also important, as is the problem of putting the equipment into place and its accessibility once installed. There must be a 1 m wide space all around the set under all circumstances. The space required is also determined by other installations such as fuel tanks, sound absorbers, closed-circuit cooling, batteries and switching and control equipment; see also Section 4.7 Structural Requirements.

The core of the automatic controller for emergency generator sets is the “ABB neacontic automatic start/stop” with a programmable controller (Procontic family or third-party). It controls the following tasks:

“automatic” mode

- all-pole system voltage monitoring
- start command in the event of system fault (preferably time-delayed)
- starting procedure
- repeated start if applicable
- operational monitoring
- control of auxiliary equipment
- monitoring of generator voltage
- switching from network to generator operation (interlocked) or initialization of parallel circuit.
- detection of return of system availability
- delayed automatic return switching of consumers from generator to network operation with and without interrupting power supply.
- aftercooling
- shutdown
- cancellation of the shutdown procedure in the event of another system fault while the set is still running and immediate supply of power.

“manual” mode

- manual operation for startup and shutdown. Interlocked switchover from network and generator mode and back.

“test” mode

- test operation for checking all automatic processes (including transfer of power supply).
- test operation for checking all automatic processes (not including transfer of power supply).
- automatic transfer of power supply if the system fails during test mode operation.

“Off” mode

- all equipment operation blocked, e.g. for maintenance. The power supply to the consumers is not interrupted.

“EMERGENCY OFF” mode

- with mechanically interlocked “OFF” position
- stops in the event of danger to personnel or installation, regardless of the selected mode.

Fault monitoring operates at a higher level than all other operating modes and displays the fault message and shuts down the generator if required.

A generator operating in “automatic” mode can, depending on its size, take over supplying power after 10–15 s. Additional measures such as heating the room, preheating lubricant and coolant, assisted starting, compressed air starting and high-speed excitation can reduce this time to 5–10 s.

The automatic transfer synchronization ensures uninterruptible switchover of the consumers from the generator to the network and from the network to the generator, e.g. ABB synchrotact 4 (see also Section 14.3.6).

Emergency power systems with several generators operating in parallel require an automatic synchronization device for parallel switching. Another option is starting synchronization. This involves several generator sets being simultaneously switched in parallel over busbars during starting. The consumers are separated from the busbars during this process.

The use of equipment for automatic effective and/or reactive power sharing enables the output to be distributed in accordance with the percentage ratio of the load capacity of the individual generator sets.

An additional device (cosφ controller) makes it possible to retain a setpoint for the desired power factor for parallel system operation.

15.1.3 Uninterruptible power supply with stand-by generating sets (rotating UPS installations)

Rotating UPS installations are characterized by a generator running continuously at its rated speed. Its output must be sufficient to supply power to all consumers dependent on an uninterruptible power supply. This also applies for the design of the associated mechanical generator sets.

Rotating UPS installations are classified for the possible override time as follows:

– converter and flywheel for short-term override (about 1 s),

– converter and storage battery for part-time override (to about 30 min.),

– converter and flywheel and coupled diesel machine for long-term override (practically unlimited).

Uninterruptible power systems

The classical design of an uninterruptible power set has the most important components, a diesel engine, an electromagnetic clutch, a flywheel, a three-phase asynchronous motor and a three-phase alternator, installed on a common base frame (Fig. 15-1a).

The asynchronous motor is connected to the public power supply and runs the generator with the flywheel. The consumers that require uninterrupted power are continuously supplied with power from the system through the three-phase converter. The diesel engine is uncoupled and not operating at this time. In the event of a system fault, the asynchronous motor is shut down; at the same time the magnetic clutch is closed and the diesel engine is started by the flywheel.

During the transition from the faulty network to emergency diesel operation, the flywheel alone supplies the driving force for the generator while simultaneously supplying the energy to start the diesel engine. The flywheel start brings the diesel engine to its working speed within 1 . . . 1.2 s. This virtually precludes a failed start.

While in the first standard design described a motor generator supplies the consumers that require protection, in many cases one single electrical machine (reversing machine) is sufficient. It uses the available system voltage to drive the flywheel as a synchronous motor and operates as a diesel generator in the event of a power failure. Fig. 15-1b illustrates the principle of an uninterruptible power system with a synchronous reversing machine.

See Figs. 15-1c) and 15-1d) for other options.

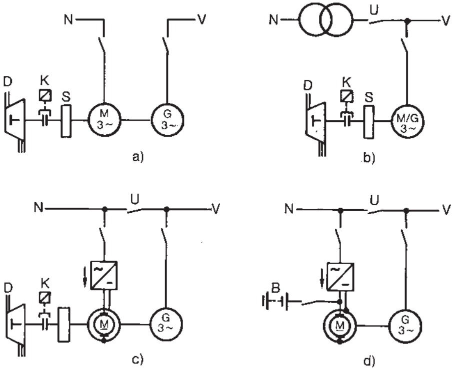


Fig.15-1

Basic design of uninterruptible power sets: a) with induction-synchronous generator set, flywheel and coupled emergency power diesel engine; b) with synchronous reversing machine, flywheel and coupled emergency power diesel engine, c) with direct current three-phase converter, flywheel and coupled emergency power diesel engine, d) with direct current-three-phase converter and storage battery separate from network; N network lead, U clutch, V consumer, S flywheel, B battery, K magnetic clutch, D emergency power diesel engine

Fast-start power sets

Fast-start power sets are special emergency power systems with flywheels that can be used where short-time interruptions of approximately 250 ms are permissible. Their design is generally similar to the uninterruptible power set with converter set. The difference is that with the uninterruptible power set, the generator supplies power continuously to the consumers while the consumers connected to the fast-start power set receive their energy from the network.

The total cost of all rotating UPS installations (purchase, maintenance, operation) is high. For this reason, they are primarily used with high power requirements.

15.1.4 Uninterruptible power supply with static rectifiers (static UPS installations)

Uninterruptible power supply systems that operate with static rectifiers and storage batteries are increasingly being installed in many areas, particularly for small to medium output applications.

Operation

ABB UPS installations are based on a rotary converter. The UPS circuit diagram shows the six most important components (Fig. 15-2):

- – rectifier/battery charger (6-pulse) (GR)
- – battery (B)
- – inverter (WR)
- – static reversing switch (SW)
- – static bypass (SB)
- – maintenance bypass (WB)

All components are installed in one housing. The controller electronics for the rectifier, inverter and the bypass area are completely independent of one another. This means that a fault in one area cannot cause a fault in the adjacent area.

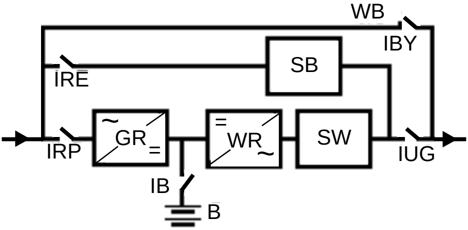


Fig.15-2

UPS circuit diagram

Features

UPS function

The **U**ninterruptible **P**ower **S**upply (UPS) is connected to the circuit between the power supply network and the power consumers (load). They are designed to guarantee a constant voltage supply for the load. If a network failure occurs, it can supply the load for a preset period (autonomous period). The UPS has also other advantages compared to conventional supply systems (network, engine-powered generators, etc.):

Better output characteristics

Monitoring the UPS output voltage and frequency guarantees constant output power. Variations in the system voltage and frequency, which are generally present in electrical power systems, do not influence the output voltage of the UPS.

Decoupling system distortions

The double conversion from AC to DC and back to AC filters out all system distortions. All UPS consumers are also fused for protection against power system faults, which can occur in industrial power supply systems. This is particularly important for sensitive electronic equipment such as computer systems, control systems and medicinal equipment.

Complete protection against power system faults

If the power supply system fails, the UPS supplies energy to the load from the battery. The battery is connected to the UPS rectifiers and inverters. The inverter supplies power to the load.

During standard operation, the inverter receives energy from the rectifier. The rectifier then charges the battery at the same time.

In the event of a power system fault, the connected battery automatically supplies power to the inverter. This means that the power supply to the load continues without interruption. However, the battery can only supply the load for a specified period (autonomy period). If longer periods of autonomy are required, it is worthwhile supplying the UPS with a diesel generator as an emergency power supply. In this case, the autonomy period is calculated for the period between network failure and full generator power.

Rectifier/battery charger

In the standard configuration, the charger is a 6-pulse three-phase rectifier. It converts the network AC voltage to DC voltage. It is normally connected directly to the power supply system via commutating reactors (no galvanic isolation). The commutating reactors reduce the system perturbations of the rectifier. The charger feeds the battery and the inverter. The battery is connected to the charger via a saturable reactor to reduce the residual ripple of the DC voltage. This ensures maximum battery life.

The rectifier is designed to supply the inverter and charge the battery with the maximum loading current simultaneously at maximum load. The floating charging voltage for standard batteries (maintenance-free lead battery) with 192 cells is kept constant at 432 V (2.25 V per cell). The battery is charged with I/U characteristic. This means that the charging current limit is reached by reducing the intermediate circuit voltage. This ensures that the battery is not damaged by excessive charging current. A 12-pulse rectifier is optional and requires the addition of a second rectifier bridge in the UPS cabinet and a phase-shifting transformer in a separate accessory cabinet.

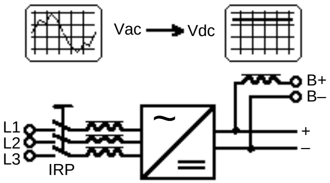


Fig.15-3

6-pulse
rectifier circuit diagram

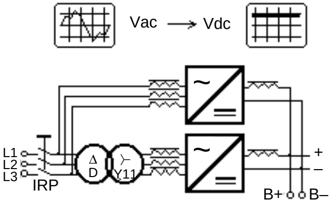


Fig.15-4

12-pulse
rectifier circuit diagram

Battery

The battery supplies the inverter in the event of a short interruption or a system failure. The battery is designed to continue to supply the load for a specified period (autonomy period) depending on the battery capacity and the actual load.

The number of cells in the battery depends on the type and also on the customer-specific requirements. The standard number is 192 cells for lead-acid and 300 cells for NiCd batteries. The battery capacity (Ah) depends on the UPS output and the required autonomy period.

Inverter

The inverter, which is supplied by the rectifier or the battery, converts the DC voltage fed from the rectifier or the battery into a.c. voltage with constant voltage and frequency, a form of power suitable for the power supply of highly sensitive electronic equipment.

Pulse duration modulation is used to generate the AC voltage. The output voltage (harmonic content < 1%) is smoothed by a high operating frequency of the power semiconductor and the use of an output filter (transformer and capacitors).

Every phase-to-earth voltage at the output of the inverter is regulated separately. This ensures that the UPS output voltages remain constant even under very non-symmetrical loads.

For protection of the inverter, the inverter electronics restrict the inverter output current to 150% of the rated current in the event of a short circuit. In the event of overload, it restricts the inverter output voltage to no more than 125 % of the rated power. If a serious overload occurs, it automatically switches to bypass mode, if the bypass is available.

Saturation monitoring or an "electronic fuse" protects the inverter transistors from destruction by short circuits.

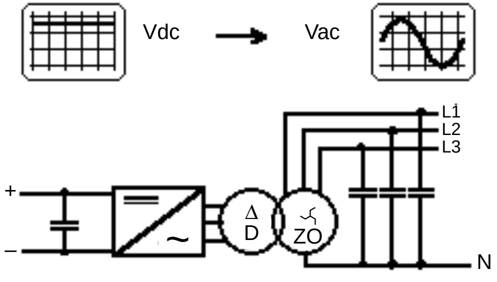


Fig.15-5

Inverter circuit diagram

Static switches

The circuit diagram shows the two static switches, which are thyristor switches. In standard operation, SW is closed and SB is open. This switches the load to the inverter output.

In the event of an overload or the destruction of an inverter, SB is closed and SW is open, switching it to an auxiliary power supply (network, output of another UPS, diesel generator, etc.). The two switches, SW and SB, are always closed at the same time for a short period when switching between inverter and bypass mode. This prevents any interruption in the power supply even in the event of a fault. This condition is essential to enable all demands by the connected sensitive devices on the voltage supply to be met.

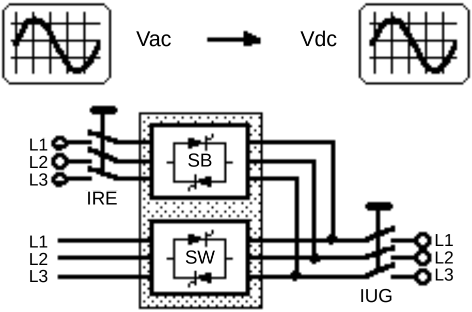


Fig.15-6

Static switch circuit diagram

Maintenance bypass

During UPS maintenance work, the maintenance bypass supplies the connected load directly over the network. The maintenance bypass consists of a switch (IBY).

The UPS installations allow switching from the various operating modes to the maintenance bypass without interrupting power. If the maintenance bypass is activated, the rest of the UPS can be switched completely voltage-free to allow maintenance or repair (up to the input and output terminals and their connections to the IRP, IRE, IUG, IB circuit-breakers).

To prevent faulty switching of the IBY maintenance bypass switch, which could be caused by parallel switching between inverter and maintenance bypass system, the IBY maintenance bypass switch is electronically interlocked against the static SW reversing switch. If IBY is closed, SW opens automatically. This prevents parallel switching between inverter and maintenance bypass system.

ABB can supply an external wall-mounted uninterruptible maintenance bypass switch as an option. This switch enables simple switchover to the maintenance bypass with no possibility of faulty switching and without interrupting the load. This makes it possible to switch all power to the UPS by shutting off its power supply completely.

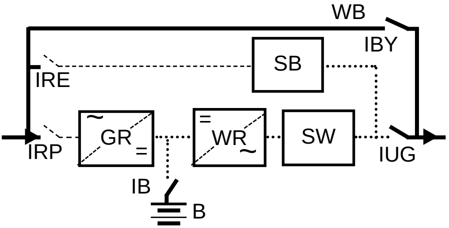


Fig. 15-7

Internal maintenance bypass circuit diagram

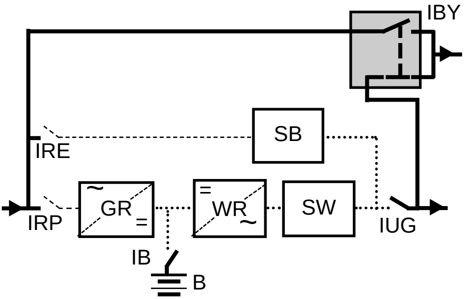


Fig. 15-8

External maintenance bypass circuit diagram

Hot stand-by operation

A hot stand-by UPS system is basically two (or more) UPS installations, which operate independently of one another. Each installation can supply the load at any time.

- All installations are in operation continuously, but at any time only one UPS is supplying the load.
- If a fault occurs in the active installation, another installation is ready to take the load without interrupting the output voltage; i.e. a constant power supply to the load is guaranteed at all times.
- The load is only supplied from the static bypass if there is no inverter in the system able to take the load.

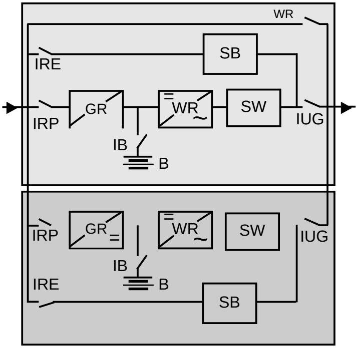


Fig. 15-9

Hot stand-by operation circuit diagram

Redundant parallel operation

A parallel UPS system consists of two to six UPS installations switched in parallel over which the load is equally distributed. Every installation has its own static bypass (SB), this ensures SB redundancy in the system. This means that if one SB fails, the bypass system is still always available.

The parallel system does not have a central controller. Each installation has its own separate paralleling electronics to monitor all functions and to provide full redundancy.

Parallel operation

This configuration is identical with that of the redundant parallel operation, except that the rated power of the UPS systems normally conforms to the output power and there are no redundant installations. UPS installations of varying output can be parallel switched in this configuration, because the load is distributed proportionally to the installation output. The parallel configuration conforms to the redundancy configuration if the load has been reduced to a value that allows the system to continue to supply the reduced load with one (or more) installation(s) fewer. This makes one (or more) installation(s) redundant and the controller is identical.

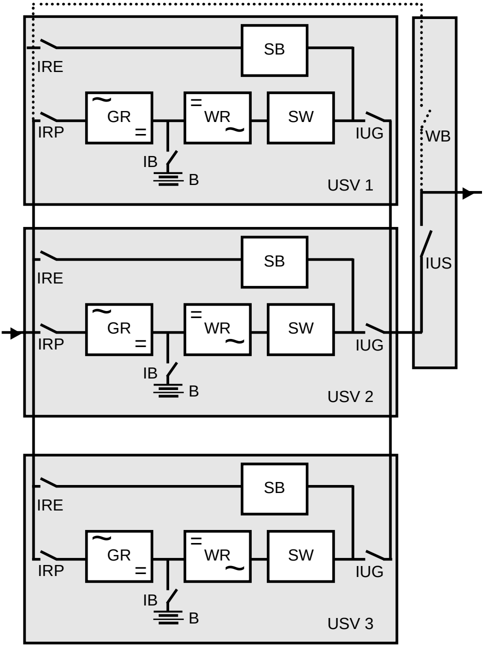


Fig. 15-10

Parallel operation circuit diagram

Table 15-2

ABB UPS system range with technical data

Type		ABB/Mini	ABB/MP	ABB/S400	ABB/PX4
Unit capacity	kVA	0.5 to 10	7.5 to 25	10 to 120	150 to 400
Input voltage	V	230/1ph.	400/230	400/230	400/230
permissible voltage tolerance	%	± 10	± 10	± 10	± 10
Input frequency	Hz	50 (60)	50 (60)	50 (60)	50 (60)
permissible frequency tolerance	%	± 5	± 5	± 5	± 5
Output voltage	V	230/1ph.	230/1ph.	400/230	400/230
voltage tolerance at:					
– symmetrical load	%	± 3	± 1	± 1	± 1
– at 50 % step change in load	%	± 4	± 4	± 4	± 4
– at 100 % step change in load	%	± 6	± 10	± 5	± 10
Output frequency	Hz	50 (60)	50 (60)	50 (60)	50 (60)
frequency tolerance	%	± 0.5	± 0.5	± 0.5	± 0.5
Distortion factor	%	< 4	< 3	< 2	< 3
Current carrying capacity:					
– inverter 1 min.	%	120	150	150	150
– static bypass 1 min.	%	150	200	200	200
Total efficiency	%	83	90	90	93
Noise level	db(A)	ca. 50	ca. 60	ca. 61	ca. 63

Notes on all ABB UPS types:

System configuration: on-line (double conversion)
setting ranges for input and output voltages:
380/220 V/400/230V/415/240 V

Radio interference suppression: limit class A as per EN 50091-2

Design: in accordance with European directives 89/336/EEC and 73/23/EEC

ABB UPS installations meet the requirements of European directives 89/336/EEC and 73/23/EEC and of EN 50091-2 (1995) and EN 50091-1 and therefore have the CE mark.

ABB UPS installations conform to limit class A as per EN 50091-2
The installation may radiate electromagnetic fields in its immediate vicinity. In this case, the operator is expected to conduct additional measurements or take action.

15.2 High-speed transfer devices

15.2.1 Applications, usage, tasks

In power and industrial plants, large motors and other important consumers must have a backup in case the general power supply system fails, because otherwise availability, production, profitability and safety will be restricted or people may be injured and the environment and process equipment may be damaged. With such high outputs, backup generators are no longer sufficient. A second power supply ready for immediate operation is required. It is important for the second power supply to be independent of the effects of a fault in the general power supply system. The supply must come from another transmission network or a different power generator.

The fast transfer to the second power supply is generally done at the same voltage level as the large consumers, i.e. in the rated voltage ranges up to 24 kV. However, in some situations, the transfer is done in the low-voltage network or at the level of a transmission voltage. This can basically involve switching over one large consumer, such as a motor, and also switching over a whole group of important consumers linked together over one busbar section.

The transfer must be done very quickly and without any serious feedback to the consumers and power supply, i.e. the switching must be controlled with very short transfer times with regard to the physical processes in the network and at the consumers. This task is handled by high-speed transfer devices, which are based on digital hardware technology and can be integrated into every modern installation protection design.

To take full advantage of the possibilities of high-speed transfer devices, the general design must meet the following requirements:

- there must be at least two, generally independent of each other synchronous power supplies
- circuit-breakers with short operating times
- switchgear installation must be suitable for system transfers
- fast protection relays for initiating the high-speed transfer device

Transfers initiated by operational conditions can be started manually using the high-speed transfer device, but in the event of a fault, the transfer system reacts automatically.

Examples of applications of the ABB SUE 2 high-speed transfer device is shown in Figs. 15-11a and 15-11b.

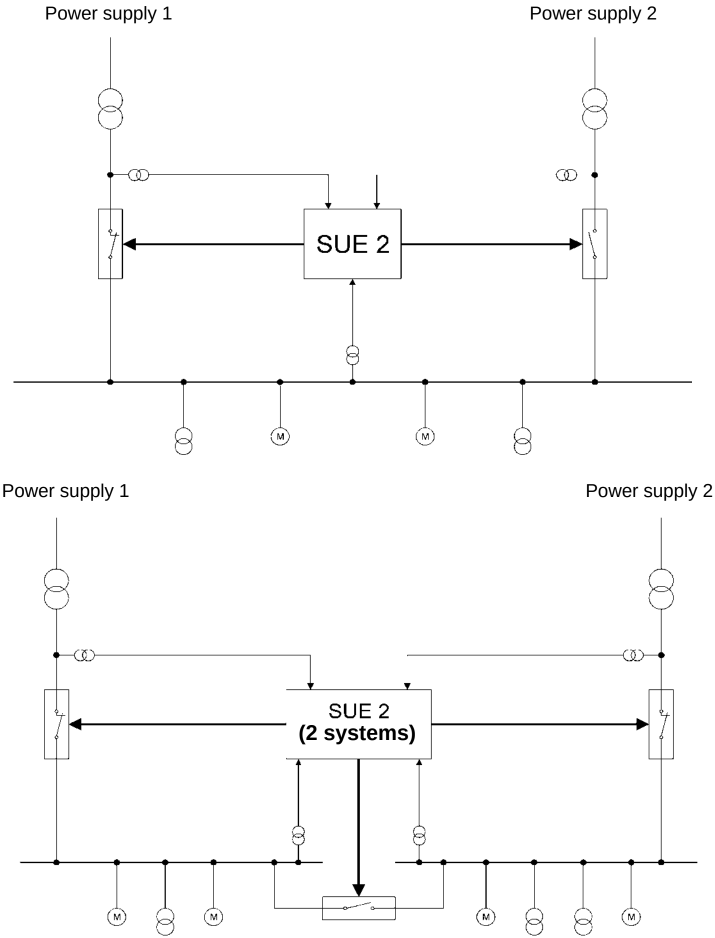


Fig.15-11

Example of a switchgear installation with high-speed transfer devices
a) Single busbar with two power supplies
b) Single busbar with two power supplies and bus sectionalizer

15.2.2 Integration into the installation

Corresponding to its great importance, the high-speed transfer device must be considered at the planning stage of a switchgear installation and its secondary components, because it communicates with many other station components (Fig. 15-12). There are interfaces to the following components, among others:

- switchgear installation (circuit-breakers, voltage transformers, overcurrent relays etc.)
- protection (block, transformer, differential, cable, undervoltage protection etc.)
- control systems/control room (remote control, signalling system)
- voltage supply (DC power supply).

Additional interlocking, releases or blocking in conjunction with other components may be required because of the large number of individual design options for a switchgear installation as well as the operational conditions.

Fast, direct and undelayed starting by external protection relays is also important for optimum conformity with all demands on the high-speed transfer device.

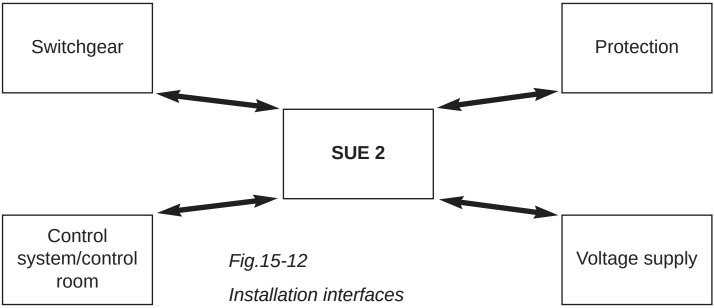


Fig.15-12

Installation interfaces

15.2.3 Design of high-speed transfer devices

The ABB Type SUE 2 high-speed transfer device primarily consists of the following three function groups:

- logical processing module
- digital phase comparison unit
- test device

The logical processing module consists of a modular, programmable logic controller (PLC). All functions required for controlling the circuit-breaker, for interlocking, blocking, acknowledgements, signalling and monitoring are controlled by the PLC.

The digital phase comparison is implemented with an intelligent, programmable microcontroller unit. The unit has integrated A/D transformers, which read in the required measurement voltages. Comparison of the electrical parameters of voltage, frequency and phase relationship is an extremely time-critical process, which is secured by its implementation in low-level assembly programming.

The test device enables the functioning of the high-speed transfer device to be tested, including a continuity test of the control coils of the circuit-breakers that they actuate. It also provides information on the system status of the installation. In the event of a fault, an internal diagnosis provides detailed information on possible faults.

15.2.4 Functionality

The high-speed transfer device continuously compares the busbar voltage with the voltage available in reserve. The transfer criteria are generated from the monitoring process of the voltage amplitudes, the frequency difference and the phase angle.

The different transfer situations described below are initiated at the moment of starting based on the current power system status.

The high-speed transfer device must always be started externally. This is normally done manually from the control room or initiated by suitable fast protection relays. Basically, if a limit value defined as an undervoltage in the current power supply is reached, an undervoltage initiation can also be independently generated. The transfer direction – either from the main to the reserve power supply or vice versa – is information taken from monitoring the corresponding circuit-breaker positions. The high-speed transfer device is only ready for operation when both circuit breakers that are to be actuated are definitely in different switching states (plausibility check) and are in operating position.

Switching commands from the high-speed transfer device to the circuit-breakers – bypassing all switchgear interlocks that might be present – are sent directly to the control coils.

15.2.5 Types of transfer

The decisive criterion for the type of transfer is the power system relationships at the moment of starting the high-speed transfer device. In principle, the following transfer options are available:

- fast transfer
- Transfer at the 1st phase coincidence
- residual voltage transfer
- long-time transfer

The preferred and most important functional principle of the SUE 2 high-speed transfer device is to conduct fast transfers. If there are no prerequisites for this, the device offers additional, optional function mechanisms.

A fast transfer occurs if the main and reserve power supply are quasi-synchronous within preset limit values, i.e. slip and phase angle between the networks are limited and the reserve voltage is above a minimum value. During this process, the high-speed transfer device sends OFF and ON commands to the circuit-breakers simultaneously. The pause without power that occurs for the consumers in this case depends almost entirely on the difference between the make and break properties of the switchgear.

A transfer in the 1st phase coincidence occurs when the networks were not synchronized at the moment of starting but specific conditions are met. In this type of transfer, the OFF command is sent immediately and the reserve power system is activated in the 1st minimum of the difference of reserve and busbar voltage.

The high-speed transfer device uses predictive calculation to determine the course of the differential voltage and the time of the 1st phase coincidence. To compensate for the processing time dictated by the equipment (SUE 2 mechanical system delay, circuit-breaker delay periods), the ON command is issued at an appropriate period before the actual occurrence of the minimum differential voltage – within a previously defined switching window.

A residual voltage transfer is initiated if the networks are not synchronized at the moment of starting and a beat transfer is also not possible. In this case the OFF command is sent immediately to the feeder circuit-breaker and the ON command is sent to the switch that is to be closed when the busbar voltage has decayed to a set permissible value and the feeder circuit-breaker is safely opened. The reserve network is activated independently from the phase angle and the slip.

There is also a residual voltage transfer if the starting is initiated by the undervoltage monitoring implemented in the SUE 2 or by external undervoltage relays.

A long-time transfer is initiated if the busbar voltage cannot be monitored during a transfer (that does not occur as a fast transfer) (e.g. because of failure of an automatic device). The OFF command is sent immediately, but the ON command is only sent after a defined period as is the return confirmation that the feeder circuit-breaker is open.

The conclusion is that the selection of the type of transfer at the moment of starting the high-speed transfer device is decisive. In general, fast transfers are initiated because the networks are usually synchronized. The principle of issuing commands simultaneously to the circuit-breakers guarantees the shortest possible transfer times and safe, virtually uninterrupted power supply. If the switch that is to be opened fails on a fast transfer, e.g. because of mechanical problems, the high-speed transfer device detects this state and the switch that was just closed is opened again after a preset period, thereby preventing non-permissible, long-duration coupling of the networks.

If the networks are not synchronized at the instant of starting, a fast transfer is not initiated. The resulting dead times without power vary depending on the installation, with the load that is to be switched determining the run-down response of the busbar voltage.

The various types of transfer can be selectively activated and deactivated depending on the direction. This ensures that the optimum transfer concept for the entire installation can be implemented with regard to the special requirements.

A fast transfer is the smoothest type of transfer and in most cases guarantees continued operation of the installation with no interruption. The busbar voltage generally remains stable and the closing currents after the transfer are limited.

When conditions allow switching at the 1st phase coincidence, this type of transfer – a fast transfer was not possible –- is the second best choice, followed by the residual voltage-dependent and the long-time transfer. If the reserve networks are not stable enough for certain transfers, the high-speed transfer device can send signals to initiate targeted load shedding before switching.

The high-speed transfer device is designed to initiate the optimum possible transfer automatically depending on the general conditions. The oscillograms in Fig. 15-13 show some typical transfers.

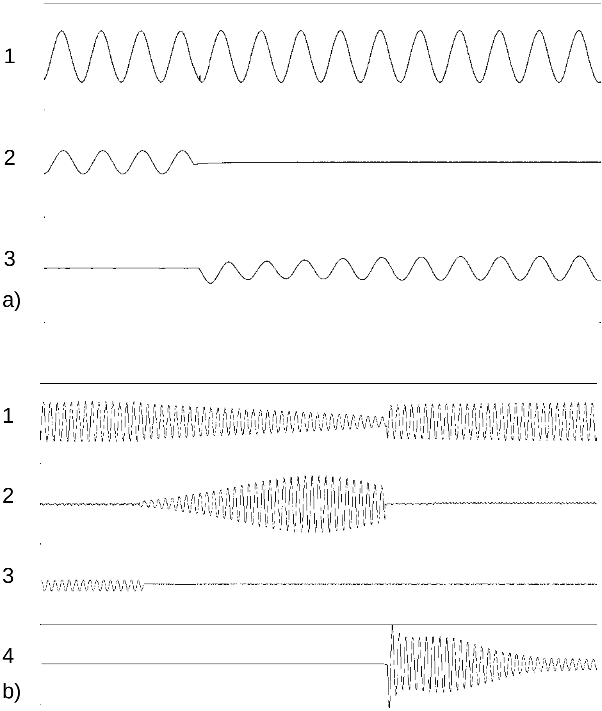


Fig. 15-13 Oscillograms

a) fast transfer
1 = busbar voltage
2 = current main Feeder
3 = current standby Feeder

b) residual voltage-dependent transfer
1 = busbar voltage
2 = differential voltage ($U_{standby}$ - U_{SS})
3 = current main Feeder
4 = current standby Feeder

15.3 Stationary batteries and battery installations, DIN VDE 0510, Part 2

15.3.1 Types and specific properties of batteries.

Battery sets are used in switchgear installations as sources of energy for network-independent power supply of controller protection, regulating and signal circuits and similar.

The battery direct voltage can also be used via inverters to generate “safe AC voltage”. In installations with modern secondary technology, the power supply modules for computers and the electronic protection and also standard data processing devices such as PCs, monitors and printers are supplied with safe alternating voltage (UPS) (Section 15.1.4).

Two types of cells are used in stationary batteries:

- The closed cell has a sealed cell cover with one or more openings through which the gas generated can dissipate or through which water can be added. The openings are closed with suitable stoppers, e.g. fastener stoppers.
- The sealed cell is maintenance-free throughout its life and can generally be installed without regard to position. The internal gas pressure can be released through an automatically closing cell valve.

Note:

It is not possible to prevent the generation of oxygen and hydrogen in a lead-acid battery! A gas density seal is possible only with the NiCd battery. Its negative electrode is above the hydrogen potential.

The nominal voltage and the capacitance of a battery are determined by the required service voltage with consideration of the permissible voltage tolerance of the individual consumers (switchgear and protection devices), the input power of the various power consumers, their duty factor and the type of current draw. Switchgear installations primarily use two types of batteries:

Lead-acid batteries with electrodes of lead and lead alloys and weak sulfuric acid as electrolyte. They are used in switchgear installations, substations and power plants to provide high power requirements for long operational periods, such as emergency lighting.

Important cell types used in lead-acid batteries:

- OGI : with positive and negative grid plates
- OPzS : with positive iron-clad plates
- GroE : with positive high-surface-area plates
- GroE-H : with positive high-surface-area plates, high-current design

Nickel-cadmium batteries with positive electrodes of nickel compounds, negative electrodes of cadmium and weak caustic potash solution as electrolyte.

Important cell types used in nickel-cadmium batteries:

- with pocket-type plates, application type .. L*), preferred for switchgear installations
- sintered cells, e.g. for aircraft
- with bonded plastic plates, application types .. L, .. H and .. M*),
- with fibre plates, application type .. H*), e.g. for motor vehicle batteries.

*) .. H = high current, short duration
.. L = low current, long duration
.. M = medium current, medium duration.

Advantages of NiCd batteries over lead-acid batteries:

- high reliability
- long life
- small footprint
- low maintenance costs
- low reduction in capacity at low temperatures
- fast recharging
- high mechanical and electrical stability
- good storage capacity
- low-charge resistant
- resistant to overcharging
- low self-discharge
- high cycle-capacity
- no pole corrosion

Disadvantages of NiCd batteries over lead-acid batteries:

- high price
- lower cell voltage
- less efficiency
- no full capacity when charged with charge retention voltage
- at high cyclic stress and high temperatures pocket-type cells may require new alkaline electrolyte after some years
- larger voltage window with charging/discharge

Electrical values of *batteries* (see also Table 15-3).

The DIN 40 729 standard defines the basic terms for batteries.

Nominal voltage:

The nominal voltage (U_N) of a cell is a specified value. In the lead-acid battery it is 2.0 V, in the nickel-cadmium battery it is 1.2 V.

The nominal voltage of a battery is the product of the number of cells connected in series and their nominal voltage.

Rated capacity:

The rated capacity ($C_N{}^1$) is the quantity of electricity that a battery can supply during discharge over a defined discharge period (nominal discharge period t_N) with the associated rated current (I_N) at nominal temperature, nominal density and nominal electrolyte status without going below the end-point voltage (U_{SN}).

The maxim is: $C_N = I_N \bullet t_N$

The n-hour capacities are associated with a battery if it can be discharged with currents different from the rated current. The index n gives the discharge time t_n in hours (e.g. C_3 = 3-hour capacity).

[1)] In international texts, C is the standard symbol for capacity.

End-point voltage:

The end-point voltage (U_S) is the set point below which the voltage must not fall during discharge with the assigned current.

The rated end-point voltage (U_{SN}) applies during draw with the nominal discharge current ($I_N = C_N/t_N$) for specifying the rated capacity C_N.

Gassing voltage:

The rated voltage (U_G) is the charging voltage above which a battery begins to discharge gas; in lead-acid batteries 2.40...2.45 V per cell, in nickel-cadmium batteries 1.50 -1.55 per cell.

Charging factor:

The charging factor $1/\eta_{Ah}$) is the ratio of the quantity of electricity required for full charge to the previously drawn quantity of electricity.
(Reciprocal efficiency of the charging η_{Ah}).

Internal resistance:

The internal resistance of a battery cell R/cell is dependent on the cell temperature and the charging or discharging status. The typical values given in Table 15-3 are based on a fully charged battery.

A contact resistance of 2 x 0.04 mΩ/cell can be assumed for the connections between cells.

Table 15-3

Specific properties of batteries.

Name	Dimension	Lead-acid batteries OPzS	GroE	GroE-H	NiCd batteries L	H
Rated capacity C_N	Ah	C_{10}	C_{10}	C_{10}	C_5	C_5
Rated discharge current I_N	A	$I_{10} = 0.1 \cdot C_{10}$	$I_{10} = 0.1 \cdot C_{10}$	$I_{10} = 0.1 \cdot C_{10}$	$I_5 = 0.2 \cdot C_5$	$I_5 = 0.2 \cdot C_5$
Rated end-point voltage U_{SN} at 20 °C	V/cell	to 1.80	1.80	1.80	1.00	1.00
Floating charging voltage U_{LE}	V/cell	2.23	2.23	2.23	1.4	1.4
Gassing voltage U_{LE}	V/cell	2.40	2.40	2.40	1.5	1.5
Charging factor $1/\eta_{Ah}$	—	1.2	1.2	1.2	1.4	1.4
Electrolyte density	kg/dm³	1.24	1.22	1.22	1.19	1.19
		± 0.01	± 0.01	± 0.01	± 0.02	± 0.02
Internal resistance R_i/cell (typical value)	mΩ/100 Ah	3.0	1.4	1.0	1.4	0.6
Load capacity[1)]	—	L	H	H	L	H
Approved temperature range		+ 5 °C to + 55 °C				– 20 °C to + 45 °C

[1)] Load capacity corresponds to:
H: high-current design for short-term load, i.e. for applications where the battery must cover a period of several minutes to a maximum of one hour if the power network fails.
L: for capacity load (long-term load), i.e. current draw for a period of 1 to 10 hours.

15.3.2 Charging and discharging batteries

All operation with batteries requires a regulated power source that recharges the battery. It must also be capable of supplying the consumers directly, depending on the operating mode. The required charging quantity for a lead-acid battery is 120%, and for a nickel-cadmium battery approximately 140 % of the previously drawn Ah. The self-discharge current of a lead-acid battery is about 0.2 % of the three-hour discharge current; that is about 1 % of the 10-hour capacity daily. The quantity of the charging current depends on the capacity of the battery and the charging time. This information is supplied by the manufacturer. In the case of lead-acid batteries the charging current is generally equal to the discharge current with a three- to five-hour discharge. In the case of nickel-cadmium batteries, the charging current should be equal to the discharge current of a five-hour discharge. Once the gassing voltage has been exceeded, it must be reduced to approximately one third of the above-mentioned charging current and should decrease further until charging is complete.

When batteries are fully charged, the charging voltage should be reduced to the floating charge voltage to prevent damage caused by continued gassing, temperature increase and water loss.

Lead-acid batteries can be fully recharged with the floating charge voltage and retain full capacity.

When NiCd batteries are charged with the floating charge voltage, they do not reach full capacity and therefore should always be charged at a higher voltage. Even if a NiCd has been previously fully charged, it still loses some capacity when receiving floating charging voltage. This loss of capacity under floating charging voltage depends on the load on the battery and can be up to 10% of the rated capacity.

For faster charging, all batteries should be charged at a higher voltage with a final automatic fallback to the floating charge voltage. When commissioning and servicing batteries, the charger should also have a boost charger device with automatic fallback to the floating charge voltage.

Battery charger:

If the battery cannot be isolated when charging with a higher characteristic but the charging voltage exceeds the maximum approved value at the consumer, the following actions may be taken in the charger:
– the use of counter-cells,
– main and end cells,
– DC stabilizer in the charger load-circuit output.

The following symbols apply for these load characteristics and for the off-switches and transfer circuit-breakers of the chargers with single or combined charging properties:

Charging characteristic for	Symbol
constant current	I
constant voltage	U
loading current falling	W
automatic tripping	a
limitation or switchover of the charging current to another charging characteristic	o (zero)
the sequence of combined symbols corresponds to the sequence of the charging process: e.g. constant current-constant voltage characteristic	IU
two sequential falling characteristics with switchover and automatic tripping	W0Wa

With automatic charging at constant voltage without tripping after reaching the fully charged state (e.g. charger with U, IU, lUW characteristic), the constant voltage must be retained as per DIN VDE 0510 with a permissible deviation of ± 1 %.

Therefore, the following applies for the output voltage of the charger:

$$U_d = n\ (U_{ZLE} \pm 1\ \%) + \Delta U.$$

n	number of battery cells
U_d	output direct voltage of the charger
ΔU	voltage drop at the connection between charger and battery
U_{ZLE}	floating charging voltage per cell

It should be possible to switch over manually to charge the battery with higher voltages.

In this case, the connected consumers or the consumer track must be switched off if the approved values are exceeded in modes deviating from the floating charge.

15.3.3 Operating modes for batteries

If consumers are supplied directly from a battery and the battery is disconnected from the consumers for charging, this is referred to as straight battery operation (Fig. 15-14a).

During parallel operation (Fig. 15-14b), consumers, rectifiers and battery are continuously connected in parallel. In this case, a distinction is made between buffer operation (battery is used to keep constant voltage and to cover peaks) and parallel operation (battery supplies power only if the rectifier fails, Fig. 15-15b). Parallel operation predominates.

Under switchover mode, the battery is disconnected from the consumers; it is kept fully charged. If the standard power source fails, the consumers are switched to the battery (Fig. 15-14c).

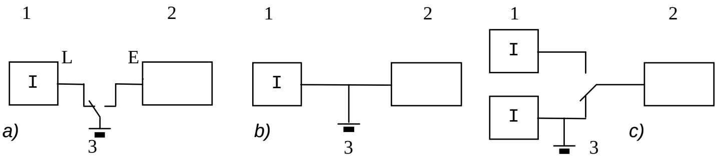


Fig.15-14

a) discharge-charge *b) parallel operation:* *c) switchover operation:*

1 DC source, 2 consumer, 3 battery

Important note!

During project planning of auxiliary installations in which the secure alternating voltage will be generated by rectifiers and inverters connected in series, the characteristics of both devices must be matched for each other for all loading cases. The selectivity of the two voltage potentials must be retained with load currents or short circuits. Correspondingly, the supplying device must be capable of supplying at five times the rated current for a short time while retaining the voltage drop approved by the VDE.

15.3.4 Dimensioning batteries

A large amount of data and operating conditions must be considered when dimensioning a battery.

It includes:
- load current,
- duration of load,
- impulse load,
- sequence of individual loads,
- permissible voltage tolerance of consumers,
- voltage drop on the connector cable,
- ambient temperature,
- end-point voltage of the battery,
- selected measures for retaining voltage tolerances
- proposed battery type.

Measures for retaining the voltage tolerances can include connecting of counter-cells, dividing a battery into main and end cells or using a stepup unit. A different procedure is used to determine the battery size depending on what measure is implemented. Battery manufacturers have suitable calculation programs. Detailed information can be found in IEEE 485 for lead-acid batteries and IEEE 1115 for Ni/Cd batteries.

Note:

It is never sufficient to calculate the capacity of a battery from the product of current x discharge time only.

15.3.5 Installing batteries, types of installation

Types of installation

Batteries are usually installed on steel racks.

The most convenient type of installation from the point of view of maintenance is on a tiered rack.

Stationary batteries are supplied in bolted or welded designs.

Inspection passages

DIN VDE 0510 specified that the rows of cells must be accessible by a passage. The width of the passage must be at least 500 mm for floor-mounted racks and at least 800 mm for tier racks. However, practice has shown that these aisle widths are too narrow, so the recommended widths for floor-mounted racks are at least 800 mm and 1000 mm for tier racks.

Battery rooms

The structural design of battery compartments is specified in worksheet J 31 of the working group for industrial structures (AGI: Arbeitsgemeinschaft für Industriebau). Battery compartments are accessible, enclosed compartments intended for installation of batteries for supplying electrical installations. As per DIN VDE 0510 and DIN VDE 0100 they are considered as

- *electrical premises/operator access area*, if the installation is designed for a nominal voltage of up to 220V
- *locked electrical premises/restricted access location,* if the installation is designed for nominal voltages over 220 V.

The requirements for the structural design of battery compartments are considered in more detail in Section 4.7.4.

15.4 Installations and lighting in switchgear installations

The operation, control and monitoring of switchgear installations inside and outside requires that they be supplied with energy (unit) and lighting.

15.4.1 Determining electrical power demand for equipment

The power demand $P_{\max}$ is calculated from the sum of the connected loads ΣP_i for the individual consumer groups and multiplied by the demand factor g.

$$P_{\max} = \Sigma P_i \cdot g$$

The requirement factor is based on values derived from experience; see Table 15-4.

Table: 15-4

Typical values for demand factor g for:

installations	offices	switchgear installations
lighting	0.8	0.8
receptacles	0.1	0.1
air-conditioning, ventilation	1	1
heating	1	1
lifts	0.5 / 0.7	—
kitchen equipment	0.5	—
outside lighting (floodlight installations)	—	1
cranes	—	0.7
control and signalling equipment	—	0.5
data processing equipment	depending on the individual case	

See Table 6-6 for demand factors for other equipment.

Equipment for station services

The equipment for station services in switchgear installations is described in Section 7.1 and 7.2.

In most cases, low-voltage distributors in the form of switch cabinets or distributor boxes are used, with all requirements for maximum operational dependability regarding design and equipment selection being met.

Important consumers and functions are supplied with direct voltage, which also ensures an uninterrupted power supply even in the event of a malfunction with the use of stationary batteries.

15.4.2 Layout and installation systems

The complex cable and wiring networks comprise a significant portion of the entire installation system. For this reason, the correct selection of materials and systems appropriate for the application is particularly important. Installations with multiple fire compartments require appropriate barriers between them. If emergency exits are provided, they must be installed in F90; materials conforming to DIN 4102 must be used. Fasteners and installation materials that are easy to install must be selected to allow economical installation. Proper tools and construction equipment are also required to ensure rational installation work processes.

See Sections 6.1.7 and 13.2.4 for information on laying cables and wiring.

The manufacturer’s working guidelines must also be observed.

There are single modules and complete layout systems for the various layout types.

The fastening methods and layout materials must be selected in accordance with the anticipated stresses caused by mechanical, thermal, chemical or other environmental effects. The following must also be taken into account:

- adequate heat dissipation,
- safe isolation of the power and communications circuits and the networks for stand-by power,
- open or covered configuration,
- sufficient flexibility for changes and retrofitting,
- technical fire protection measures.

The following are used for individual installation:
- plastic and metal nail, screw, bracket and glue clips,
- plastic and metal installation conduits, rigid and flexible (see Tables 15-5 to 15-9 for specifications).

The following are used for composite installation:
- plastic register clips and line-up saddles of plastic,
- plastic and metal bracket clips,
- plastic and metal strips and clamps,
- plastic and metal underfloor, wall and ceiling ducting,
- mesh cable racks of round steel bars,
- plastic and metal gutters and trays,
- metal racks and cable conduits.

Installation systems have been developed from the layout systems for interiors that not only protect and support elements for the wiring but also include tap boxes and terminal boards.

This development has been greatly assisted by construction technology which now offers not just the wall area but also the floor and ceiling for horizontal energy distribution. The window sill area is also available for this purpose.

Typical installation systems are:

The subfloor installation

with single- and multiple-duct metal or plastic conduits for laying power and communications wiring with floor-level or sub-floor connections for different components. The conduits can be laid in or on the unfinished floor, in the flooring material or flush with the floor.

Covered accesses for every terminal point must be included with a special design of the system. The wiring is run to the floor below on troughs or racks. The sub-floor installation is also suitable for double-floor systems.

Designs for every type of floor construction are available. The right design should be selected on the basis of the specific requirements and conditions and economy of installation.

The window-sill conduit installation (preferred for office space)

using plastic or metal conduits with built-in installation devices for power and communications wiring. The conduits are generally a component of the structural sill covering. Sufficient heat dissipation must be provided for installations adjacent to heaters and air-conditioning units.

In laboratories, the conduits are also used for utilities.

The terminal board installation

in the ceiling area, in combination with a suitable rack system. The terminal board consists of a plastic or metal housing with separate compartments for the power and communications circuits. Protection and switchgear is also included as well as terminals and terminal blocks. The terminal board can also be supplied as a complete module with added ceiling or built-in lights.

This installation system provides a wiring network without individual tapping boxes and is preferably used for decentralized supply of large spaces and anywhere that individual tapping boxes cannot be used for technical or structural reasons.

The busbar trunking system installation

in the vertical shafts of the central part of the building and as a connection between transformer and low-voltage main switchgear installation. This installation system has been developed from the classical plug-in busway installation used in industrial power supplies and has been switched from the horizontal to the vertical with slightly modified components.

The open or closed duct installation is preferably used for laying cables and wiring to individual consumers in the switchgear compartments and areas.

Plastic or steel conduits are used depending on the demands on the mechanical strength of the installation. They are installed in the ground, on and in the walls or ceilings of buildings and on structural framework.

See the following Tables 15-5 to 15-9 for data on installation ducts

Table 15-5

Electrical installation ducts as per DIN VDE 0605; non-threadable heavy-gauge steel conduits as per DIN 49 020 and flexible, corrugated steel conduits for heavy pressure loads as per DIN 49 023

Type	DIN 49 020 Steel conduits Non-threadable conduits, plug-in AS				DIN 49 023 Flexible, corrugated steel conduits for heavy loads AS			
	Diameter		Bundle Conduit length 3 m		Diameter		Ring	
	Interior mm	Exterior mm	Content m	Weight kg	Interior mm	Exterior mm	Content m	Weight kg Ω
9	13.2	15.2	90	33	10.0	14.7	25	4.5
11	16.4	18.6	60	30	14.0	18.4	25	5.5
13.5	18.0	20.4	60	32	16.0	20.2	20	7.0
16	19.9	22.5	30	20	18.0	22.3	25	7.5
21	25.5	28.3	30	27	23.5	28.0	25	9.0
29	34.2	37.0	15	18	31.5	36.7	25	15.0
36	44.0	47.0	15	26	41.0	46.6	25	19.0
42	51.0	54.0	15	32				
48	55.8	59.3	15	34	51.8	59.0	25	27.0

Application:
on concrete, in concrete, on plaster, in plaster, under plaster, on wood, on steel structures, in fill (flexible conduits not in hot fill).

Table 15-6

Electrical installation conduits DIN VDE 0605; flexible, corrugated, fire-retardant insulating conduits for light and medium pressure loads as per DIN 49018/1

Type	DIN 49 018/1 Flexible, corrugated, fire-retardant insulating conduits for light pressure loads B + C + F				DIN 49 018/1 Flexible, corrugated, fire-retardant insulating conduits for medium pressure loads A + C + F			
	Diameter		Ring		Diameter		Ring	
	Interior mm	Exterior mm	Content m	Weight kg	Interior mm	Exterior mm	Content m	Weight kg
9	9.9	13.0	50	1.1	9,6	13.0	50	1.3
11	11.8	15.7	50	1.5	11.3	15.8	50	2.1
13.5	14.5	18.6	100	3.7	14.3	18.7	100	5.2
16	16.6	21.1	50	2.4	16.5	21.2	50	3.0
23	23.8	28.5	50	4.0	23.6	28.5	50	5.0
29	29.6	34.5	25	2.5	29.0	34.5	25	3.3
36	36.8	42.5	25	4.0	36.6	42.5	25	4.6
48	48.5	54.5	25	6.0	48.3	54.5	25	6.5

Application:
in plaster, under plaster for prefabricated
timber construction

Application:
on plaster, in plaster, under plaster
in poured concrete

Table 15-7

Electrical installation conduits DIN VDE 0605; flexible, corrugated, fire-retardant insulating conduits for heavy pressure loads as per DIN 49 018/2 and flexible, smooth, non-fire-retardant insulating conduits for medium pressure loads as per DIN 49 019/2

Type	DIN 49 019/2 Flexible, corrugated, fire-retardant insulating conduits for heavy pressure loads B + C + F				DIN 49 019/2 Flexible, smooth, non-fire-retardant insulating conduits for medium pressure loads A + C			
	Diameter		Ring		Diameter		Ring	
	Interior mm	Exterior mm	Content m	Weight kg	Interior mm	Exterior mm	Content m	Weight kg
11	13.8	18.5	50	5.4	13.7	18.6	50	5.1
13.5	14.4	20.4	50	6.8	14.9	20.4	50	6.4
16	16.0	22.5	50	7.9	16.6	22.5	50	7.3
21	22.0	28.3	25	5.2	21.2	28.3	25	5.8
29	29.8	36.5	25	7.6	29.2	37.0	25	9.0
36	38.5	46.4	25	9.9	36.0	47.0	25	14.0
48	50.1	58.4	25	17.9				

Application:
on plaster, in plaster, under plaster,
in poured, vibrated and tamped concrete
for prefabricated concrete buildings
for machine terminals and industrial installations

Application:
in plaster, under plaster,
in concrete
outdoors and in ground

Table 15-8

Electrical installation conduits DIN VDE 0605; rigid, smooth, fire-retardant insulating conduits for medium and heavy pressure loads as per DIN 49016

Type	DIN 49 016 Rigid, smooth, fire-retardant insulating for medium pressure loads A + C + F				DIN 49 016 Rigid, smooth, fire-retardant insulating conduits for heavy pressure loads AS + C + F			
	Diameter		Bundle Conduit length 3 m		Diameter		Bundle Conduit length 3 m	
	Interior mm	Exterior mm	Content m	Weight kg	Interior mm	Exterior mm	Content m	Weight kg
9	12.6	15.2	120	10.8				
11	16.0	18.6	120	12.0				
13.5	17.5	20.4	120	16.5	16.0	20.4	120	21.6
16	19.4	22.5	60	8.0	18.1	22.5	60	12.9
21	24.9	28.3	60	12.2	22.1	28.3	60	20.4
29	33.6	37.0	30	8.0	30.8	37.0	30	14.6
36	42.8	47.0	15	5.5	39.0	47.0	15	11.6
42	49.6	54.0	15	6.0				
48	54.7	59.3	15	7.5	51.3	59.3	15	16.3

Application: on plaster, in plaster, under plaster
on concrete, in concrete
for industrial installations

on concrete
in poured and tamped concrete
for prefabricated concrete construction
in industrial installations

Table 15-9

Electrical installation conduits DIN VDE 0605, flexible, corrugated, non-fire-retardant insulating conduits for light pressure loads and heat resistance to 105 °C as per DIN 49019/3 and flexible, corrugated cable conduits of rigid PVC, compressive strength as per DIN 1187 (not as per VDE 0605)

Type	DIN 49 019/3 Flexible, corrugated, non-fire-retardant insulating conduits for light pressure Heat resistance to 105 °C B + C + 105				not as per VDE 0605 Flexible, corrugated cable conduits of rigid PVC Compressive strength as per DIN 1187			
	Diameter		Ring			Diameter		Weight each 100 m
	Interior mm	Exterior mm	Content m	Weight kg	NW	Interior mm	Exterior mm	kg
11	11.5	15.6	50	2.0	40	36.5	42.5	13.2
13.5	14.0	18.6	100	4.8	50	43.9	50.5	15.0
16	16.0	21.1	50	3.1	65	58.0	65.5	22.0
23	22.9	27.7	50	4.6	80	71.5	80.5	30.0
29	28.4	33.6	25	2.7	100	91.0	100.5	45.0
36	35.9	41.5	25	4.0	125	115.0	126.0	62.0
48	47.7	53.5	25	5.5	160	148.5	160.0	90.0
					200	182.0	200.0	140.0
Application:	in concrete and prefabricated construction in plaster, under plaster				in ground in concrete construction as lost sheathing			

There is a direct relationship between the internal diameter of the conduit, the approved space factor of the wiring in the conduit and the maximum permissible conduit length between the cable insertion points. This must be considered when planning the installation.

The limited options for pulling wiring and cables into the conduits require that some selection criteria be met:

- external diameter of cable,
- number of cables per conduit,
- permissible cable bending radii (see Table 13-64)
- permissible cable pull force (see Table 13-63)
- internal diameter of conduit,
- permissible conduit length between two cable pull points,
- number of conduit bends between two cable pull points,
- permissible space factor of the conduits based on heat given off by cables.

The cable data can be found in the manufacturers' lists.

Table 15-10 shows an overview of typical values for space factors, for pull lengths of 3-35 m with various conduit types and various installation types for single cables and bundled cables.

Table 15-10

Selection of conduits and conduit filling factor, typical values for space factors with manual insertion

Approved space factors of conduits with a max. draw length	3 m	6 m	9 m	12 m	20 m	25 m	30 m	35 m
PVC/steel conduit in open conduit installation, single cable								
D_{Ri} = 18 – 44 mm	0.7	0.7	0.5	0.5	—	—	—	—
≥ 45 mm	0.4	0.4	0.4	0.4	0.4	0.4	0.4	—
PVC/steel conduit in open conduit installation, bundled cable								
D_{Ri} = 18 – 44 mm	0.6	0.5	0.4	0.3	—	—	—	—
≥ 45 mm	0.3	0.3	0.3	0.3	0.3	0.3	—	—
PVC/steel conduit in closed conduit installation, single cable								
D_{Ri} = 18 – 44 mm	0.4/0.3	0.4/0.3	0.3/0.2	0.3/0.2	—	—	—	—
≥ 45 mm	0.2/0.2	0.2/0.2	0.2/0.2	0.2/0.2	—	—	—	—
½ conduit bend								
PVC/steel conduit in closed conduit installation, bundled cable								
D_{Ri} = 18 – 44 mm	0.4/0.3	0.4/0.3	0.3/0.2	0.3/0.2	—	—	—	—
≥ 45 mm	0.2/0.2	0.2/0.2	0.2/0.2	0.2/0.2	—	—	—	—
½ conduit bend								
PVC/concrete conduit in ground or concrete, single cable								
D_{Ri} ≤ 50 mm	0.5	0.5	0.5	0.5	0.5	—	—	—
> 50 mm	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4
PVC/concrete conduit in ground or concrete, bundled cable								
D_{Ri} ≤ 50 mm	0.4	0.4	0.4	0.4	0.4	—	—	—
> 50 mm	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3

D_{Ri} = interior conduit diameter (mm)

The effective space factor is calculated from the square of the interior diameter of the conduit (D_{Ri}) and the sum of the squares of the external diameter of all cables (ΣD_{KA}^2) that will be pulled into the conduit according to the following formula:

$$P_r = \frac{\Sigma D_{KA}^2}{D_{Ri}^2} \leqq P_r \text{ approved}$$

Conduits with an interior diameter of less than 18 mm (in ground and concrete less than 50 mm) should generally not be used.

If the cables are pulled in by machine, as is often the case with conduit installations in ground or concrete, the max. draw length may not exceed 100 m.

15.4.3 Lighting installations

Installations for lighting indoor and outdoor switchgear installations and their auxiliary equipment are subject to very varied requirements regarding intensity of lighting, limiting glare, colour and colour reproduction.

Table 15-11 lists recommendations conforming to ASR 7/3 and DIN 5035 Part 2.

Workplace directive ASR 7/3 and DIN 5035 specify nominal lighting intensities for illuminating workplaces. ASR 7/3 was released by the Federal Minister for Labor and Social Affairs and therefore forms the legal basis for lighting workplaces.

DIN 5035 Part 3 (hospitals), Part 4 (educational institutions), Part 5 (emergency lighting) and Part 7 (computer workstations) are subject to additional regulations.

Planners of lighting installations should take into consideration that lights become dirty and that they deteriorate with age. For this reason, a planning factor is calculated into new installations.

Standard planning factor for contamination and deterioration:

1.25	standard,
1.43	enhanced,
1.67	strong.

These factors are multiplied with the rated value of the required illumination intensity to find the required installation intensity.

The set rated lighting intensities E_n are rated values of the average lighting intensity. They must not be below these values. The quality criteria of lighting colour, colour reproduction and limitation of glare are covered in ASR 7/3 and DIN 5035.

Table15-11

Lighting with artificial light.
Recommendations for various lighting tasks
(extracts from ASR 7/3 and DIN 5035 Part 2)

Type of space or activity	Rated lighting intensityE_n lx	Light colour	Stages of colour reproduction properties	Quality class of glare restriction
General spaces				
Traffic zones in storage rooms, warehouses	50	ww, nw	3	3
Warehouses for similar or large items	50	ww, nw	3	3
Warehouses with search tasks among dissimilar storage items	100	ww, nw	3	3
Warehouses with read tasks	200	ww, nw	3	2
Automatic high-rack warehouses, aisles	20	ww, nw	3	3
Operator station	200	ww, nw	2A	1
Shipping	200	ww, nw	3	2
Lunchrooms, sanitation rooms and canteens	200	ww, nw,	2A	1
Other rest areas and sleeping rooms	100	ww, nw	2A	1
Changing rooms, bathrooms, toilets	100	ww, nw	2A	2
Sanitation rooms, rooms for first aid and medical treatment	500	ww, nw	1A	1
Passageways in buildings				
For persons	50	ww, nw	3	3
For persons and vehicles	100	ww, nw	3	3
Stairs, escalators, inclined passageways	100	ww, nw	3	2
Loading ramps	100	ww, nw	3	3

(continued)

Table 15-11 (continued)

Lighting with artificial light.
Recommendations for various lighting tasks
(extracts from ASR 7/3 and DIN 5035 Part 2)

Type of space or activity	Rated lighting intensity E_n lx	Light colour	Stages of colour reproduction properties	Quality class of glare restriction
Offices and similar spaces				
Supplementary daylight lighting for offices with workstations exclusively adjacent to windows	300	ww, nw	2A	1
Offices	500	ww, nw	2A	1
Open-plan offices high reflection	750	ww, nw	2A	1
Open-plan offices moderate reflection	1000	ww, nw	2A	1
Technical drafting	750	ww, nw	2A	1
Conference and meeting rooms	300	ww, nw	2A	1
Rooms open to the public	200	ww, nw	2A	1
Rooms for data processing	500	ww, nw	2A	1 for 750 lx
Work on CAD devices	500	ww, nw	2A	1 for 1000 lx
Exclusively for viewing television images, e.g. process monitoring	200	ww, nw	2A	1 for 1000 lx
Power plants				
Loading systems	50	ww, nw, tw	3	3
Boiler house	100	ww, nw, tw	3	3
Machine sheds	100	ww, nw, tw	3	2
Control rooms with CRT monitors	300	ww, nw, tw	2A	1 for 1000 lx
Repairs and maintenance work on turbines and generators	500	ww, nw, tw	2B	2

(continued)

Table 15-11 (continued)

Lighting with artificial light.
Recommendations for various lighting tasks
(extracts from ASR 7/3 and DIN 5035 Part 2)

Type of space or activity	Rated lighting intensity E_n lx	Light colour	Stages of colour reproduction properties	Quality class of glare restriction
Switchgear installations – values from in-house experience				
Switchgear installations in buildings	100	nw	2	2
Switchgear installations outdoors	20	ww, nw	3,4	3
Control rooms	300	ww, nw	2	1
Electrical engineering industry				
Cable and wiring manufacture, coating and impregnating coils, assembly of large machines, simple assembly work, winding coils and armatures with coarse wire	300	ww, nw, tw	3	1
Assembly of telephone sets, small motors, winding coils and armatures with medium wire	500	ww, nw, tw	3	1
Assembly of precision devices, radio and television equipment, winding fine wire coils, manufacturing fuses, adjusting, testing and calibrating	1000	ww, nw, tw	3	1
Assembly of high-precision parts, electronic components	1500	ww, nw, tw	2A	1
Assembly of high- and very high-precision parts with CRT monitors	1000	ww, nw, tw	2	1 for 1500 lx

In addition to the lighting intensity the colour and colour reproduction determine the selection of lights for the required purpose (Table 15-12).

Table15-12

Colour and colour reproduction properties of light sources

Stages of colour reproduction properties	Light colour	Typical light sources	Remarks	Typical applications
1	daylight white (tw)	xenon lamps, fluorescent lights (daylight) and halogen metal-vapour lamps with very good colour reproduction properties		textile industry, graphical commercial, factory sheds, outdoor manufacturing halls, sales rooms
	neutral white (nw)	fluorescent lights (white) with very good colour reproduction properties	can be combined with daylight	offices, schools, laboratories, sales rooms, art galleries
	warm-white (ww)	incandescent lights, halogen incandescent lights, fluorescent lights (warm tone) with very good colour reproduction properties	can be combined very well with incandescent lights	mood lighting, living area, restaurants, sales rooms
2	daylight white (tw)	fluorescent lights (daylight) and halogen metal-vapour lamps with good colour reproduction properties		factory halls, exhibition halls
	neutral white (nw)	fluorescent lights (white) with good colour reproduction properties	can be combined with daylight	offices, schools, laboratories, sales rooms, show window, industrial commercial work rooms
	warm-white (ww)	fluorescent lights (warm tone) with good colour reproduction properties	can be combined well with incandescent lights	hallways, stairwells houses, lighting outdoors

Table 15-12 (continued)

Colour and colour reproduction properties of light sources

Stages of colour reproduction properties	Light colour	Typical light sources	Remarks	Typical applications
3	neutral white (nw)	fluorescent lights (white) with few good colour reproduction properties, mercury vapour high-pressure lamps with fluorescent material, mixed lamps	can be combined with daylight	industrial and commercial work rooms, lighting outdoors
	warm-white (ww)	fluorescent lights (warm tone) with few good colour reproduction properties		warehouses lighting outdoors
4		sodium-vapour lamps mercury vapour high-pressure lamps without fluorescent material		floodlighting, lighting outdoors

Three quality classes are distinguished with very individual criteria with the requirements for the glare limitation:

Quality class 1:	high demands, ca. 10 % of persons surveyed still detect distracting glare.
Quality class 2:	moderate demands, ca. 30 % of persons surveyed still detect distracting glare.
Quality class 3:	low demands, ca. 40 % of persons surveyed still detect distracting glare.

The requirements for a lighting installation are determined by the following criteria:

– horizontal lighting intensity,
– if applicable, vertical lighting intensity,
– even lighting distribution,
– limitation of glare,
– colour reproduction stage.

The following must also be considered:

– room dimensions,
– colour of the reflecting surfaces around the outside of the room,
– mounting height above working plane.

The vertical lighting intensity is significant where vertically mounted instruments and devices need to be continuously monitored.

Refer to the “Manual for Lighting”, published by the “technical lighting associations (Lichttechnischen Gesellschaften)” and “working group (Arbeitsgemeinschaft)” of Switzerland, Austria and Germany, for descriptions of the calculation procedures. An explanation of the two calculation procedures is given there as follows:

– efficiency method

and

– point calculation method.

The point calculation method is generally recommended for outside lighting systems and for demanding interior applications (such as control rooms, network control rooms).

The efficiency method is generally sufficiently accurate for offices and workshops, switchgear rooms and access passages.

The requirements for lighting emergency and escape paths are described in DIN 5035 Part 5. The Workplace Directive ASR 7/4 “Emergency Lighting” must also be taken into account.

15.4.4 Fire alarm systems

Fires can occur even in installations that are protected by structural measures.

An important component of preventive fire protection (see Section 4.7.6) is fire alarm equipment that is automatically or manually activated in accordance with DIN VDE 0833 Parts 1+2. Both the directives of the VdS (association of property insurers) and the structural fire regulations must be observed.

If a fire can be detected early and action to extinguish it taken quickly and directly, the damage caused by the fire or the process of extinguishing it can be reduced.

Automatic fire alarm systems are recommended for switchgear installations, control rooms and data processing systems that are not continuously staffed.

Switchgear installations supplying hospitals and other critical installations must be equipped with fire alarm systems or be included in the general fire alarm system.

Fire alarms are forwarded to a central monitoring site. An incoming fire alarm automatically initiates the appropriate firefighting measures. Fig. 15-15 shows a circuit diagram of an automatically or manually actuated alarm system.

Smoke, temperature or the optical appearance of flames are the quantities for early detection of fires that set off the alarm when maximum values are exceeded. These alarms actuate stationary extinguishing systems and also alert the fire department through a central monitoring system.

A fire alarm system generally consists of the following components

- automatic fire alarms (heat, smoke, flames) installed in groups,
- central fire alarm,
- secure power supply from power system or battery,
- alarm equipment such as sirens, horns, flashing lights,
- actuation, tripping,
- transmission equipment for fire alarms to a continuously staffed monitoring centre (fire department),
- non-automatic manual alarms for less important areas.

The design of an automatic fire alarm system should also include any existing air intake and exhaust systems (corresponding placement of the spot alarms, otherwise an alarm may be delayed).

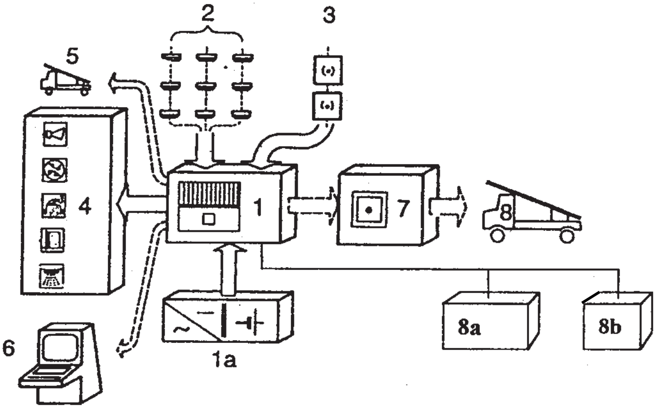


Fig.15-15

Circuit diagram of a fire alarm system

1	*Central fire alarm,*
1a	*Power supply (power system and battery)*
2	*Automatic fire detectors*
3	*Non-automatic fire alarm (manual alarm)*
4	*Alarms and actuation/tripping*
5	*Plant fire department*
6	*Building services (fault alarms)*
7	*Transmission equipment for fire alarms (main fire alarm)*
8	*Public fire department*
8a	*Fire department control panel*
8b	*Fire department key compartment*

15.5 Compressed-air systems in switchgear installations

15.5.1 Application, requirements, regulations

Because air is available everywhere and can be compressed, dehumidified and stored, compressed air was long considered a particularly economical power source for equipment and machines. It has been used in switchgear installations for the following purposes:

– actuation force for mechanisms,

– arc-extinguishing medium for current interruption,

– dielectric in the interrupter chambers of circuit-breakers,

– ventilation of busbars for cooling and to prevent condensation.

The introduction of new technologies (SF_6 as extinguishing and insulating gas, mechanical spring energy storage, hydraulic power transmission) has greatly reduced the importance of compressed air for new systems. However, because a large number of switchgear installations with compressed-air systems are still in operation, the following deals with the basic principles.

The following standards are among those used as the basis:

DIN 1314 – Pressure, basic terms, units
DIN 43 609 – Graph. symbols for compressed-air system diagrams
DIN 43 615 – Rated pressures and pressure ranges for compressed-air systems
DIN 43 691 – Pressure terms
DIN 43 903 – Moisture in compressed air, terms, measurement methods
DIN 43 690 – Air compressors for compressor systems in electrical switchgear installations
DIN 43 686 – Pressure tanks for compressor systems in electrical switchgear installations

Reference is also made to the “directives for compressed-air systems in electrical switchgear installations from the association of German electricity companies (Vereinigung Deutscher Elektrizitätswerke), Frankfurt, 3rd edition 1985”.

15.5.2 Physical basis

Atmospheric air consists of approximately 21 % oxygen and 79 % nitrogen and also traces of other gases. It also has a specific moisture content in the form of vapour. The moisture per unit of space is determined by the atmospheric conditions and the temperature. Atmospheric air has a moisture content that nears saturation point only in foggy and rainy conditions. Absolute moisture is the quantity of water in grams in one m^3 of air.

Compressed air is produced in compressors which draw in the atmospheric air with all the moisture it contains. The compression process reduces the volume of air in inverse proportion to the increase of pressure at a constant temperature (isothermal). With increasing compression pressure, the water vapour partial pressure and the relative humidity increase at constant saturation pressure.

The quantity of water Q is automatically separated by oil and water separators (between the individual compression stages) and can be calculated with the formula shown below.

$$Q = V_a \left(\frac{U}{100\ \%} \cdot f_{sn1} - \frac{p_1 (T_0 + t_2)}{p_2 (T_0 + t_1)} \cdot f_{sn2} \right)$$

The following letters are used:

f_{sn1}	maximum possible moisture content at intake temperature t_1 (g/l),
f_{sn2}	maximum possible moisture content at discharge temperature t_2 (g/l),
V_a	volume of intake air (l/min),
U	relative humidity (%),
p_1	pressure of intake air (bar),
p_2	pressure of compressed air (bar),
t_1	temperature of intake air (°C),
t_2	temperature of compressed air (°C).

Example:

V_a = 500 l/min,
p_1 = 1 bar,
p_2 = 200 bar,
t_1 = + 10 °C, according to Table 15-13: f_{sn1} = 0.0094 g / l,
t_2 = + 25 °C, according to Table 15-13: f_{sn2} = 0.023 g/ l,
U = 60 %.
Q = ?

Separated water:

$$Q = 500 \frac{\mathrm{l}}{\mathrm{min}} \left(\frac{60\%}{100\%} \cdot 0.0094 \frac{\mathrm{g}}{\mathrm{l}} - \frac{1\ \mathrm{bar}}{200\ \mathrm{bar}} \cdot \frac{(273 + 25)\ \mathrm{K}}{(273 + 10)\ \mathrm{K}} \cdot 0.023 \frac{\mathrm{g}}{\mathrm{l}} \right) = 2.76 \frac{\mathrm{g}}{\mathrm{min}}$$

Water separators in the compressor only removed the condensed water in the compressed air but not the moisture content in the form of vapour. If compressed air is to be used to actuate switchgear, the moisture content must be reduced. This is generally done by reducing the pressure and cooling the pressure tanks, or if this is not sufficient, by using air dryers.

The requirements for air quality regarding moisture content vary for indoor and outdoor installations. A moisture reduction to 40 % is sufficient for indoor installations but air-blast breakers for outdoor installations require a reduction to ca. 15 . . . 20 % to go below the dew point and thereby to prevent condensation in the switching device. In general, this means a pressure-reduction ratio of 5:1. This reduction ratio assures protection even in case of a fall in temperature of ca. 20 K over the temperature range –35 °C ... +50 °C. As can be seen in Table 15-13, even at low temperatures the air contains a small quantity of moisture. Air heated by compression should therefore be cooled to the ambient temperature of the switchgear if at all possible.

Table 15-13

Water content of air at various temperatures for standard pressure p_n (atmospheric pressure)

Dew point temperature ° C	Saturation moisturef_{sn} g/m³	° C	g/m³	° C	g/m³
– 30	0.33	+ 5	6.790	+ 35	39.286
– 20	0.88	+ 10	9.356	+ 40	50.672
– 15	1.38	+ 15	12.739	+ 45	64.848
– 10	2.156	+ 20	17.148	+ 50	82.257
– 5	3.230	+ 25	22.830		
0	4.860	+ 30	30.878		

Fig. 15-16 shows the relationship between saturated moisture content f_s, pressure dew point t_{pd} and compression pressure p.

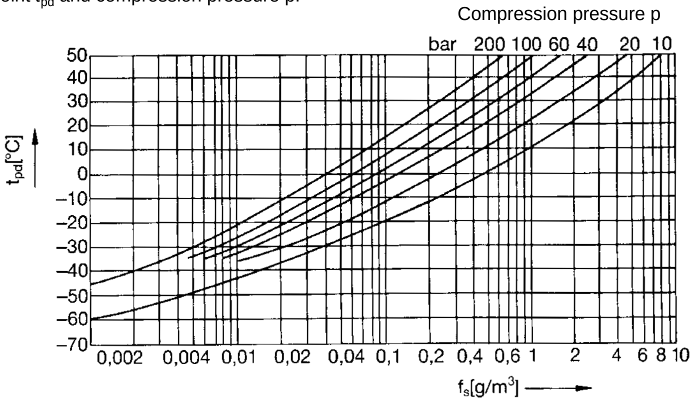


Fig. 15-16

Saturated moisture content of compressed air

Definitions of some important compressed air quantities:

f = absolute moisture content, in g/m³ or ppm, the quantity of moisture present at a specified temperature

f_{sn} = saturated moisture content, in g/m³ or ppm, is the maximum quantity of water vapour that can be absorbed by one m³ of dry air at atmospheric pressure

f_s = saturation moisture content of compressed air, in g/m³ or ppm, is dependent on temperature and pressure

k = saturation compensation factor takes into account the non-proportional change of the saturation moisture of compressed air to the saturation moisture content of air at standard pressure p_n.

$$f_s = k \cdot \frac{f_{sn}}{p}$$

$$U = \frac{\text{absolute moisture content}}{\text{saturation moisture content}} 100\ \% = \frac{f}{f_{sn}} 100\ \% = \text{relative humidity}$$

ppm = parts per million, $1\ \text{ppm} = \frac{1\ \text{cm}^3\ \text{water vapour}}{1\ \text{m}^3\ \text{dry air}}$

t_d = dew point temperature = dew point in °C

t_{pd} = pressure dew point is the dew point of compressed air in °C

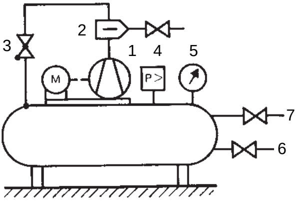
15.5.3 Design of compressed-air systems

A compressed-air system for supplying electrical switchgear consists of compressors, storage tanks and the distribution system with the pipes, pressure reducers and the control, protection and monitoring equipment. A distinction is made between working compressed-air systems and storage compressed-air systems.

In working compressed-air systems, the equipment is supplied with air at the compressor output pressure. It is only used in switchgear installations with low air requirements.
The compressor units are supplied as modules installed on a horizontal tank of 125 ... 500 l; see Fig. 15-17.

Fig.15-17

Pneumatic circuit diagram of a small compressed-air system:
1 Compressor
2 Water separator
3 Pressure valve
4 Pressure switch
5 Manometer
6 Drainage
7 Distribution system



Storage compressed-air systems

The air is compressed to a higher pressure than the operating pressure of the equipment and is stored. To supply the equipment in high-voltage installations, the air pressure is mostly reduced in the switchbay on an individual basis and centrally in medium-voltage substations.

Fig. 15-18 shows the general design of storage compressed-air systems with the preferred storage, reduction and distribution methods.

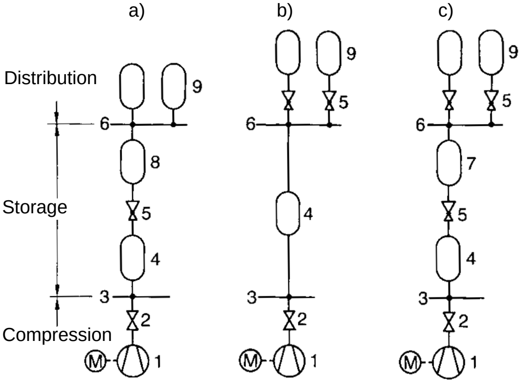


Fig.15-18

Storage compressed-air systems, schematic design:

a) central reduction to breaker pressure b) local reduction, storage at distribution pressure.
c) central/local reduction, storage at high pressure and distribution pressure.

1 Compressor, 2 Pressure valve, 3 Combined line for compression, 4 Storage tank (high-pressure), 5 Pressure reduction valve, 6 Combined line for distribution, 7 Storage tank (distribution pressure), 8 Storage tank (operating pressure), 9 Tanks at the switching device

15.5.4 Rated pressures and pressure ranges

Compressed air generating and distribution systems for specialized applications consist of compressor, storage, reduction equipment and distribution. Table 15-14 shows an overview of the pressure ranges of the various sections of the system.

Table 15-14

Rated pressures and pressure ranges for compressed-air systems as per DIN 43 615

Rated pressure bar	Compression pressure[1)] bar	Storage pressure bar	Distribution pressure bar	Rated breaker pressure bar
10	5… 10	5… 10		
40	25	25		
64	30… 44	30… 44	5, 15, 20, 40, 60, 160, 200	5, 15, 20, 25, 30, 35
64	60… 64	60… 64		
100	100…120	100…120		
250	200…250	170…200		

[1)] The compressor pressure may be higher when pressure valves are used.

The selection of pressure levels depends largely on the breaker operating pressure, air requirements, required storage volume, repressurizing times and the permissible moisture in the breaker tank. To meet all possible daily and seasonal temperature variations, pressure levels must be selected to ensure that no condensation occurs in the breaker tank or in the interior of the breaker at even the maximum possible fall in temperature. Fig. 15-19 shows an overview of the connections between the air temperature t, fall in temperature Δt and the expansion ratio ε.

Example:

$\Delta t = 23\ K$

$t = 35\ °C$

$\varepsilon = 6:1$

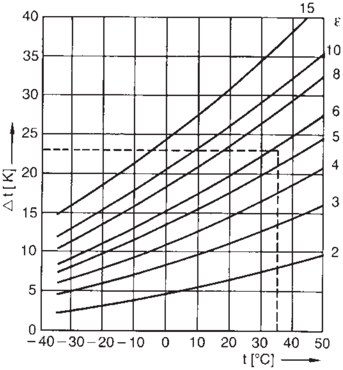


Fig. 15-19

Temperature fall diagram

15.5.5 Calculating compressed air generating and storage systems

Calculation quantities:

a	air requirement of a switch for CO
a_1	air requirement for O-CO
b	leakage air requirement/h
n	number of generator circuit-breakers/high-current bus ducts
n_1	number of switching cycles/day
n_2	number of switching cycles in the event of a fault
p	rated pressure of the high-pressure storage
p_1	breaker blocking pressure
p_2	compressor starting pressure or repressurizing valve “Open”
p_3	minimum tank storage pressure or rated breaker pressure
p_4	opening pressure of charging valve (high-pressure reduction)
p_5	rated breaker operating pressure +5 bar
q	effective output of compressor
t	compressor operating time/day
t_1	fill time for CO
t_2	fill time to autoreclosure block
V	total air quantity/day
V_G	volume/high-current bus duct
V_M	medium pressure storage volume
V_H	high-pressure storage volume
z	percentage air loss of V_G/h

Calculating the compressor output

The size of a compressed-air system is determined by the number of switching cycles occurring in practice. Table 15-15 shows an overview.

Table 15-15

Switching cycles of circuit-breakers, typical values

Number of circuit-breakers when fully installed in the installation	power plant, transformer substation 10 ... 30 kV Number of switching cycles: in 24 h	immediately on faults
n	n_1	n_2
1	2	1
2	5	2
4	9	4
6	11	6
8	13	8
10	15	9

The compressor output is derived as follows:

$$q = \frac{n_1 \cdot a + n \cdot b}{t}$$

For switchgear "*b*" takes the leakage losses over 24 hours into account. They are included in the circuit-breaker datasheets.

With high-current bus ducts $b = \frac{z \cdot V_G \cdot 24}{100}$

The storage volume of the compressed-air systems is calculated for medium- and high-pressure storage as follows:

Medium- and high-pressure storage

$$V_H = \frac{2\, n_2 \cdot a}{3\,(p_2 - p_3)}$$

$$V_M = \frac{n_2 \cdot a}{3\,(p_4 - p_5)}$$

If high-pressure storage only is used, then

$$V_H = \frac{n_2 \cdot a}{p_2 - p_3}$$

15.5.6 Compressed air distribution systems

Copper and steel pipes are used for the compressed air distribution system. The joints are designed with soldered fittings for an operating pressure of up to 60 bar. A soft solder with 95% Sn + 5% Sb is used for copper pipes at a working temperature of approximately 245 °C.

A hard solder with 40% Ag can be used for applications with severe mechanical stresses. Because the melting point of this solder is over 600 °C, the pipes are heated during soldering. They must therefore only be stressed with the load value of the next lower strength class of the soft state.

At an operating pressure of over 60 bar, cutting ring screws as per DIN 43685 or 2353 are generally used.

The lines between the compressor system and the switchgear are either radial lines or ring lines, depending on the size of the system.

Copper pipes with external diameters of 6, 8, 10, 12, 18, 20 and 28 mm and steel pipes of 6, 8, 10 and 12 mm are used.

The wall thickness and pressure ranges of the compressed air lines in switchgear installations are specified in DIN 43614.

Changes in the length of the pipes caused by changes in temperature must be compensated by installing expansion loops. Pipes must be able to move slightly when installed.

16 Materials and Semi-Finished Products for Switchgear Installations

16.1 Iron and steel

16.1.1 Structural steel, general

The material specifications for structural steels to DIN EN 10 029 apply to carbon steels and low-alloy steels: these are used in the hot-worked condition, and to a lesser extent after normalizing, for reasons of tensile strength and yield strength. The specifications are also valid for forgings, section steel, strip, and heavy and medium plates made from these steels. This standard DIN EN 10 029 does not apply to the products given in Table 16-2.

Weldability is better with low-carbon steels having less than 0.22% C. Weldability is best with steels of grade 3, e.g. St 37-3 (S235 JR), and poorest with steels of grade 1. Killed steels are to be preferred to rimmed steel, especially if segregation zones might be encountered when welding.

Identification codes for structural steels are contained in DIN EN 10027. This also shows the chemical composition and method of melting or casting.

The standards giving the dimensions of general structural steels are listed in Table 16-1.

Table 16-1

Dimensional standards	
Round steel, general purpose	DIN 1013
Square steel	DIN 1014
Flat steel, general purpose	DIN 1017
Equal angle section and deep-web T bars, square edge	DIN 1022
T bars, round edge	DIN EN 10055
I bars and I beams	DIN 1025
Channel bars and beams	DIN 1026
Steel angle	DIN 1028
Steel angle, unequal widths	DIN 1029
Steel sheet less than 3 mm (thin sheet)	DIN EN 10131
Steel sheet 5 mm and above (heavy plate)	DIN EN 10130

Table 16-2

Dimensional standards

Steel for screws, bolts and nuts	DIN 1654, DIN 17 240, DIN 59 130
Heat-treatable steel	DIN EN 10 083
Case-hardening steel	DIN 17 210
Thin sheet less than 3 mm thick	DIN 1623, Sheet 1 and DIN EN 10 130
Identification code for surface type and treatment	(DIN 1623)

16.1.2 Dimensions and weights of steel bars, sections and tubes

Table 16-3

Dimensions and weight of steel bars

Square and flat steel DIN 1014/1017

Dimensions mm	Cross-section cm²	Weight kg/m
8 × 4	0.32	0.249
10 × 5	0.5	0.390
12 × 5	0.6	0.470
13 × 2.5	0.325	0.255
15 × 5	0.75	0.595
20 × 3	0.6	0.471
20 × 4	0.8	0.624
20 × 5	1.0	0.780
20 × 8	1.6	1.26
25 × 3	0.75	0.589
25 × 4	1.0	0.785
25 × 5	1.25	0.981
26 × 2 1)	0.52	0.408
30 × 3	0.9	0.705
30 × 3.5 1)	1.05	0.825
30 × 4	1.2	0.936
30 × 5	1.5	1.170
30 × 30	9.0	7.065
35 × 3	1.05	0.825
35 × 4	1.4	1.09
35 × 5	1.75	1.36
35 × 35	12.25	9.62
40 × 3	1.2	0.942
40 × 4 1)	1.6	1.26
40 × 5	2.0	1.56
40 × 6	2.4	1.87
40 × 8	3.2	2.50
40 × 10	4.0	3.12
40 × 40	16.0	12.60
45 × 5	2.25	1.75
45 × 8	3.6	2.81
45 × 10	4.5	3.51
50 × 3	1.5	1.17
50 × 4	2.0	1.56
50 × 5	2.5	1.95
50 × 6	3.0	2.34
50 × 8	4.0	3.12
50 × 10	5.0	3.90
60 × 5	3.0	2.34
60 × 8	4.8	3.74
60 × 10	6.0	4.68
65 × 5	3.25	2.53
80 × 5	4.0	3.12
80 × 6	4.8	3.74
80 × 8	6.4	4.99
80 × 10	8.0	6.24
100 × 5	5.0	3.90
100 × 6	6.0	4.68
100 × 8	8.0	6.24
100 × 10	10.0	7.8

1) also galvanized for earth conductors

Earthing plate 1000 · 1000 · 3 mm with strip 2.5 m long, approx. 30 kg
Earth rod 1" diameter, 2000 mm long, 5.3 kg
Earth rod 2" diameter, 3000 mm long, 16.5 kg

Table 16-4

Dimensions and weights of round steel and steel tubes

Round steel bright DIN 671

Diameter mm	Cross-section cm²	Weight kg/m
1	0.0079	0.0062
2	0.0314	0.0247
3	0.0707	0.0555
4	0.1257	0.0986
5	0.1963	0.154
6	0.283	0.222
8	0.503	0.395
10	0.785	0.617
12	1.131	0.888
14	1.539	1.21
15	1.767	1.39
18	2.245	2.00
20	3.142	2.47
22	3.801	2.98
25	4.91	3.85
28	6.158	4.83
30	7.069	5.55
32	8.042	6.31
36	10.18	7.99
38	11.34	8.9
40	12.57	9.86
42	13.85	10.9
45	15.9	12.5
48	18.10	14.2
50	19.63	15.4

Steel tube

Out-side diameter inches	Outside diameter, wall thickness mm	Weight kg/m
Seamless precision tube DIN 2391		
	5 × 1	0.10
	6 × 1	0.12
	10 × 1[2]	0.222
	10 × 2[2]	0.395
	12 × 2	0.493
	15 × 1	0.36
	16 × 2	0.691
	20 × 2	0.89
	22 × 1	0.52
	28 × 1.5	1.0
	30 × 2	1.37
	32 × 3[2]	2.15
	50 × 2	2.36
Medium-heavy threaded tube DIN 2440		
¼ "	13.5 × 2.35	0.65
⅜ "	17.2 × 2.35	0.852
½ "	21.3 × 2.65	1.22
¾ "	26.9 × 2.65	1.58
1 "	33.7 × 3.25	2.44
1¼ "	42.4 × 3.25	3.14
1½ "	48.3 × 3.25	3.61
2 "	60.3 × 3.65	5.10
Seamless tube DIN 2448		
	25 × 2.6[1]	1.44
	30 × 4	2.59
	30 × 2.6	1.77
	31.8 × 2.9[1]	2.08

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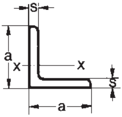
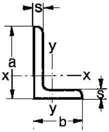
[1] also galvanized for earth conductors

[2] Tube for operating mechanism linkages

Table 16-5

Steel angle





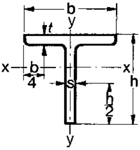
Equal width DIN 1208			Unequal width DIN 1029			
Symbol L a × s mm	Weight kg/m	Section modulus cm³	Symbol L a × b × s mm	Weight kg/m	Section modulus W_x cm³	W_y cm³
20 × 3	0.88	0.28	30 × 20 × 4	1.45	0.81	0.38
25 × 3	1.12	0.45	40 × 20 × 3	1.35	10.8	0.30
25 × 4	1.45	0.58	40 × 20 × 4	1.77	1.42	0.39
30 × 3	1.36	0.65	45 × 30 × 4	2.25	1.91	0.91
30 × 4	1.78	0.86	45 × 30 × 5	2.77	2.35	1.11
35 × 4	2.10	1.18	60 × 30 × 5	3.37	4.04	1.12
40 × 4	2.24	1.56	60 × 30 × 7	4.59	5.50	1.52
40 × 5	2.97	1.91	50 × 40 × 5	3.36	3.20	2.01
45 × 5	3.38	2.43	60 × 40 × 5	3.76	4.25	2.02
50 × 5	3.77	3.05	60 × 40 × 6	4.46	5.03	2.38
50 × 6	4.47	3.61	80 × 40 × 6	5.41	8.73	2.44
55 × 6	4.95	4.40	80 × 65 × 8	8.66	12.3	8.41
60 × 6	5.42	5.29	65 × 50 × 5	4.35	5.11	3.18
60 × 8	7.09	6.88	65 × 50 × 7	5.97	6.99	4.31
65 × 7	6.83	7.18	100 × 50 × 6	6.85	13.08	3.86
65 × 9	8.62	9.04	100 × 50 × 8	8.99	18.0	4.05
70 × 7	7.38	8.43	90 × 60 × 6	6.82	11.7	5.61
70 × 9	9.34	10.6	90 × 60 × 8	8.96	15.4	7.31
75 × 8	9.03	11.0	80 × 65 × 6	6.60	9.41	6.44
80 × 8	9.66	12.6	80 × 65 × 8	8.66	12.3	8.41
80 × 10	11.9	15.5	100 × 65 × 7	8.77	16.6	7.54
90 × 9	12.2	18.0	100 × 65 × 9	11.1	21.0	9.52
90 × 11	14.7	21.6	100 × 75 × 9	11.8	21.5	12.7
100 × 10	15.1	24.7	120 × 80 × 10	15.0	34.1	16.2
100 × 12	17.8	29.2	130 × 65 × 10	14.6	38.4	10.7
110 × 10	16.6	30.1	130 × 90 × 10	16.6	40.5	20.6
120 × 11	19.9	39.5	150 × 75 × 11	18.6	56.6	15.9
140 × 13	27.5	63.3	150 × 100 × 10	19.0	54.1	25.9
150 × 14	31.6	78.2	150 × 100 × 14	26.1	74.1	35 2
150 × 15	36.2	95.6				
Steel angle, square edge						
30 × 3.5	1.55	L section 121	30 × 16 × 4	1.32	L section 180	
40 × 4	2.39	L section 124	45 × 30 × 4	2.23	L section 203	
			60 × 40 × 5	3.73	L section 218	

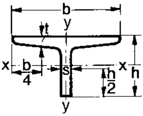
Permissible tolerance up to 50 mm ± 1 mm, up to 100 mm ± 1.5 mm, above ± 2 mm.

For other angle sections, see:
DIN 1022, DIN 1028, DIN 1029,
DIN 59 370.

Table 16-6

T bars, normal lengths 3 to 12 m, DIN 1024



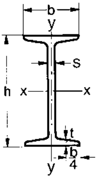


Symbol	Dimensions in mm			Weight	Section modulus for bending axis	
					x – x	y – y
					W_x	W_y
	b	*h*	*s* = *t*	kg/m	cm³	cm³
T	Deep-web T bar DIN EN 10 055					
20	20	20	3	0.88	0.27	0.20
25	25	25	3.5	1.29	0.49	0.34
30	30	30	4.0	1.77	0.80	0.58
35	35	35	4.5	2.33	1.23	0.90
40	40	40	5	2.96	1.84	1.29
45	45	45	5.5	3.67	2.51	1.78
50	50	50	6	4.44	3.36	2.42
60	60	60	7	6.23	5.48	4.07
70	70	70	8	8.32	8.79	6.32
80	80	80	9	10.7	12.8	9.25
90	90	90	10	13.4	18.2	13.0
100	100	100	11	16.4	24.6	17.7
TB	Broad-flange T bar DIN EN 10 055					
30	60	30	5.5	3.64	1.11	2.87
35	70	35	6.0	4.66	1.65	4.31
40	80	40	7.0	6.21	2.50	7.13
50	100	50	8.5	9.42	4.78	13.5
60	120	60	10	13.4	8.09	22.8
T	Square-edge T bar					
16/16	16	16	2.5	0.58	Mannstädt I 596	
20/30	30	20	3.0	1.11	Mannstädt I 4966	
25/35	35	25	3.5	1.55	Mannstädt I 3981	
25/38	38	25	3	1.41	Mannstädt I 4981	

Tolerances: up to 50 mm ±1 mm, up to 100 mm ±1.5 mm.

Table 16-7

I beams, normal length 4 to 15 m, DIN 1025 Sheet 1

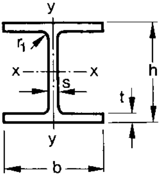


Symbol	Dimensions in mm				Weight	Section modulus for bending axis	
	h	*b*	*s*	*t*	kg/m	x – x W_x cm³	y – y W_y cm³
I	I beams DIN 1025, Sheet 1						
80	80	42	3.9	5.9	5.94	19.5	3.00
100	100	50	4.5	6.8	8.34	34.2	4.88
120	120	58	5.1	7.7	11.1	54.7	7.41
140	140	66	5.7	8.6	14.3	81.9	10.7
160	160	74	6.3	9.5	17.9	117.0	14.8
180	180	82	6.9	10.4	21.9	161.0	19.8
200	200	90	7.5	11.3	26.2	214.0	26.0
220	220	98	8.1	12.2	31.1	278.0	33.1
240	240	106	8.7	13.1	36.2	354.0	41.7
260	260	113	9.4	14.1	41.9	442.0	51.0
280	280	119	10.1	15.2	47.9	542.0	61.2
300	300	125	10.8	16.2	54.2	653.0	72.2
320	320	131	11.5	17.3	61.0	782.0	84.7
340	340	137	12.2	18.3	68.0	923.0	98.4
360	360	143	13	19.5	76.1	1090.0	114.0
380	380	149	13.7	20.5	84.0	1260.0	131.0
400	400	155	14.4	21.6	92.4	1460.0	149.0

Height tolerances: up to 200 mm ± 2 mm, above ± 3 mm.

Table 16-8

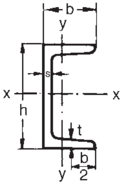
Wide flange beams with parallel flanges and normal web, DIN 1025 Sheet 2



Symbol	Dimensions in mm					Weight	Section modulus for bending axis	
							x – x	y – y
							W_x	W_y
	h	*b*	*s*	*t*	r_1	kg/m	cm^3	cm^3
IPB	IPB beams DIN 1025, Sheet 2							
100	100	100	6.5	10	10	21	89.3	33.4
120	120	120	7	11	11	28	144	52.9
140	140	140	8	12	12	36	217	78.6
160	160	160	9	14	14	47	329	120
180	180	180	9	14	14	53	426	151
200	200	200	10	16	15	66	595	214
220	220	220	10	16	15	73	732	258
240	240	240	11	18	17	89	974	346
260	260	260	11	18	17	97	1 160	406
280	280	280	12	20	18	116	1 480	523
300	300	300	12	20	18	124	1 720	600
320	320	300	13	22	20	138	2 020	661
340	340	300	13	22	20	140	2 170	661
360	360	300	14	24	21	153	2 510	721
380	380	300	14	24	21	156	2 680	721
400	400	300	14	26	21	168	3 030	781
425	425	300	14	26	21	170	3 270	781
450	450	300	15	28	23	186	3 740	841
475	475	300	15	28	23	189	4 010	841
500	500	300	16	30	24	204	4 530	902
550	550	300	16	30	24	211	5 100	902
600	600	300	17	32	26	232	6 030	962
650	650	300	17	32	26	239	6 670	962
700	700	300	18	34	27	259	7 720	1 020
750	750	300	18	34	27	267	8 430	1 020
800	800	300	18	34	27	274	9 160	1 020
900	900	300	19	36	30	305	11 250	1 080
1000	1000	300	19	36	30	321	12 900	1 080

Table 16-9

Steel channel, normal lengths 4 to 15 m, DIN 1026



Symbol	Dimensions in mm				Weight	Section modulus for bending axis	
						x – x	y – y
						W_x	W_y
	h	b	s	t	kg/m	cm^3	cm^3
U	Channel DIN 1026						
30	30	33	5	7	4.27	4.26	2.68
40 × 20	40	20	5	5.5	2.87	3.79	0.86
40	40	35	5	7	4.87	7.05	3.08
50 × 25	50	25	5	6	3.86	6.73	1.48
50	50	38	5	7	5.59	10.6	3.75
60	60	30	6	6	5.07	10.5	2.16
65	65	42	5.5	7.5	7.09	17.7	5.07
80	80	45	6	8	8.64	26.5	6.36
100	100	50	6	8.5	10.6	41.2	8.49
120	120	55	7	9	13.4	60.7	11.1
140	140	60	7	10	16.0	86.4	14.8
160	160	65	7.5	10.5	10.5	116.0	18.3
180	180	70	8	11	22.0	150	22.4
200	200	75	8.5	11.5	25.3	191	27.0
220	220	80	9	12.5	29.4	245	33.6
240	240	85	9.5	13	33.2	300	39.6
260	260	90	10	14	37.9	371	47.7
280	280	95	10	15	41.8	448	57.2
300	300	100	10	16	46.2	535	67.8
U	Square-edge channel						
1 600	33	33	2.75	2.75	2.02		
1 440	50	30	4	4	3.2		
3 744	60	30	3	3	2.68		
4 631	120	24	4	4	5.06		

Height tolerances: up to 65 mm ± 1.5 mm, up to 200 mm ± 2.0 mm, above ± 3.0 mm.

16.1.3 Stresses in steel components

The permissible stresses in steel components for transmission towers and structures for outdoor switchgear installations are laid down in DIN VDE 0210, Table 9. Values for different kinds of stress, such as tensile, shear, compressive and bearing stresses are specified for the steel sections given in DIN VDE 0210, 8.4.2.

Permissible stresses:

mechanical engineering materials, cf. “Hütte”, 29th edition, and “Stahlschlüssel”, 15th edition,
structural steel, cf. DIN 18800, Part 1
structural aluminium, cf. DIN 4113, Part 1.

Remarks:

Structural steels to DIN EN 10 025, screws and bolts to DIN 267. Permissible weld stresses for welded towers are given in DIN 18800, Part 1.

According to VDE 0210, structural steels of grade St 37-2 (S 235 JR) and above may be used for overhead power lines.

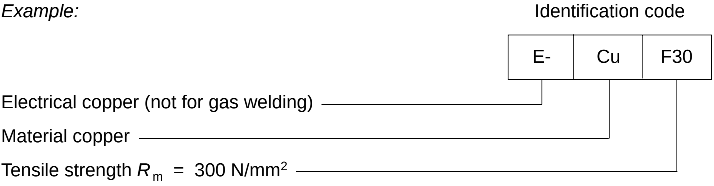
16.2 Non-ferrous metals

16.2.1 Copper for electrical engineering

Cathode copper is covered by DIN EN 1976 and DIN EN 1978. Semi-finished products, such as sheet, strip, tubes, rods, wire and cast and extruded sections, are covered by DIN 1787. Semis of electrical copper must conform to the specifications of DIN 40500. Oxygen-free copper (SE-Cu) is used to meet special requirements regarding formability, for gas welding or for flame soldering.

The identification code is important for ensuring conductivity, composition and strength characteristics.

Example:



For special properties as conductor material, see Section 13.1.1.

16.2.2 Aluminium for electrical engineering

High-purity aluminium, denoted Al 99.99 R, is obtained direct from primary aluminium or aluminium returns by metallurgical means, cast into ingots at the smelting plant and marked.

Primary aluminium, denoted Al 99.8 H, is aluminium obtained from the smelting process which conforms to the specified purity.

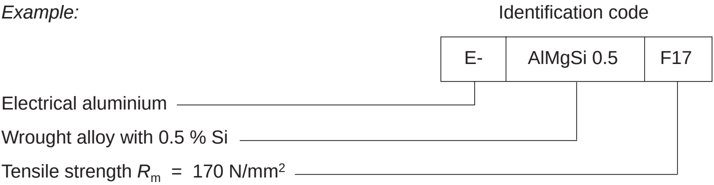
Aluminium for electrical engineering is available as:

1. Pure aluminium to DIN EN 573-2, supplied as primary aluminium (code 99.5 H) or pure aluminium (code 99.5) and unless specified otherwise must not contain more than 0.03 % Ti + Cr + V + Mn.
2. Wrought aluminium alloys to DIN EN 573-3.

The requirements specified in DIN 40501 and DIN EN 1715 must also be observed.

When ordering, for example, it is important to state the identification code for the conductivity, composition and strength characteristics.

Example:



For special properties as conductor material, see Section 13.1.1.

16.2.3 Brass

Information regarding the use of copper-zinc alloys, their composition and types of semi-finished products is to be found in DIN 17660.

The corresponding strength properties and the technical terms of delivery are given in the following standards:

DIN EN 1652 for sheet and strip,
DIN EN 12168 for tubes,
DIN EN 12163, 12164, 12165 and 12167 for rods,
DIN EN 17673 for forgings,
DIN EN 12167 and 12168 for extruded sections.

For special properties as conductor material, see Section 13.1.1.

16.3 Insulating materials

16.3.1 Solid insulating materials

Table 16-10

Abbreviations and properties of solid insulating materials

Abbreviation	Material	Density DIN 53479 ρ kg/dm^3	Bending strength DIN 53452 σ_b MPa	Tensile strength DIN 53455 σ_z MPa	Impact strength ISO 180/C a_n kJ/m^2	Elasticity modulus DIN 53457 E MPa	Linear thermal expansion DIN 53328 α_1 10^{-4}/K	Thermal conductivity DIN 52612 λ W/(m · K)	Max. temperature DIN 53458 °C	Tracking resistance DIN IEC 60112 Comparative figure	Breakdown field strength DIN IEC 60243-2 E_d kV/mm	Resistivity DIN IEC 60093 ρ_D $\Omega \cdot$ cm	Dielectric constant IEC 60250 ε_r (50 Hz)	Product label
	Insulating materials for cables and conductors													
PVC-P	polyvinyl chloride non-rigid	1.3				150	1 – 2	0.2	60	600	10 – 25	10^{15}	3.5 – 7.5	Astralon, Mipolam, Trovidur
PVC-U	polyvinyl chloride rigid	1.38	100	50	30	2 500	1.0	0.2	90	600	30 – 40	10^{15}	3.3 – 4	Vestolit, Vinoflex, DC-Fix, Pegulan, Hostalit Fibres: PW, Rhovyl, Thermovyl
PE	high-pressure polyethylene	0.917	80	12	without rupture	100	1.8	0.3	80	600	40	10^{17}	2.25	Lupolen H, Vestolen, Trolen
	low-pressure polyethylene	0.96	80	25	without rupture	1 400	2.0	0.5	95	600	45	10^{17}	2.3	Hostalen, Marlex Foils: Baulen, Hellaflex Fibres: Polytrene, Trofil
XLPE (VPE)	cross-linked polyethylene				without rupture		2.5		130	600	>45	10^{17}	2.4	Cable insulation (XLPE)

(continued)

Table 16-10 (continued)

Abbreviations and properties of solid insulating materials

Abbreviation	Material	Density DIN 53479 ρ kg/dm^3	Bending strength DIN 53452 σ_b MPa	Tensile strength DIN 53455 σ_z MPa	Impact strength ISO 180/C a_n kJ/m^2	Elasticity modulus DIN 53457 E MPa	Linear thermal expansion DIN 53328 α_1 10^{-4}/K	Thermal conductivity DIN 52612 λ W/(m · K)	Max. temperature DIN 53458 °C	Tracking resistance DIN IEC 60112 Comparative figure	Breakdown field strength DIN IEC 60243-2 E_d kV/mm	Resistivity DIN IEC 60093 ρ_D $\Omega \cdot$ cm	Dielectric constant IEC 60250 ε_r (50 Hz)	Product label
	Insulating materials for foils, semi-finished products, struct. comp.(thermoplastics, mouldings)													
PC	polycarbonate (PC 300)	1.2	75	65	without rupture	2 200	0.6	0.2	130	275	25	10^{15}	3.0	Lexan, Makrolon
PTFE	polytetrafluorethylene	2.2	19	20	without rupture	4 000	0.6	0.24	250	600	35	$>10^{18}$	2.0	Teflon, Hostaflon TE, Fluon
PS	polystyrene	1.05	100		22	2 000	0.8	0.14	60-90	375-475	50	$>10^{16}$	2.5	Polystyrol, Styroflex, Novodur,Trolitul, Styron, Vestyron Foils: Trolit, Elektroiso.
	foam polystyrene	0.02–0.06	0.3-2.5	0.3-5.5										Styropor
PET	polyethylene terephthalate	1.38	117	54	without rupture	2 800	0.6	0.2	120	250	30	10^{17}	3.5	Foils: Hostaphan, Mylar Fibres: Diolen, Dacron
PF	phenolic formaldehyde resins	1.4–1.9	50–60	20–25	20–120	6 000–16 000	0.15–0.3	0.7–0.3	100-150	125-175	5–20	10^8–10^{11}	4–15	Albertit, Bakelite, Formica, Pertinax
	PF-Hgw 2072	1.6–1.8	200	100	50	14 000	0.2–0.4	0.3	130	25-150	20–25	10^{11}	5	with woven glass silk VDE 0334
MF	melamine resins	1.5	40–80	15–30	3.5–25	6 000–13 000	0.1–0.5	0.3–0.7	100–140	600	10–30	10^8–10^{12}	6–10	Albamit, Chemoplast, Resopal, Ultrapas, Bakelite
	MF-Hgw 2272 (in sheet)	1.8–2.0	270	120	50	14 000	0.1–0.2	0.3	130	600	20–25	10^{10}	7.0	Woven glass silk to VDE 0334
	melamine phenolic resins	1.6	70-80	30	6	6 000–8 000	0.15–0.3	0.35	120	600	30	10^{10}	6.0–15.0	Aminoplast, Phenoplast Moulding compound

(continued)

Table 16-10 (continued)

Abbreviations and properties of solid insulating materials

Abbreviation	Material	Density DIN 53479 ρ kg/dm³	Bending strength DIN 53452 σ_b MPa	Tensile strength DIN 53455 σ_z MPa	Impact strength ISO 180/C a_n kJ/m²	Elasticity modulus DIN 53457 E MPa	Linear thermal expansion DIN 53328 α_1 10^{-4}/K	Thermal conductivity DIN 52612 λ W/(m · K)	Max. temperature DIN 53458 °C	Tracking resistance DIN IEC 60112 Comparative figure	Breakdown field strength DIN IEC 60243-2 E_d kV/mm	Resistivity DIN IEC 60093 ρ_D $\Omega \cdot$ cm	Dielectric constant IEC 60250 ε_r (50 Hz)	Product label
	Insulating materials for structural components (thermoplastics)													
PA 66	polyamide A	1.13	50-120	70	without rupture	2 000	0.7-1.0	0.2	120	600	25	10^{14}	4-8	Ultramid A, Durethan A, Zytel
PA 66	polyamide A with fibreglass	1.35	270	190	50	10 000	0.15-0.2	0.2	130	550	30	10^{12}		Ultramid A, Durethan A, Zytel
PA 6	polyamide B	1.14		60	without rupture	1 500	0.7-1.0	0.2	110	600	20-50	10^{12}-10^{15}	3.0-7.0	Ultramid B, Durethan B, Zytel
PA 6	polyamide B with fibreglass	1.38	250	180	65	10 000	0.2-0.3	0.2	120	550	30	10^{12}	3.0-7.0	Ultramid B, Durethan B, Zytel
GFN	PPO-reinforced	1.21			15	6 500			180					Noryl GFNZ halogenfree
PBT	polybutylene-terephthalate	1.3	90		without rupture	2 500	0.8	0.2	140	600	22-30	10^{16}	3.8	Vestadur, Pocan, Crastin
PBT	polybutyleneterephthalate with fibreglass	1.42	210	140	56	10 000	0.3	0.3	150	250	28-34	10^{15}	4.5	Vestadur, Pocan, Crastin
PUR	polyurethane (linear)	1.21	25–70	65	without rupture	2 200	0.6	0.2	130	220	20	10^{15}	3.0	
ABS	acrylic butadiene styrene	1.06			without	2 400	0.8	0.2	80	575	22	$>10^{15}$	3.3	Novodur, Terluran

(continued)

Table 16-10 (continued)

Abbreviations and properties of solid insulating materials

Abbreviation	Material	Density DIN 53479 ρ kg/dm^3	Bending strength DIN 53452 σ_b MPa	Tensile strength DIN 53455 σ_z MPa	Impact strength ISO 180/C a_n kJ/m^2	Elasticity modulus DIN 53457 E MPa	Linear thermal expansion DIN 53328 α_1 10^{-4}/K	Thermal conductivity DIN 52612 λ W/(m · K)	Max. temperature DIN 53458 °C	Tracking resistance DIN IEC 60112 Comparative figure	Breakdown field strength DIN IEC 60243-2 E_d kV/mm	Resistivity DIN IEC 60093 ρ_D $\Omega \cdot$ cm	Dielectric constant IEC 60250 ε_r (50 Hz)	Product label
	Cast resin mouldings (duroplastics)													
EP	epoxy resins (with 60–70 % filler)	1.6–1.8	70–80	75	10–68	14 000	0.3	0.6	125	600	30	10^{15}	4.2	Araldite 60 % powdered quartz, Resodip
	EP-Hgw 2372.2 (flame resistant)	1.7–1.9	350	220	100	18 000	0.1–0.2	0.3	155	180	40	10^{12}	4.0	EP + woven glass silk to VDE 0334
UP	unsaturated polyester resins (with 60-70 % filler)	1.6–1.8	40–60		10–40		0.3		110-130	600	25	10^{15}	4.5–7.5	Supraplast
	UP-Hgw 2472 (in sheet)	1.6–1.8	200	100	100	10 000	0.15–0.3	0.3	130	500-600	25–30	10^{12}	5.0	Glass mat to VDE 0334
PUR	polyurethane resin with 60-70% filler	1.6-1.8	120	70-100	10-100	10 000	0.4	0.8	110	600	30	10^{15}	4,3	Baygal, Baymidur

(continued)

Table 16-10 (continued)

Abbreviations and properties of solid insulating materials

Abbreviation	Material	Density	Bending strength		Tensile strength		Impact strength	Elasticity modulus	Linear thermal expansion	Thermal conductivity	Max. temperature	Tracking resistance	Breakdown field strength	Resistivity	Dielectric constant		Product label
		DIN 53479	DIN 53452		DIN 53455		ISO 180/C	DIN 53457	DIN 53328	DIN 52612	DIN 53458	DIN IEC 60112	DIN IEC 60243-2	DIN IEC 60093	IEC 60250		
		ρ	σ_b		σ_z		a_n	E	α_1	λ	°C	Comparative figure	E_d	ρ_D	ε_r (50 Hz)	$\varepsilon_r \tan\delta \cdot 10^3$	
		kg/dm^3	MPa		MPa		kJ/m^2	MPa	$10^{-4}/K$	W/(m · K)			kV/mm	Ω · cm			
	Ceramic insulating materials, e.g. post insulators, insulators, bushings																
			1)	2)	1)	2)										3)	
KER 110.1	predominantly aluminium silicate	2.4	60	40	30	25	1.8		0.038	1.6			30–35	10^{11}–10^{12}	6	17/120	Porcelain, Hard porcelain, Melatith, Karbowid 1203
KER 110.2		2.5	100	80	60	45	2.2		0.045	2.3			30–35	10^{11}–10^{12}	6	17/120	
KER 220	predominantly magnesium silicate	2.6	120	120	60	45	3		0.07	2.3			20	10^{12}	6	2.5/65	Skalit
KER 221		2.8	140	140	60	45	4		0.06	2.3			30	10^{12}	6	1.0/15	Frequenta, Calit, Dettan
KER 310	predominantly titanium oxide	3.5–	900–		300–				0.06–				10–		60		
KER 311		3.9	1500		800				0.08				20		40		
KER 610	sintered corundum Al_2O_3	3.4	–	120	183	40			0.07	16			25		7		AD 85 Degussit
KER 611		3.9	–	90					0.08	36							AD 99.9 furnace ceramic
	zirconium ceramic	3.1	552						0.04	110							furnace ceramic

1) Glazed   2) Unglazed   3) 20 °C / 100 °C

Note: The values given for mechanical properties may vary in practice, depending on how the materials are processed and the shape of the insulator.

16.3.2 Liquid insulating materials

Table 16-11

Types and properties of liquid insulating materials

Property	Unit	Mineral oil 1)	Liquid silicone Poly-dimethyl siloxane	HTK mineral oil I	Synthetic ester I	Synthetic ester II
Density	g/ml at 25 °C	0.84/0.88	0.96	0.88	0.98	0.98
Kin. viscosity	mm^2/s at 25 °C	11/18	50	350	90	60
	mm^2/s at 100 °C	1.5/2.5	16	16	6	5.6
Pour point	°C	–40/–60	–55	–15/–30	–52	–50
Thermal conductivity	W/cmK at 25 °C	0.00132	0.00151	0.00130	0.00155	0.00155
Spec. heat	J/g K	1.93	1.53	1.93	2.1	2.1
Expansion coefficient	1/K	0.00083	0.00104	0.00080	0.00080	0.0011
Dielectric constant	at 25 °C	2.2/2.4	2.7	2.38	3.2	3.2
Flashpoint	°C	130/160	305	210/285	257	260
Firepoint	°C	150/175	360	310/320	310	300
Spontaneous ignition temp.	°C	330	430	540	435	435
Flammability	—	Flammable	Flame-retardant	Flame-retardant	Flame-retardant	Non-flammable
Gases	—	Explosive	Explosive	Explosive	Explosive	Explosive
Ecological aspects	—	Bio-degradable	Non-toxic, non-polluting	Bio-degradable	Bio-degradable	Bio-degradable

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1) Class A (standard)/Class B (low-temperature oil)

16.3.3 Gaseous insulating materials

Table 16-12

Properties of air and SF_6

Gas	Density[1)] kg/m³	Breakdown field strength E_d kV/mm (50 Hz)	Dielectric constant ε_r (50 Hz)
Air (dry)	1.205	2.1	1.000576
Sulphur hexafluoride SF_6	6.07	6	1.0021

1) at 20 °C and 1013 mbar

Curves of pressure, temperature and density for SF_6 gas are shown in Fig. 11-1. The insulating and arc-quenching properties of this gas are dealt with in Sections 10.4.4 and 11.2.2.

16.4 Semi-finished products

16.4.1 Dimensions and weights of metal sheets, DIN EN 10130

Table 16-13

Weight per 1 m² of sheet, in kg

Thickness *s* in mm	Steel	Aluminium	Copper	Brass	Zinc	Ribbed sheet	Profiled treadplate
0.5	3.925	1.34	4.45	4.275	3.6	–	–
0.75	5.888	2.01	6.657	6.413	5.4	–	–
1	7.85	2.68	8.9	8.55	7.2	–	–
1.5	11.775	4.02	13.35	12.825	10.8	–	–
2	15.7	5.36	17.8	17.10	14.4	–	–
2.5	19.63	6.7	22.25	21.38	18.0	–	–
3	23.6	8.04	26.7	26.65	21.6	30	25
4	31.4	10.72	35.6	34.20	28.8	38	34
5	39.3	13.4	44.5	42.75	36	46	42
6	47.2	16.08	53.4	51.3	43.2	54	51
8	64.0	21.6	71.6	68.4	57.6	70	67

Normal panel size 1000 mm × 2 000 mm
Switchboard sheet 1250 mm × 2 500 mm
Ribbed sheet and profiled treadplate 1250 mm × 2 500 mm

16.4.2 Slotted steel strip

Table 16-14

Slotted steel strip, hot-galvanized

Dimensions mm	Slot size mm	Weight kg / m	Standard roll, length m	in cut lengths 3 m approx., m / bundle
20 × 1.5	40 × 5.5	0.187	200	60
20 × 2	40 × 5.5	0.245	200	60
25 × 2	40 × 5.5	0.326	200	60
30 × 2.5	40 × 5.5	0.508	150	60
20 × 3	40 × 6.5	0.368	120	60
25 × 3	40 × 6.5	0.489	120	60
30 × 3	40 × 6.5	0.640	120	60
30 × 4	60 × 8.5	0.716	100	30
40 × 4	70 × 8.5	1.038	80	30
50 × 4	70 × 8.5	1.360	80	30

Steel earthing strip, hot-galvanized, DIN 48801

Dimensions mm	Weight kg / m	Standard roll m
20 × 2.5	0.400	100
30 × 3.5	0.840	100 (50)
30 × 4.0	0.961	30
40 × 5.0	1.600	50

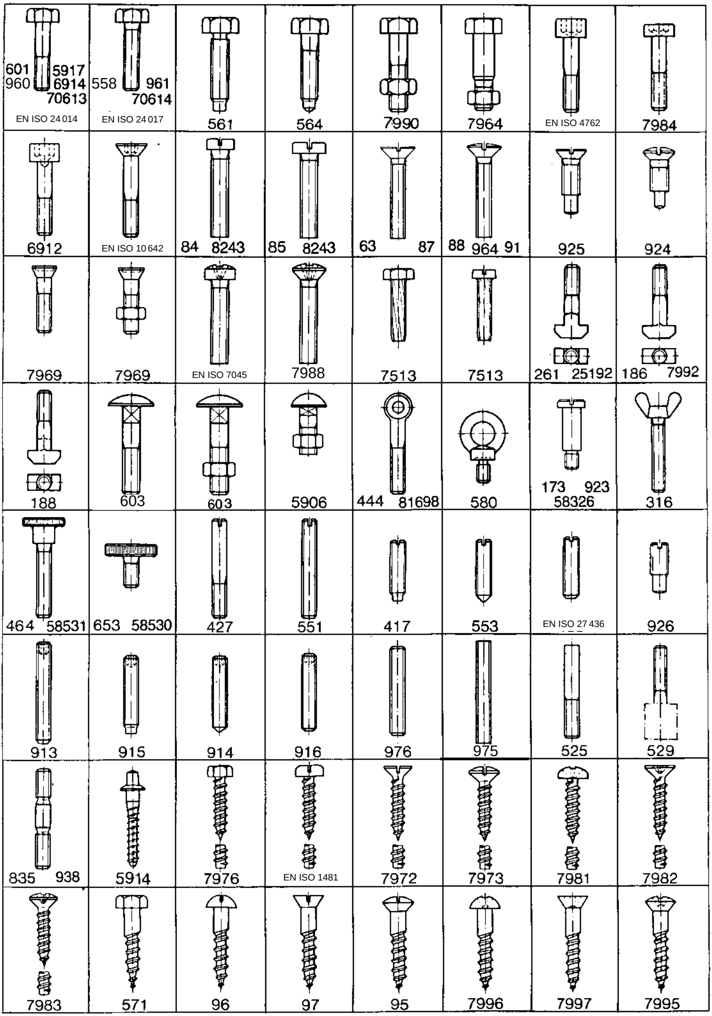
Accessories, plastic anchor plugs

Size mm	Plug length mm	Hole dia. mm	For screws dia. mm
5	25	5	2.5 – 4
6	30	6	3.5 – 5
6	60	6	3.5 – 5
8	40	8	4.5 – 6
8	75	8	4.5 – 6
10	50	10	6 – 8
12	60	12	8 – 10

16.4.3 Screws and accessories

Table 16-15

Standard screws and bolts (the figures denote DIN numbers)[1]



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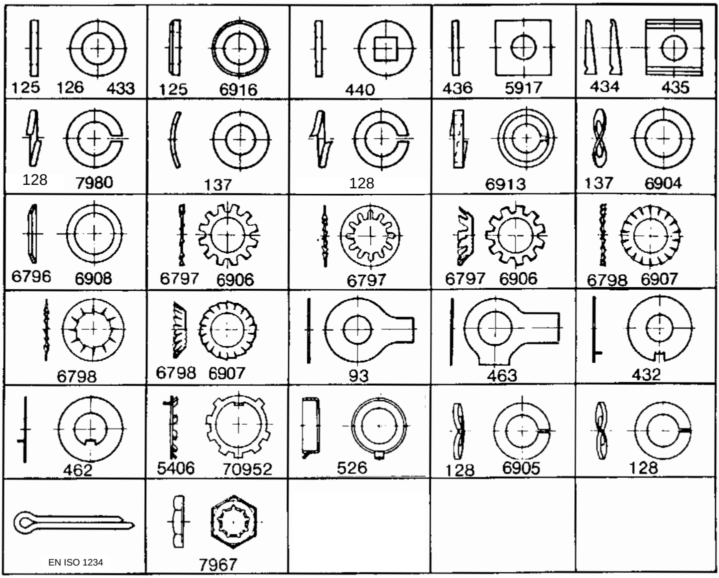
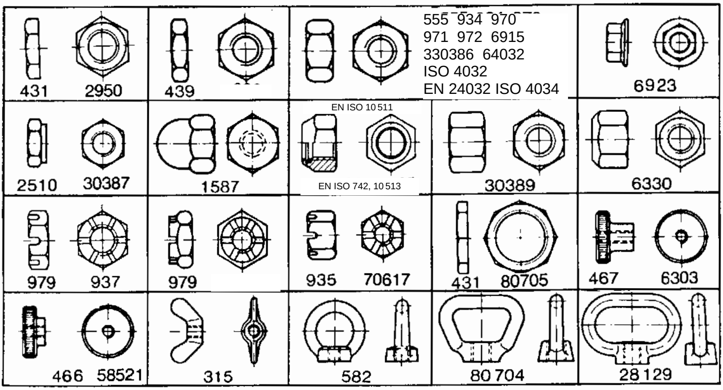
[1] as DIN-Normblatt-Verzeichnis. Published by Deutscher Normenausschuß (DNA). DIN and DIN ISO numbers shown abridged.

Table 16-16

Standard washers and nuts (the figures denote DIN numbers)[1]





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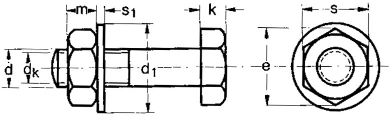
[1] as DIN-Normblatt-Verzeichnis. Published by Deutscher Normenausschuß (DNA).
DIN and DIN ISO numbers shown abridged.

16.4.4 Threads for bolts and screws

Table 16-17

Bolts and screws with metric thread, DIN 13 and DIN ISO 1502, dimensions in mm



Bolt threads Nominal diameter	Minor thread diameter	Lead	Thickness of head	Thickness of nut	Width across flats	angles	Washer		Drill hole pass through dia.	for thread dia.
d	d_k	*h*	*k*	*m*	*s*	*e*	d_1	s_1		
2	1.509	0.4	1.4	1.6	4	4.6	5	0.3	2.4	1.6
3	2.387	0.5	2	2.4	5.5	6.4	7	0.5	3.4	2.5
4	3.141	0.7	2.8	3.2	7	8.1	9	0.8	4.5	3.3
5	4.019	0.8	3.5	4.7	8	9.2	10	1.0	5.5	4.2
6	4.737	1	4.0	5.2	10	11.6	12.5	1.6	6.6	5.0
8	6.466	1.25	5.3	6.8	13	15	17	1.6	9	6.8
10	8.160	1.5	6.4	8.4	16	18.5	21	2.0	11	8.5
12	9.853	1.75	7.5	10.8	18	20.8	24	2.5	14	10.2
14	11.546	2	9	12.8	21	24.3	28	2.5	16	12
16	13.546	2	10	14.8	24	27.7	30	3	18	14
18	14.933	2.5	11.5	15.8	27	31.2	34	4	20	15.5
20	16.933	2.5	12.5	18	30	34.7	37	3	22	17.5
22	18.933	2.5	14	19.4	34	38.3	39	3	24	19.5
24	20.319	3	15	21.5	36	41.6	44	4	26	21
27	23.051	3	17	23.8	41	47.4	50	4	30	24
30	25.706	3.5	18.7	25.6	46	53.2	56	4	33	26.5
33	28.706	3.5	21	28.7	50	57.8	60	5	36	29.5
36	31.093	4	22.5	31	55	63.5	66	5	39	32
39	34.093	4	25	32	60	69.3	72	6	42	35
42	36.479	4.5	26	34	65	75	78	7	45	37.5

Quality identification and mechanical properties of nuts and bolts: see technical terms of supply as per DIN 267, and also DIN ISO 8992, DIN EN 20898-2, DIN ISO 3269, DIN ISO 4042, DIN ISO 3506 and DIN EN ISO 2320.

16.4.5 Threads for electrical engineering

Table 16-18

Steel conduit threads, DIN 40430, dimensions in mm

Designation	External threads				Lead	Internal threads			
	Major diameter		Minor diameter			Major diameter		Minor diameter	
	d max.	d min.	d_1 max.	d_1 min.	P	D min.	D max.	D_1 min.	D_1 max.
Pg 7	12.5	12.3	11 28	11.08	1.27	12.5	12.65	11.28	11.43
Pg 9	15.2	15	13.86	13.66	1.41	15.2	15.35	13.86	14.01
Pg 11	18.6	18.4	17.26	17.06	1.41	18.6	18.75	17.26	17.41
Pg 13.5	20.4	20.2	19.06	18.86	1.41	20.4	20.55	19.06	19.21
Pg 16	22.5	22.3	21.16	20.96	1.41	22.5	22.65	21.16	21.31
Pg 21	28.3	28	26.78	26.48	1.588	28.3	28.55	26.78	27.03
Pg 29	37	36.7	35.48	35.18	1.588	37	37.25	35.48	35.73
Pg 36	47	46.7	45.48	45.18	1.588	47	47.25	45.48	45.73
Pg 42	54	53.7	52.48	52.18	1.588	54	54.25	52.48	52.73
Pg 48	59.3	59	57.78	57.48	1.588	59.3	59.55	57.78	58.03

Table 16-19

Electrical threads, DIN 40400, dimensions in mm

Designation	Bolt				Lead	Nut			
	Major diameter		Minor diameter			Major diameter		Minor diameter	
	d max.	d min.	d_1 max.	d_1 min.	P	D min.	D max.	D_1 min.	D_1 max.
E 14	13.89	13.70	12.29	12.10	2.822	13.97	14.16	12.37	12.56
E 16	15.97	15.75	14.47	14.25	2.500	16.03	16.25	14.53	14.75
E 18	18.50	18.25	16.80	16.55	3.000	18.60	18.85	16.90	17.15
E 27	26.45	26.15	24.26	23.96	3.629	26.55	26.85	24.36	24.66
E 33	33.05	32.65	30.45	30.05	4.233	33.15	33.55	30.55	30.95

17 Miscellaneous

17.1 DIN VDE specifications and IEC publications for substation design

The VDE catalogue of (primarily technical safety) specifications for the entire field of electrical engineering in Germany is among the most important tasks of the VDE Verband der Elektrotechnik Elektronik Informationstechnik e.V. (VDE Association for Electrical Electronic & Information Technologies). The content, design, development and legal significance of the VDE catalogue of specifications are described in detail in VDE specification 0022 (latest edition: September 1994). Selected extracts of a fundamental nature are quoted below:

> “The stipulations contained in the VDE catalogue are drawn up by the Deutsche Elektrotechnische Kommission (DKE) of DIN and VDE.
>
> The DKE is the German national organization for compiling national and international standards and VDE specifications in the entire field of electrical engineering in the Federal Republic.”
>
> “Results of international work are to be adopted as far as possible without alteration into the VDE standards catalogue and simultaneously into the DIN catalogue of standards.
>
> In the interests of European and worldwide harmonization, the rules of CENELEC (European Committee for Electrotechnical Standardization) impose an obligation to adopt certain standards of the International Electrotechnical Commission (IEC) and also European standards (EN) and harmonization documents (HD) issued by CENELEC.”
>
> The component parts of the VDE standards catalogue are:
> – the rules and other rules relating thereto,
> – VDE specifications,
> – VDE guidelines,
> – attachments to rules, VDE specifications and VDE guidelines.
>
> “The results of the DKE’s work on electrotechnical standardization, which include safety regulations where appropriate, are registered as DIN standards, with additional identification as VDE specification or VDE guideline, in the VDE standards catalogue. The results of this work also include draft standards, amendments and the draft standards of the VDE:”

Standardization work for the field of electrical engineering is conducted almost entirely on an international level. DKE is actively involved with the appointment of specialists to the working groups, committees and other bodies of the international organizations and submits position papers on drafts and other queries and approves the acceptance of regulations. The position papers are prepared by the relevant DKE committee.

Agreements between IEC and CENELEC on one hand and between CENELEC and DKE on the other regulate the incorporation of international standards into national standards. The national committee and the relevant DKE advisers section share the responsibility for the publication schedule of the international standard translated into German – without deviations or with only minor, clearly defined deviations – as a German standard.

VDE regulations, guidelines and the associated supplements have an identification number combined from a DIN numbering system and a VDE classification number. The DIN numbering system also includes information on the origins of the content of the standard, while the VDE classification makes it much easier to find. The following scheme is used:

DIN EN 6 .... (VDE 0 ...) – European standard (EN), formed by using an IEC standard word by word (1st number = 6) *)

DIN EN 5 .... (VDE 0 ...) – European standard (EN) of other origin (1st number = 5)

DIN IEC 6 .... (VDE 0 ...) – IEC standard incorporated word for word but is not EN

DIN VDE 0 .... (VDE 0 ...) – IEC standard incorporated with deviations

– CENELEC (HD) harmonization document that is not equivalent to an IEC standard

– national standard

In comprehensive standards comprising several parts the part numbers are preceded by a hyphen or in the case of the VDE classification by the word “Part”.

Because the new identification system has only been defined since 1993, at present a whole series of VDE regulations is still valid whose DIN reference number was specified under a different system. They are to be adapted to the new system during the next technical revision.

Existing working results of the former type such as VDE guidelines, VDE standards, VDE codes of practice, VDE directives, VDE regulations, VDE publications are also being adapted to the above components of the VDE catalogue, when they are revised.

*) The number of the DIN numbering system corresponds to the new 5-digit numbering system, which is currently in the process of introduction by the International Electrotechnical Commission (IEC). It also begins with 6 in the first position followed by the former 2, 3 or 4-digit IEC reference number and zeros in the vacant positions.

The legal significance of the specifications of the VDE catalogue is clarified by the following citations from VDE 0022.

> “At the time of their publication VDE specifications are the basis for correct engineering practice.“
>
> “According to § 1 of the 2nd implementing regulation effective 1 January 1987 to the energy supply act (2nd DVO to the EnWG, BGBl. (federal gazette)1987 I, p. 146), the generally accepted rules of engineering must be observed for the erection and maintenance of installations for the generation, transmission and supply of electricity. Where installations must meet the state of safety engineering set in the community on the basis of European Community regulations, these regulations are mandatory.”

The VDE specifications must always be observed if one does not wish to be accused of not meeting the duty of care in the manufacture and maintenance of electrical installations and devices.

The following list shows an overview of the most important VDE specifications for switchgear engineering. They are listed with their full numbering as at the end of 2000 and the month in which they became effective. Because of the extent of the current DIN VDE catalogue of specifications, this list cannot be considered complete. For example, later amendments, draft standards, supplements and drafts have generally not been included. The majority of listed DIN VDE standards also have corresponding IEC or EN standards. Where this is not the case, international standards are given if possible.

For improved clarity and to save space, some titles of standards are slightly abbreviated. In standard series the general header has not been repeated in the list of standards immediately following.

Group 1 Power installations

DIN 57100-100	**(VDE 0100 Part 100)** Erection of power installations with rated voltages up to 1000 V – Scope; general requirements	1982-05
DIN VDE 0100-200	**(VDE 0100 Part 200)** Electrical installations of buildings – Terms and definitions	1998-06
DIN VDE 0100-300	**(VDE 0100 Part 300)** Erection of power installations with nominal voltages up to 1000 V – Assessment of general characteristics of installations IEC 60364-3, HD 384.3 S2	1996-01
DIN VDE 0100-410	**(VDE 0100 Part 410)** – Protection against electric shock IEC 60364-4-41, HD 384.4.41 S2	1997-01
DIN VDE 0100-420	**(VDE 0100 Part 420)** – Protection against thermal effects	1991-11
DIN VDE 0100-430	**(VDE 0100 Part 430)** – Protection of cables and cords against overcurrent	1991-11
DIN VDE 0100-442	**(VDE 0100 Part 442)** Electrical installations of buildings – Protection of low-voltage installations against faults between high-voltage systems and earth, HD 384.4.442 S1	1997-11

further parts: 450, 460, 470, 482, 510, 520, 530, 537, 540, 550, 551, 559, 560, 610,
620, 704, 705, 706, 707, 708 etc.

DIN VDE 0100-729	**(VDE 0100 Part 729)** Erection of power installations with nominal voltages up to 1000 V – Installation and connection of switchgear and control gear and distribution boards	1986-11
DIN 57100-736	**(VDE 0100 Part 736)** – Low-voltage circuits in high-voltage switchboards	1983-11
DIN VDE 0100-737	**(VDE 0100 Part 737)** – Humid and wet areas and locations; Outdoor installations	1990-11
DIN VDE 0100-739	**(VDE 0100 Part 739)** – Additional protection in case of direct contact in dwellings by residual current devices in TN and TT systems.	1989-06
DIN VDE 0101	**(VDE 0101)** Power installations exceeding AC 1 kV replaces DIN VDE 0101: 1989-05 and, partly, DIN VDE 0141: 1989-07, HD 637 S1: 1999	2000-01
DIN VDE 0102	**(VDE 0102)** Short-circuit current calculation in three-phase AC systems	1990-01
DIN 57102-2	**(VDE 0102 Part 2)** VDE recommendation to the calculation of short-circuit currents in three-phase AC systems up to 1000 V	1975-11
DIN IEC 60909-3	**(VDE 0102 Part 3)** Short-circuit currents Calculation of currents in three-phase AC systems – currents during two separate simultaneous single phase line-to-earth short-circuits and partial short-circuit currents flowing through earth	1997-06
DIN EN 60865-1	**(VDE 0103)** Short-circuit currents – Calculation of effects, definitions and calculation methods	1994-11
DIN EN 50110-1	**(VDE 0105 Part 1)** Operation of electrical installations	1997-10
DIN VDE 0105-100	**(VDE 0105 Part 100)** Operation of electrical installations	2000-06
DIN VDE 0105-103	**(VDE 0105 Part 103)** – Particular requirements for railways	1999-06
DIN VDE 0105-111	**(VDE 0105 Part 111)** – Particular requirements for underground mines	2000-09
DIN VDE 0105-7	**(VDE 0105 Part 7)** – Supplementary requirements for atmospheres endangered by potentially explosive material	1987-12

DIN VDE 0105-9	**(VDE 0105 Part 9)** – Supplementary requirements for potentially explosive atmospheres	1986-05
DIN 57106-1	**(VDE 0106 Part 1)** Protection against electric shock – Classification of electrical and electronic equipment	1982-05
further parts: 100, 101, 102		
DIN VDE 0107	**(VDE 0107)** Electrical installations in hospitals and locations for medical use outside hospitals	1994-10
DIN VDE 0108-1	**(VDE 0108 Part 1)** Power installations and safety power supply in communal facilities – General	1989-10
further parts: 2, 3, 4, 5, 6, 7 and 8		
E DIN VDE 0109-13	**(VDE 0109 Part 13)** Insulation coordination in low-voltage systems – voltage testing of clearances, currently indraft IEC 60664	1990-09
further parts: 16, 19, 21, 22, 23, 24 (currently all in draft)		
DIN VDE 0110-1	**(VDE 0110 Part 1)** Insulation coordination for electrical equipment within low-voltage systems – Principles, requirements, tests IEC 60664-1, HD 625.1 S1	1997-04
further parts: 3, 20		
DIN EN 60071-1	**(VDE 0111 Part 1)** Insulation coordination – Definitions, principles and rules	1996-07
DIN EN 60071-2	**(VDE 0111 Part 2)** – Application guide	1997-09
DIN EN 60204-1	**(VDE 0113 Part 1)** Safety of machinery – Electrical equipment of machines – General requirements	1998-11
numerous further parts		
DIN EN 50163	**(VDE 0115 Part 102)** Railway applications – Supply voltages of traction systems	1996-05
DIN EN 50153	**(VDE 0115 Part 2)** – Rolling stock – Protective provisions relating to electrical hazards	1996-12

DIN EN 50122-1	**(VDE 0115 Part 3)** – Fixed installations – Protective provisions relating to electrical safety and earthing	1997-12
numerous further parts		
DIN VDE 0118-1	**(VDE 0118 Part 1)** Erection of electrical installations in mines – General requirements	1990-09
DIN VDE 0118-2	**(VDE 0118 Part 2)** – Supplementary requirements for power installations	1990-09
DIN VDE 0132	**(VDE 0132)** Measures to be taken in the case of fire in or near electrical installations	1989-11
DIN VDE 0141	**(VDE 0141)** Earthing systems for special power installations with nominal voltages above 1 kV replaces DIN VDE 0141: 1989-07 and see DIN VDE 0101: 2000-01	2000-01
DIN EN 50186-1	**(VDE 0143 Part 1)** Live-line washing systems for power installations with rated voltages above 1 kV – General requirements	1999-01
DIN 57150	**(VDE 0150)** Protection against corrosion due to stray currents of DC installation	1983-04
DIN VDE 0151	**(VDE 0151)** Material and size requirements for earth electrodes from the corrosion point of view.	1986-06
DIN EN 50178	**(VDE 0160)** Electronic equipment for use in power installations	1998-04
DIN EN 60079-14	**(VDE 0165 Part 1)** Electrical apparatus for explosive gas atmospheres – Electrical installations in hazardous areas (other than mines)	1998-08
see also parts 1, 10, 101 and VDE 0166.		
DIN VDE 0168	**(VDE 0168)** Erection of electrical installations in open-cast mines, quarries and similar plants	1992-01
DIN EN 50014	**(VDE 0170/0171 Part 1)** Electrical apparatus for potentially explosive atmospheres – General requirements	2000-02
numerous further parts		

DIN 57185-1	**(VDE 0185 Part 1)** Lightning protection system – General with regard to installation	1982-11

further parts: 100, 103, 105, 110, 2, 201.

DIN EN 60446	**(VDE 0198)** Basic and safety principles for man-machine interface – Identification of conductors by colours or numerals	1999-10
DIN EN 60073	**(VDE 0199)** – Coding principles for indication devices and actuators	1997-09

Group 2 Power guides

DIN 40500 [1]	Copper for electrical engineering, technical terms of delivery	
Parts 1-3	Sheets, tubes, sections	
Part 4	Wire	
Part 5	Tinned wire	
DIN 40501 [1]	Aluminium for electrical engineering, technical terms of delivery	
Parts 1-3	Sheets, tubes, sections	
Part 4	Wire	
DIN EN 1715 [1]	Aluminium, continuous-cast wire rod	
DIN VDE 0207-2	**(VDE 0207 Part 2)** Insulating and sheathing compounds for cables and flexible cords – Polyethylene insulating compounds	1999-02

further parts: 20, 21, 22, 23, 24, 3, 4, 5, 6, 7.

DIN VDE 0210	**(VDE 0210)** Planning and design of overhead power lines with rated voltages above 1 kV	1985-12
DIN EN 61773	**(VDE 0210 Part 20)** Overhead lines – Testing of foundations for structures	1997-08
DIN VDE 0211	**(VDE 0211)** Planning and design of overhead power lines with rated voltages up to 1000 V	1985-12
DIN EN 61284	**(VDE 0212 Part 1)** Overhead lines – Requirements and tests for fittings	1998-05

further parts: 2, 3, 51, 54, 55.

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[1] DIN standard, not part of the DIN-VDE Group 2.

DIN VDE 0220-1	**(VDE 0220 Part 1)** Specifications for detachable cable clamps to be used in power cable installations up to 1000 V	1971-11
DIN VDE 0220-2	**(VDE 0220 Part 2)** Specifications for pressed connectors to be used in power cable installations	1971-11
DIN VDE 57220-3	**(VDE 0220 Part 3)** Single and multiple cable clamps with insulating parts in power cable installations up to 1000 V	1977-10
DIN VDE 0228-1	**(VDE 0228 Part 1)** Proceedings in the case of interference on telecommunication installations by electric power installations – General	1987-12
DIN VDE 0228-2	**(VDE 0228 Part 2)** – Interference by three-phase installations	1987-12

further parts: 3, 4, 5, 6.

DIN 57250-1	**(VDE 0250 Part 1)** Cables, wires and flexible cords for power installation – General	1981-10

further parts: 102, 106, 201, 203, 204, 205, 206, 209, 210, 212, 213, 214, 407, 502, 602, 603, 802, 806, 809, 811, 812, 813, 814, 815, 816

DIN VDE 0262	**(VDE 0262)** XLPE insulated and PVC sheated installation cables with nominal voltages 0.6/1 kV	1995-12
DIN VDE 0265	**(VDE 0265)** Cables with plastic-insulated lead-sheath for power installation	1995-12
DIN VDE 0266	**(VDE 0266)** Power cables with improved characteristics in the case of fire; nominal voltages 0.6 /1 kV	1997-11
DIN VDE 0271	**(VDE 0271)** PVC-insulated cables and sheathed power cables for rated voltages up to and including 3.6/6 (7.2) kV	1997-06
DIN VDE 0276-1000	**(VDE 0276 Part 1000)** Power cables – Current-carrying capacity, general, conversion factors	1995-06
DIN VDE 0276-603	**(VDE 0276 Part 603)** – Distribution cables of nominal voltages 0.6/1 kV, HD 603 S1	2000-05
DIN VDE 0276-604	**(VDE 0276 Part 604)** – Power cables of nominal voltages 0.6/1 kV with special fire performance for use in power stations, HD 604 S1	1995-10

DIN VDE 0276-620	**(VDE 0276 Part 620)** – Power distribution cables with extruded insulation for nominal voltages from 3.6 kV to 20.8/36 kV, HD 620 S1	1996-12
DIN VDE 0276-621	**(VDE 0276 Part 621)** – Power distribution cable with impregnated paper insulation for medium voltage, HD 621 S1	1997-05
DIN VDE 0276-622	**(VDE 0276 Part 622)** – Power cable of rated voltages from 3.6/6 (7.2) kV up to 20.8/36 (42) kV with special fire performance for use in power stations, HD 622/S1	1997-02
DIN VDE 0276-626	**(VDE 0276 Part 626)** – Overhead distribution cables of rated voltage 0.6/1 (1.2) kV, HD 626 S1	1997-01
DIN VDE 0276-632	**(VDE 0276 Part 632)** Power cables with extruded insulation and their accessories – Rated voltages above 36 kV up to 150 kV, HD 632 S1	1999-05
DIN VDE 0276-633	**(VDE 0276 Part 633)** Tests on oil-filled, paper- or polypropylene paper laminate-insulated, metal-sheathed cables and accessories – Alternating voltages up to and including 400 kV, HD 633 S1	1999-05
DIN VDE 0276-634	**(VDE 0276 Part 634)** Tests on internal gas-pressure cables and accessories – Alternating voltages up to and including 275 kV, HD 634 S1	1999-05
DIN VDE 0276-635	**(VDE 0276 Part 635)** Tests on external gas-pressure cables and accessories – Alternating voltages up to and including 275 kV, HD 635 S1	1999-05
DIN VDE 0278-623	**(VDE 0278 Part 623)** Power cable accessories with rated voltages up to 30 kV (36 kV) – Specifications for joints, stop ends and outdoor terminations for distribution cables of rated voltage 0.6/1 kV, HD 623 S1	1997-01
DIN VDE 0278-628	**(VDE 0278 Part 628)** – Test methods for accessories for power cables, with rated voltages from 3.6/6 (7.2 kV) up to and including 20.8/36 (42) kV, HD 628 S1	1997-11
DIN VDE 0278-629-1	**(VDE 0278 Part 629-1)** – Test requirements on accessories for use on power cables of rated voltage from 3.6/6 (7.2) kV up to 20.8/36 (42)kV – Cables with extruded solid insulation. HD 629.1 S1	1997-11
DIN VDE 0278-629-2	**(VDE 0278 Part 629-2)** – Cables with impregnated paper insulation, HD 629.2 S1	1998-06

DIN VDE 0281-1	**(VDE 0281 Part 1)** Polyvinyl chloride insulated cables of rated voltages up to and including 450/750 V – General requirements, IEC 60227-1, HD 21.1 S3	1999-01
DIN VDE 0281-2	**(VDE 0281 Part 2)** – Test methods, IEC 60227-2, HD 21.2 S3	1999-01

further parts: 3, 5, 7, 9.

DIN VDE 0282-1	**(VDE 0282 Part 1)** Rubber insulated cables of rated voltages up to and including 450/750 V – General requirements, IEC 60245-1, HD 22.1 S3	1999-01

further parts: 10, 11, 12, 13, 14, 2, 4, 6, 7, 9.

DIN VDE 0289-1	**(VDE 0289 Part 1)** Definitions for cables, wires and flexible cords for power installation – General definitions	1988-03

further parts: 2, 3, 4, 5, 6, 7, 8.

DIN VDE 0291-1	**(VDE 0291 Part 1)** Regulations for sealing compounds for cable components – Hot-application sealing compounds, cold-press casting compounds, cold-moulding compounds and compounds applied with hot water	1972-02
DIN 57291-2	**(VDE 0291 Part 2)** Casting compounds for use in cable fittings, cast resin compounds and moulding materials.	1979-11
DIN VDE 0293	**(VDE 0293)** Identification of cores in cables and flexible cords used in power installations with nominal voltages up to 1000 V	1990-01
DIN VDE 0295	**(VDE 0295)** Conductors of cables, wires and flexible cords for power installation	1992-06
DIN 57298-3	**(VDE 0298 Part 3)** Application of cables and flexible cords in power installations – General for cables	1983-08
DIN VDE 0298-4	**(VDE 0298 Part 4)** – Recommended current-carrying capacity for sheathed and non-sheathed cables for fixed wiring in buildings and of flexible cables and cords	1998-11
DIN VDE 0298-100	**(VDE 0298 Part 100)** – Economic optimization of cable size, IEC 61059, HD 558 S1	1992-12

DIN VDE 0298-300	**(VDE 0298 Part 300)** Guide to use of low-voltage harmonized cables, HD 516 S2	1999-04

Group 3 Insulating materials

DIN VDE 0302-1	**(VDE 0302 Part 1)** Insulation systems of electrical equipment – Evaluation and identification, IEC 60505	1986-09
DIN VDE 0302-2	**(VDE 0302 Part 2)** – Functional evaluation; aging mechanisms and diagnostic procedures, IEC 60610	1986-09
DIN VDE 0302-3	**(VDE 0302 Part 3)** – Thermal endurance, fundamentals for test procedures, IEC 60611	1986-09

further parts: 4, 5, 6, 7, 8.

DIN IEC 60112	**(VDE 0303 Part 1)** Method for determining the comparative and the proof-tracking indices of solid insulating materials under moist conditions	1984-06

further parts: 4, 5, 6, 8, 10, 11, 12.

DIN EN 60243-1	**(VDE 0303 Part 21)** Electric strength of insulation materials, test methods – Testing at power frequencies.	1999-03

further parts: 22, 23, 30, 31, 32 etc.

DIN VDE 0304-1	**(VDE 0304 Part 1)** Testing of solid insulation materials for assessment of their thermal stability – Determination of thermal properties of solid insulating materials	1959-07

further parts: 3, 21, 22, 23, 23-3-2, 24.

DIN 57370-1	**(VDE 0370 Part 1)** Insulating oils – New insulating oils for transformers and switchgear, IEC 60296	1978-12
DIN 57370-2	**(VDE 0370 Part 2)** – Insulating oils in service in transformers and switchgear	1978-12
DIN IEC 60475	**(VDE 0370 Part 3)** – Method for sampling of liquid dielectrics	1980-02
DIN EN 60156	**(VDE 0370 Part 5)** – Determination of the breakdown voltage at power frequency, test method	1996-03

further parts: 6, 8, 9, 11, 12, 13, 14, 16, 20.

DIN IEC 60376	**(VDE 0373 Part 1)** Requirements and acceptance of new sulfur hexafluoride (SF_6)	1980-04
DIN IEC 60480	**(VDE 0373 Part 2)** Guideline to the checking of sulfur hexafluoride (SF_6) taken from electrical equipment	1980-04

Group 4 Measurement, control, testing

DIN EN 61010-1	**(VDE 0411 Part 1)** Safety requirements for electrical equipment for measurement, control and laboratory use – General requirements	1994-03
DIN EN 61557-1	**(VDE 0413 Part 1)** Equipment for testing, measuring or monitoring of protective measures – General requirements	1998-05
DIN EN 61557-2	**(VDE 0413 Part 2)** – Insulation resistance	1998-05
DIN EN 61557-3	**(VDE 0413 Part 3)** – Loop impedance	1998-05
DIN EN 61557-4	**(VDE 0413 Part 4)** – Resistance of earth connections and equipotential bonding	1998-05
DIN EN 61557-5	**(VDE 0413 Part 5)** – Resistance to earth	1998-05
DIN EN 61557-6	**(VDE 0413 Part 6)** – Residual current devices (RCD) in TT, TN and IT systems	1999-05
DIN EN 61557-7	**(VDE 0413 Part 7)** – Phase sequence	1998-05
DIN EN 61557-8	**(VDE 0413 Part 8)** – Insulation monitoring devices for IT systems	2000-04
DIN EN 60044-1	**(VDE 0414 Part 1)** Instrument transformers – Current transformers	1994-01
DIN VDE 0414-10	**(VDE 0414 Part 10)** – Partial-discharge measurement, IEC 60044-4	1985-05
DIN EN 60044-2	**(VDE 0414 Part 2)** – Inductive voltage transformers	1999-12

DIN IEC 60044-3	**(VDE 0414 Part 5)** – Combined transformers, HD 548.3 S1	1994-04
DIN VDE 0414-6	**(VDE 0414 Part 6)** – Three-phase voltage transformers for voltage levels up to 52 kV, HD 587 S1	1995-04
DIN EN 60044-6	**(VDE 0414 Part 7)** – Requirements for protective current transformers for transient performance	1999-10
DIN EN 60521	**(VDE 0418 Part 12)** Classes 0.5, 1 and 2 a.c. watt-hour meters	1995-07
DIN VDE 0418-2	**(VDE 0418 Part 2)** Electric integrating meters – Var-hour (reactive energy) meters	1966-03
DIN EN 61268	**(DE 0418 Part 20)** Alternating current static var-hour meters for reactive energy (classes 2 and 3)	1996-11
DIN VDE 0418-3	**(VDE 0418 Part 3)** Electric integrating meters – Direct-current meters	1965-03
DIN VDE 0418-4	**(VDE 0418 Part 4)** – Maximum demand indicators	1967-07
DIN VDE 0418-5	**(VDE 0418 Part 5)** – Telemetering devices	1973-04
DIN EN 60514	**(VDE 0418 Part 6)** Acceptance inspection of class 2 alternating current watt-hour meters	1995-07
DIN EN 61358	**(VDE 0418 Part 60)** Acceptance inspection for direct-connected alternating current static watt-hour meters for active energy	1996-11
DIN EN 61036	**(VDE 0418 Part 7)** Alternating current electronic watt-hour meters for active energy (classes 1 and 2)	1997-05
DIN EN 60687	**(VDE 0418 Part 8)** Alternating current static watt-hour meters for active energy (classes 0.2 S and 0.5 S)	1994-02
DIN EN 62053-31	**(VDE 0418 Part 3-31)** Electricity metering equipment (AC) – Particular requirements – Pulse output devices for electromechanic and electronic meters (only two-wire systems)	1999-04

DIN EN 62053-61	**(VDE 0418 Part 3-61)** – Power consumption and voltage requirements	1999-04
DIN EN 61038	**(VDE 0419 Part 1)** Time switches for tariff and load control	1994-03
DIN EN 61037	**(VDE 0420 Part 1)** Electronic ripple-control receivers for tariff and load control	1994-01
DIN IEC 60060-1	**(VDE 0432 Part 1)** High-voltage test techniques – General specifications and test requirements, HD 588.1 S1	1994-06
DIN EN 61180-1	**(VDE 0432 Part 10)** High-voltage test techniques for low-voltage equipment – Definitions, test and procedure requirements, EN 61180-1	1995-05
DIN EN 61180-2	**(VDE 0432 Part 11)** – Test equipment	1995-05
DIN EN 60060-2	**(VDE 0432 Part 2)** High-voltage test techniques – Measuring systems	1996-03
DIN VDE 0432-5	**(VDE 0432 Part 5)** – Oscilloscope and peak voltmeters for impulse test	1987-03
DIN EN 61083-1	**(VDE 0432 Part 7)** – Digital recorders for measurements in high-voltage impulse tests – Requirements for digital recorders	1994-04
DIN EN 61083-2	**(VDE 0432 Part 8)** – Evaluation of software used for the determination of the parameters of impulse waveforms	1998-01
DIN 57434	**(VDE 0434)** High-voltage test techniques – Measurement of partial discharges	1983-05
Appendix 1 to DIN VDE 0435	**(VDE 0435)** Electrical relays – Synopsis, List of standards of the DIN VDE 0435 series	1999-01
DIN VDE 0435-110	**(VDE 0435 Part 110)** – Terms and definitions	1989-04
DIN EN 61810-1	**(VDE 0435 Part 201)** Electromechanical non-specified time all-or-nothing electrical relays – General requirements	1999-04

DIN IEC 60255-18	**(VDE 0435 Part 2011)** Electrical relays – Dimensions for general purpose all-or-nothing relays	1984-05
DIN EN 61812-1	**(VDE 0435 Part 2021)** Relays with specified time response (time relays) for industrial application – Requirements and testing	1999-08
DIN EN 60255-8	**(VDE 0435 Part 3011)** Electrical relays – Thermal electrical relays	1998-06
DIN EN 60255-3	**(VDE 0435 Part 3013)** – Single input energizing quantity measuring relays with dependent or independent time	1998-07
DIN EN 60255-22-2	**(VDE 0435 Part 3022)** – Electrical disturbance test for measuring relays and protection devices – Electrostatic discharge tests	1997-05
E DIN VDE 0435-303	**(VDE 0435 Part 303)** – Static measuring relays (SMR), draft	1998-01
DIN VDE 0441-1	**(VDE 0441 Part 1)** Tests on insulators of organic material for systems with nominal alternating voltages greater than 1000 V – Tests on materials	1985-07
DIN 57441-2	**(VDE 0441 Part 2)** – Tests on outdoor composite insulators with fibre-glass core	1982-10
DIN IEC 60660	**(VDE 0441 Part 3)** Tests on indoor post insulators of organic materials for systems with nominal voltages greater than 1 kV but not including	1984-06
DIN EN 61466-1	**(VDE 0441 Part 4)** Composite string insulator units for overhead lines above 1000 V – Standard strength classes and end fittings	1997-10
DIN EN 61466-2	**(VDE 0441 Part 5)** – Dimensional and electrical characteristics	1999-05
DIN EN 60383-1	**(VDE 0446 Part 1)** Insulators for overhead lines with a nominal voltage above 1 kV – Ceramic and glass insulator units for AC systems – Terms, test methods, acceptance criteria	1997-05
DIN VDE 0446-2	**(VDE 0446 Part 2)** Requirements for insulators for power overhead lines and contact wires up to 1000 V and for overhead telecommunications lines	1971-03

DIN VDE 0446-3	**(VDE 0446 Part 3)** – Requirements for accessories and fittings permanently connected to the insulating body	1973-05
DIN EN 60383-2	**(VDE 0446 Part 4)** Insulators for overhead lines above 1000 V – Insulator strings and insulator sets for alternating voltage systems – Terms and definitions, test methods, acceptance criteria	1995-08
DIN EN 61325	**(VDE 0446 Part 5)** – Ceramic or glass insulator units for DC systems – Terms and definitions, test methods, acceptance criteria	1996-04
DIN EN 60305	**(VDE 0446 Part 6)** – Ceramic and glass insulators for AC systems – Characteristics of insulator units of the cap-and-pin type	1996-10
DIN EN 60433	**(VDE 0446 Part 7)** – Ceramic insulators for AC systems – Characteristics of insulators in long-rod design	1996-10
DIN EN 60507	**(VDE 0448 Part 1)** Artificial pollution tests on high voltage insulators for AC systems	1994-04
DIN EN 60529	**(VDE 0470 Part 1)** Degrees of protection provided by enclosures (IP Code)	2000-09
DIN EN 50102	**(VDE 0470 Part 100)** Degrees of protection provided by enclosures for electrical equipment against external mechanical impacts (IK Code)	1997-09
DIN EN 61032	**(VDE 0470 Part 2)** Test probes for verification of protection of persons provided by enclosure	1998-10
DIN EN 60695-1-1	**(VDE 0471 Part 1-1)** Fire hazard testing Guidance for assessing the fire hazard of electrotechnical products – General guidelines	2000-10

numerous further parts

Group 5 Machines, transducers

DIN 57510	**(VDE 0510)** VDE Specifications for electric storage batteries and battery plants	1977-01
DIN VDE 0510-2	**(VDE 0510 Part 2)** Safety requirements for secondary batteries and battery installations – Stationary batteries	1997-10
DIN EN 60034-1	**(VDE 0530 Part 1)** Rotating electrical machines – Rating and performance	2000-09

further parts: 12, 14, 15, 16, 18-1, 18-21, 18-31, 2, 22, 3, 33, 4, 5, 6, 7, 8, 9.

DIN 57532-10	**(VDE 0532 Part 10)** Transformers and reactors – Application of transformers IEC 60606	1982-03
DIN EN 60076-1	**(VDE 0532 Part 101)** Power transformers – General	1997-12
DIN EN 60076-2	**(VDE 0532 Part 102)** – Temperature rise	1997-12
DIN 57532-13	**(VDE 0532 Part 13)** Transformers and reactors – Lightning and switching-impulse testing of transformers and reactors	1984-07
DIN VDE 0532-14	**(VDE 0532 Part 14)** – External clearances and protective spark gaps on bushings	1991-03
DIN EN 60289	**(VDE 0532 Part 20)** Reactors	1994-05
DIN VDE 0532-222	**(VDE 0532 Part 222)** Three-phase oil-distribution transformer – Distribution transformers with cable boxes, on the high-voltage and/or low voltage side HD 428.2.2 S1	1997-12
DIN VDE 0532-23	**(VDE 0532 Part 23)** Transformers and reactors – Stationary transformers in traction systems	1994-08
DIN VDE 0532-3	**(VDE 0532 Part 3)** – Insulation levels and dielectric tests	1987-07

DIN EN 60214	**(VDE 0532 Part 30)** On-load tap-changers	1998-06
DIN VDE 0532-31	**(VDE 0532 Part 31)** Transformers and reactors – Selection and application of on-load tap-changers	1993-04
DIN 57532-5	**(VDE 0532 Part 5)** – Ability to withstand short-circuit	1984-05
DIN VDE 0532-6	**(VDE 0532 Part 6)** – Dry-type power transformers	1994-01
DIN EN 60551	**(VDE 0532 Part 7)** Determination of transformer and reactor sound levels	1993-11
DIN VDE 0558-1	**(VDE 0558 Part 1)** Semiconductor converters – General specifications and particular specifications for line-commutated convertors, IEC 60119	1987-07
DIN EN 60146-1-1	**(VDE 0558 Part 11)** – General requirements and line-commutated converters – Specification of the basic requirements	1994-03
DIN 57558-2	**(VDE 0558 Part 2)** – Particular requirements for self-commutated converters	1977-08
DIN 57558-3	**(VDE 0558 Part 3)** – Particular requirements for DC convertors (DC chopper convertors)	1977-08
DIN 57558-5	**(VDE 0558 Part 5)** – Uninterruptible power systems (UPS), IEC 60146-4	1988-09
DIN EN 50091-1-1	**(VDE 0558 Part 511)** Uninterruptible power systems (UPS) – General requirements and safety requirements for UPS used in operator access areas	1997-07
DIN EN 50091-1-2	**(VDE 0558 Part 512)** – General requirements and safety requirements for UPS used in restricted access locations	1999-05
DIN EN 50091-2	**(VDE 0558 Part 520)** – EMC requirements	1996-05
DIN VDE 0558-6	**VDE 0558 Part 6)** – Switches for UPS, IEC 60146-5	1992-04
DIN EN 60146-1-3	**(VDE 0558 Part 8)** – General requirements and line-commutated converter – Transformers and reactors	1994-03

DIN VDE 0560-1	**(VDE 0560 Part 1)** Specification for capacitors – General requirements	1969-12

further parts: 10, 11, 120, 121, 15, 16, 2, 3.

DIN EN 60871-1	**(VDE 0560 Part 410)** Shunt capacitors for power systems over 1 kV – General, design, testing and rating, safety requirements, instructions for installation and operation	1998-09
DIN IEC 60871-2	**(VDE 0560 Part 420)** – Endurance testing	1993-04
DIN EN 60871-4	**(VDE 0560 Part 440)** – Internal fuses	1997-08
DIN EN 60143-1	**(VDE 0560 Part 42)** Series capacitors for power systems – General, performance, testing and rating, safety requirements, guidelines for erection	1995-01
DIN EN 60143-2	**(VDE 0560 Part 43)** – Protection devices for batteries of series capacitors	1995-12
DIN EN 60143-3	**(VDE 0560 Part 44)** – Internal fuses	1999-03
DIN EN 60381-1	**(VDE 0560 Part 46)** Self-restoring shunt power capacitors up to 1000 V – General, performance, testing and rating, safety requirements, instructions for installation and operation	1997-12
DIN EN 60381-2	**(VDE 0560 Part 47)** – Aging test, self-healing test and destruction test	1997-09
DIN EN 60931-1	**(VDE 0560 Part 48)** Non-self-restoring shunt power capacitors up to 1 kV – General, requirements, testing and rating, safety requirements, instructions for installation and operation	1997-12
DIN EN 60931-2	**(VDE 0560 Part 49)** – Aging test and destruction test	1997-08
DIN EN 60252	**(VDE 0560 Part 8)** Motor capacitors	1994-11

further parts: 430, 800, 810, 811.

Group 6 Installation material, switchgear

DIN VDE 0603-1	**(VDE 0603 Part 1)** Consumer units and meter panels AC 400 V – Consumer units and meter panels	1991-10
DIN VDE 0603-2	**(VDE 0603 Part 2)** – Main line branch terminals	1998-03
DIN EN 50085-1	**(VDE 0604 Part 1)** Cable trunking systems and cable ducting systems for electrical installations – General requirements	1998-04
DIN VDE 0604-2	**(VDE 0604 Part 2)** – Trunking for appliances	1986-05
DIN VDE 0604-3	**(VDE 0604 Part 3)** – Skirting board ducts	1986-05
DIN EN 50086-1	**(VDE 0605 Part 1)** Conduit systems for electrical installations – General requirements	1994-05
DIN EN 50086-2-1	**(VDE 0605 Part 2-1)** – Rigid conduit systems	1995-12
DIN EN 50086-2-2	**(VDE 0605 Part 2-2)** – Pliable conduit systems	1995-12
DIN EN 50086-2-3	**(VDE 0605 Part 2-3)** – Flexible conduit systems	1995-12
DIN EN 50086-2-4	**(VDE 0605 Part 2-4)** – Underground buried conduit systems	1994-09
DIN VDE 0606-1	**(VDE 0606 Part 1)** Connecting materials up to 690 V – Installation boxes for accomodation of equipment and/or connecting terminals	2000-10
DIN EN 60999-1	**(VDE 0609 Part 1)** Connecting devices - Electrical copper conductors – Safety requirements for screw-type and screwless-type clamping units	2000-12
DIN EN 60947-7-1	**(VDE 0611 Part 1)** Low-voltage switchgear and controlgear – Anciliary equipment Section 1: Terminal blocks for copper conductors	2000-05

further parts: 20, 3, 4

DIN VDE 0618-1	**(VDE 0618 Part 1)** Equipment for equipotential bonding	1989-08
DIN EN 50262	**(VDE 0619)** Metric cable glands for electrical installations	1999-04
DIN VDE 0620	**(VDE 0620)** Plugs and socket-outlets up to 400 V, 25 A	1992-05

further parts: 101, 300.

DIN EN 60309-1	**(VDE 0623 Part 1)** Plugs and socket-outlets and couplers for industrial purposes, general requirements	2000-05

further parts: 20, 4, 100.

DIN EN 61058-1	**(VDE 0630 Part 1)** Switches for appliances – General requirements	1993-05
DIN VDE 0630-12	**(VDE 0630 Part 12)** Switches for appliances for a rated voltage not exceeding 500 V and a rated current not exceeding 63 A, – Electronic switches	1988-09
DIN EN 60669-1	**(VDE 0632 Part 1)** Switches for household and similar fixed electrical installations – General requirements	1996-04

and further parts.

DIN VDE 0633-1	**(VDE 0633 Part 1)** Time switches – General requirements	1989-01
DIN VDE 0633-2	**(VDE 0633 Part 2)** – Electronic time switches	1986-02
DIN VDE 0634-1	**(VDE 0634 Part 1)** Underfloor electrical installation – Service units	1987-09

and Part 2.

DIN 57635	**(VDE 0635)** Low-voltage fuses – D-fuses 16 up to 25 A, 500 V, – D-fuses up to 100 A, 750 V, – D-fuses up to 100 A, 500 V.	1984-02
DIN EN 60269-1	**(VDE 0636 Part 10)** – General requirements	1999-11
DIN EN 60269-2	**(VDE 0636 Part 20)** – Fuses for use by authorized persons	1995-12

DIN EN 60269-3	**(VDE 0636 Part 30)** – Fuses for use by unskilled persons	1995-12
DIN EN 60269-4	**(VDE 0636 Part 40)** – Fuse links for protection of semiconductor elements	1997-04
DIN VDE 0636-201	**(VDE 0636 Part 201)** Low-voltage fuses (HRC) – Fuses for use by authorized persons, IEC 60269-2-1, HD 630.2.1 S2	1998-06
DIN VDE 0636-2011	**(VDE 0636 Part 2011)** – National supplement to VDE 0636 Part 201: protection of special electrical systems	1999-05
DIN VDE 0636-301	**(VDE 0636 Part 301)** Low-voltage fuses (D type), – Fuses for use by unskilled persons, IEC 60269-3-1, HD 630.3.1 S2	1998-01
DIN VDE 0636-3011	**(VDE 0636 Part 3011)** – National supplement to VDE 0636 Part 301	1999-05
DIN 57638	**(VDE 0638)** Low-voltage switchgear – Fuse-switch units, DO system	1981-09
DIN VDE 0641-11	**(VDE 0641 Part 11)** Circuit-breakers for overcurrent protection for domestic use IEC 60898, EN 60898	1992-08
DIN 57641-2	**(VDE 0641 Part 2)** Miniature circuit-breakers up to 63 A and up to 440 V direct voltage	1984-04
DIN 57641-3	**(VDE 0641 Part 3)** Miniature circuit-breakers up to 63 A and up to 415 V alternating voltage and up to 440 V direct voltage	1984-04
DIN EN 60934	**(VDE 0642)** Circuit breakers for equipment (CBE)	1995-04
DIN EN 60947-1	**(VDE 0660 Part 100)** Low-voltage switchgear and control gear – General rules	1999-12
DIN EN 60947-2	**(VDE 0660 Part 101)** – Circuit breakers	1997-02
DIN VDE 0660-102	**(VDE 0660 Part 102)** – Electromechanical contactors and motor-starters IEC 60947-4-1, EN 60947-4-1	1992-07

DIN 57660-103	**(VDE 0660 Part 103)** Switchgear – High-voltage alternating current contactors above 1000 V up to 12000 V	1984-03
DIN 57660-105	**(VDE 0660 Part 105)** – High-voltage motor starters, Direct-on-Line (full voltage) AC starters	1984-03
DIN EN 60941-3	**(VDE 0660 Part 107)** Low-voltage switchgear and control gear – Switches, disconnectors, switch disconnectors and fuse-combination units	2000-02
DIN VDE 0660-109	**(VDE 0660 Part 109)** – AC semiconductor controllers and contactors for non-motor loads, IEC60158-2	2000-09
DIN VDE 0660-112	**(VDE 0660 Part 112)** – Direct current air-break switches, air-break disconnectors and air-break switch-disconnectors over 1200 V up to 3000 V	1987-02
DIN VDE 0660-114	**(VDE 0660 Part 114)** – Automatic transfer switching equipment IEC 60947-6-1, EN 60947-6-1	1992-07
DIN EN 60947-6-2	**(VDE 0660 Part 115)** – Control and protective switching devices (CPS)	1993-09
DIN EN 60947-4-2	**(VDE 0660 Part 117)** – AC semiconductor-motor controllers and starters	2000-09
DIN EN 60947-5-1	**(VDE 0660 Part 200)** – Electromechanical control circuit devices	2000-08
DIN EN 60947-5-2	**(VDE 0660 Part 208)** – Proximity switches	2000-08
DIN VDE 0660-209	**(VDE 0660 Part 209)** – Proximity position switches for safety functions	1988-01
DIN EN 60947-5-5	**(VDE 0660 Part 210)** – Control circuit devices and switching elements – Electrical emergency stop devices with mechanical latching function	1998-01
DIN VDE 0660-302	**(VDE 0660 Part 302)** Thermal rotating machines protection – Thermal detectors and control units	1987-02
DIN VDE 0660-303	**(VDE 0660 Part 303)** – PTC thermal detectors and control units	1987-02

DIN EN 60439-1	**(VDE 0660 Part 500)** Low-voltage switchgear and controlgear assemblies – Type-tested and partially type-tested assemblies	2000-08
Appendix 2 to DIN EN 60439-1	**(VDE 0660 Part 500)** – Guide for testing under arc fault conditions IEC61641	1997-10
DIN EN 60439-4	**(VDE 0660 Part 501)** – Assemblies for construction sites (ACS)	1992-02
DIN EN 60439-2	**(VDE 0660 Part 502)** – Busbar trunking systems (busways)	1993-07
DIN EN 60439-5	**(VDE 0660 Part 503)** – Assemblies intended to be installed outdoors in public places, cable distribution cabinets (CDCs)	1997-02
DIN VDE 0660-504	**(VDE 0660 Part 504)** – Low voltage switchgear and controlgear assemblies for use by unskilled persons and installation in public places, distribution boards IEC 60439-3, EN 60439-3	1992-04
DIN VDE 0660-505	**(VDE 0660 Part 505)** – House connection boxes and fuseboxes	1998-10
DIN VDE 0660-506	**(VDE 0660 Part 506)** – Slotted trunking, requirements, tests	1989-10
DIN VDE 0660-507	**(VDE 0660 Part 507)** – Assessing of the temperature rise of partially type-tested assemblies (PTTA) by extrapolation IEC 60890/A1, HD 528S2	1997-11
DIN IEC 61117	**(VDE 0660 Part 509)** – Assessing of the short-circuit current capability of partially type-tested assemblies (PTTA)	1993-09
DIN EN 50298	**(VDE 0660 Part 511)** Empty enclosures for low-voltage switchgear and control gear assemblies – General requirements	1999-06
DIN EN 62020	**(VDE 0663)** Residual current monitors for household and similar uses (RCMs)	1999-07
DIN EN 61008-1	**(VDE 0664 Part 10)** Residual current-operated circuit breakers without integral overcurrent protection for household and similar uses (RCCBs)	1999-12

DIN EN 61009-2	**(VDE 0664 Part 20)** Residual current-operated circuit breakers with integral overcurrent protection for household and similar uses (RCBOs)	2000-09
DIN VDE 0664-3	**(VDE 0664 Part 3)** – Residual current-operated protective devices for alternating voltage over 500 V and over 63 A	1988-10
DIN VDE 0670-101	**(VDE 0670 Part 101)** AC switchgear and control gear for voltages above 1 kV High-voltage alternating current circuit-breakers – General, terms and definitions IEC60056-1	1992-12
DIN VDE 0670-102	**(VDE 0670 Part 102)** – Rating IEC60056-2	1992-12
DIN VDE 0670-103	**(VDE 0670 Part 103)** – Design and construction IEC60056-3	1992-10
DIN VDE 0670-104	**(VDE 0670 Part 104)** – Type-tests and routine tests	1992-10
DIN VDE 0670-105	**(VDE 0670 Part 105)** – Selecting circuit-breakers for service IEC60056-5	1992-10
DIN VDE 0670-106	**(VDE 0670 Part 106)** – Information in enquiries, tenders and orders and rules for transport, storage, erection and maintenance IEC60056-6	1992-10
DIN 57670-107	**(VDE 0670 Part 107)** – Testing under out-of-phase conditions IEC60056-7	1980-07
DIN EN 60427	**(VDE 0670 Part 108)** – Synthetic testing of high-voltage alternating current circuit-breakers	1996-03
DIN EN 61166	**(VDE 0670 Part 111)** – Guide for seismic qualification of high-voltage alternating current circuit-breakers	1994-08
DIN EN 60129	**(VDE 0670 Part 2)** Alternating current disconnectors and grounding switches	1998-03

DIN EN 61129	**(VDE 0670 Part 212)** – Alternating current grounding switches, induced current switching	1995-02
DIN EN 61259	**(VDE 0670 Part 213)** Gas-insulated metal-enclosed switchgear for rated voltages of 72.5 kV and above – Requirements for switching bus charging currents by disconnectors	1996-06
DIN EN 60265-1	**(VDE 0670 Part 301)** High-voltage. switches	1999-05
–	High-voltage switches over 1 kV and below 52 kV	
DIN EN 60265-2	**(VDE 0670 Part 302)** – High-voltage switches for rated voltages of 52 kV and above	1998-09
DIN EN 60420	**(VDE 0670 Part 303)** – High-voltage alternating current switch-fuse combinations	1994-09
DIN EN 60282-1	**(VDE 0670 Part 4)** High-voltage fuses – Current-limiting fuses	1998-02
DIN EN 60644	**(VDE 0670 Part 401)** – High voltage fuse – links for motor circuit applications	1997-03
DIN VDE 0670-402	**(VDE 0670 Part 402)** – Selection of fuse-links for transformer circuits	1988-05
DIN EN 60298	**(VDE 0670 Part 6)** AC metal-enclosed switchgear and control gear for rated voltages above 1 kV and up to and including 52 kV	1998-05
DIN EN 61330	**(VDE 0670 Part 611)** High-voltage/low-voltage prefabricated substations	1997-08
DIN EN 60517	**(VDE 0670 Part 8)** Gas-insulated metal-enclosed high-voltage switchgear and controlgear for rated voltages of 72.5 kV and above	1998-10
DIN VDE 0670-801	**(VDE 0670 Part 801)** Alternating-current switchgear for voltages above 1 kV – Cast aluminium alloy enclosures for gas-filled high-voltage switchgear and controlgear EN 50052	1987-04
DIN VDE 0670-803	**(VDE 0670 Part 803)** – Wrought-aluminium and aluminium alloy enclosures for gas-filled high-voltage switchgear and controlgear EN 50064	1991-05

DIN EN 50068	**(VDE 0670 Part 804)** – Wrought steel enclosures for gas-filled high-voltage switchgear and controlgear	1993-08
DIN EN 50069	**(VDE 0670 Part 805)** – Welded composite enclosures of cast and wrought aluminium alloys for gas-filled high-voltage switchgear and controlgear	1993-08
DIN EN 50089	**(VDE 0670 Part 806)** Cast resin parttions for metal-clad gas-filled high-voltage switchgear and controlgear	1994-04
DIN EN 50187	**(VDE 0670 Part 811)** Gas-filled compartments for alternating-current switchgear and controlgear for rated voltages above and 1 kV up to and including 52 kV	1997-05
DIN EN 60694	**(VDE 0670 Part 1000)** Common specifications for high-voltage switchgear and controlgear standards	1998-10
DIN EN 60168	**(VDE 0674 Part 1)** Tests on indoor and outdoor post insulators of ceramic material or glass for systems with nominal voltages greater than 1 kV	1995-11
DIN IEC 60233	**(VDE 0674 Part 2)** Tests on hollow insulators for electrical equipment	1984-12
DIN EN 61264	**(VDE 0674 Part 3)** Ceramic pressurized hollow insulators for high-voltage switchgear and controlgear	1999-06
DIN IEC 60273	**(VDE 0674 Part 4)** – Characteristics of indoor and outdoor insulators for systems over 1000 V, HD 578 S1	1993-08
DIN EN 60137	**(VDE 0674 Part 5)** Insulated bushings for alternating voltages over 1000 V	1996-10
DIN EN 60099-1	**(VDE 0675 Part 1)** Surge arresters – Non-linear resistor type gapped surge arresters for AC systems	2000-08
DIN VDE 0675-102	**(VDE 0675 Part 102)** Overvoltage protection equipment – “Artificial pollution; tests of surge arresters”	1986-09
DIN 57675-3	**(VDE 0675 Part 3)** – Tests for protective spark gaps for AC networks	1982-11

DIN EN 60099-4	**(VDE 0675 Part 4)** – Metal oxide surge arresters without gaps for AC systems	1994-05
DIN EN 60099-5	**(VDE 0675 Part 5)** Surge arresters, selection and application recommendations	1997-08
DIN 57680-1	**(VDE 0680 Part 1)** Personal protective equipment, protective devices and apparatus for work on electrically energized systems up to 1000 V – Personal protective equipment and protective insulating devices	1983-01
DIN 57680-3	**(VDE 0680 Part 3)** – Operating rods and current-collecting devices	1977-09
DIN 57680-4	**(VDE 0680 Part 4)** – Fuse handles for low-voltage HRC fuses	1980-11
DIN 57680-6	**(VDE 0680 Part 6)** – Single-pole voltage testers up to 250 V AC	1977-04
DIN 57680-7	**(VDE 0680 Part 7)** – Socket spanner	1984-02
DIN VDE 0681-1	**(VDE 0681 Part 1)** Operating, testing and safeguarding devices for work on electrically energized systems with rated voltages exceeding 1 kV – General requirements	1986-10
DIN 57681-2	**(VDE 0681 Part 2)** – Operating rods	1977-03
DIN 57681-3	**(VDE 0681 Part 3)** – Fuse tongs	1977-03
DIN VDE 0681-5	**(VDE 0681 Part 5)** – Phase comparators	1985-06
DIN VDE 0681-6	**(VDE 0681 Part 6)** – Voltage detectors for overhead contact systems on electrical railways 15 kV, 16 $^{2}/_{3}$ Hz	1985-06
DIN VDE 0681-8	**(VDE 0681 Part 8)** – Insulating protective shutters	1988-05
DIN EN 60900	**(VDE 0682 Part 201)** Hand-tools for live working up to AC 1000 V and DC 1500 V	1994-08
DIN EN 60832	**(VDE 0682 Part 211)** Insulating poles and universal tool attachments (fittings) for live working	1998-01

DIN EN 60903	**(VDE 0682 Part 311)** – Specification for gloves and mitts of insulating material for live working	1994-10
DIN EN 60984	**(VDE 0682 Part 312)** – Sleeves of insulating material for live working	1994-10
DIN EN 61243-3	**(VDE 0682 Part 401)** – Two-pole low-voltage voltage detectors	1999-09
DIN EN 61243-1	**(VDE 0682 Part 411)** Live working – Voltage detectors, capacitive type for alternating voltage over 1 kV	1998-05
DIN EN 61229	**(VDE 0682 Part 551)** Rigid protective covers for live working on AC installations	1997-01
DIN EN 61236	**(VDE 0682 Part 651)** Saddles, pole clamps (stick clamps) and accessories for live working	1996-11
DIN EN 61057	**(VDE 0682 Part 741)** Aerial devices with insulating boom for live working over AC 1 kV	1995-08
DIN EN 61230	**(VDE 0683 Part 100)** Live working – Portable equipment for earthing or earthing and short-circuiting	1996-11
DIN EN 61219	**(VDE 0683 Part 200)** – Earthing or earthing and short-circuiting equipment using lancesas short-circuiting device	1995-01

Group 8 Information technology

DIN VDE 0800-1	**(VDE 0800 Part 1)** Telecommunications – Requirements and tests for the safety of facilities and apparatus	1989-05
DIN VDE 0800-2	**(VDE 0800 Part 2)** – Earthing and equipotential bonding	1985-07
DIN VDE 0800-3	**(VDE 0800 Part 3)** – Telecommunication facilities with remote supply	1983-06
DIN VDE 0800-4	**(VDE 0800 Part 4)** – Erection of telecommunications lines	1986-03
DIN VDE 0800-5	**(VDE 0800 Part 5)** – Power supply	1991-01

DIN V VDE 0801	**(VDE 0801) Draft standard** – Principles for computers in safety-related systems	1990-01
DIN EN 41003	**(VDE 0804 Part 100)** Particular safety requirements for equipment to be connected to telecommunication networks	1999-08
DIN EN 60950	**(VDE 0805)** Safety of information technology equipment	1997-11
DIN EN 50116	**(VDE 0805 Part 116)** Information-technology equipment – Testing (100 %) for production	1997-06
DIN EN 50065-1	**(VDE 0808 Part 1)** Signaling on low-voltage electrical installations in the frequency range 3 kHz to 148.5 kHz.	1996-11
DIN VDE 0812	**(VDE 0812)** Telecommunications and data-processing systems – Equipment wires and stranded equipment wires with PVC insulation sheaths	1988-11
DIN VDE 0813	**(VDE 0813)** – Switchboard cables	1988-11 s
DIN VDE 0814	**(VDE 0814)** – Cords	1981-10
DIN VDE 0815	**(VDE 0815)** – Wiring cables and wires	1985-09
DIN VDE 0816-1	**(VDE 0816 Part 1)** – External cables with insulation and sheaths of polyethylene	1988-02
DIN VDE 0816-2	**(VDE 0816 Part 2)** – External cables, signal and measuring cables, mine cables	1988-02
DIN VDE 0816-3	**(VDE 0816 Part 3)** – External cables with paper insulation	1988-02
DIN VDE 0817	**(VDE 0817)** – Lines with stranded conductors for increased mechanical stress	1990-08
DIN 57818	**(VDE 0818)** Self supporting telecommunication aerial cables on overhead power lines above 1 kV	1983-02
DIN VDE 0819-1	**(VDE 0819 Part 1)** Multicore and symmetric pair / quad and multicore cables for digital data transmission, HD 608 S1	1994-04

DIN VDE 0819-100	**(VDE 0819 Part 100)** Materials used in communication cables – General, HD 624.0 S1	1998-05
DIN VDE 0819-101	**(VDE 0819 Part 101)** – PVC insulating compounds, HD 624.1 S1	1995-02
DIN VDE 0819-102	**(VDE 0819 Part 102)** – PVC sheathing compounds, HD 624.2 S1	1995-02
DIN VDE 0819-103	**(VDE 0819 Part 103)** – Polyethylene insulating compounds, HD 624.3 S1	1995-02
DIN VDE 0819-104	**(VDE 0819 Part 104)** – Polyethylene sheathing compounds, HD 624.4 S1	1997-07
DIN VDE 0819-105	**(VDE 0819 Part 105)** – Polypropylene insulation compounds, HD 624.5 S1	1996-02
DIN VDE 0819-106	**(VDE 0819 Part 106)** – Halogen-free, fire-retardant insulation compounds, HD 624.6 S1	1996-02
DIN VDE 0819-107	**(VDE 0819 Part 107)** – Halogen-free, fire-retardant thermoplastic sheating compounds, HD 624.7 S1	1995-02
DIN VDE 0819-108	**(VDE 0819 Part 108)** – Filling compounds for filled cables, HD 624.8 S1	1996-02
DIN VDE 0819-109	**(VDE 0819 Part 109)** – Cross-linked PE insulation, HD 624.9 S1	1997-07
DIN EN 50167	**(VDE 0819 Part 2)** Sectional specification for cables for digital communications – Floor wiring cables with common overall screen	1995-08
DIN EN 50168	**(VDE 0819 Part 3)** – Work area wiring cables with common overall screen	1995-08
DIN EN 50169	**(VDE 0819 Part 4)** – Backbone cables, riser and campus with common overall screen	1995-08
DIN VDE 0819-5	**(VDE 0819 Part 5)** – Equipment cables for digital and analog communications, HD 609 S1	1997-11
DIN VDE 0820-1	**(VDE 0820 Part 1)** Miniature fuses – Terms and definitions, requirements for cartridge fuse links IEC 60127-1, EN 60127-1	1992-11
DIN EN 60127-2	**(VDE 0820 Part 2)** – Cartridge fuse links	1996-08

DIN EN 60127-3	**(VDE 0820 Part 3)** – Sub-miniature fuse links	1996-11
DIN EN 60127-4	**(VDE 0820 Part 4)** – Universal modular fuse links (UMF)	1997-05
DIN VDE 0820-5	**(VDE 0820 Part 5)** – Quality assessment of miniature fuse links IEC 60127-5, EN 60127-5	1992-11
DIN EN 60127-6	**(VDE 0820 Part 6)** – Fuse holders for miniture cartridge fuse-links	1996-12
DIN EN 60691	**(VDE 0821)** Thermal links, requirements, application guide	1996-08
DIN EN 50130-4	**(VDE 0830 Part 1-4)** Alarm systems – Electromagnetic compatibility (product familiy standard)	1996-11
DIN EN 50134-7	**(VDE 0830 Part 4-7)** – Social alarm systems, application guidelines	1996-12
DIN EN 50132-7	**(VDE 0830 Part 7-7)** – CCTV surveillance systems for use in security applications - Application guidelines	1997-07
DIN VDE 0833-1	**(VDE 0833 Part 1)** Alarm systems for fire, intrusion and hold-up – General specifications	1989-01
DIN VDE 0833-2	**(VDE 0833 Part 2)** – Fire alarm systems	2000-01
DIN 57833-3	**(VDE 0833 Part 3)** – Intruder and hold-up alarm systems	1982-08
DIN EN 60825-1	**(VDE 0837 Part 1)** Safety of laser products – Classification of systems, requirements and user guidelines	1997-03
DIN EN 60825-2	**(VDE 0837 Part 2)** – Fibre-optic communication systems	1994-07
DIN VDE 0838-1	**(VDE 0838 Part 1)** Disturbances in power supply systems caused by household appliances and similar electrical equipment – Definitions IEC 60555-1, EN 60555-1	1987-06
DIN EN 61000-3-2	**(VDE 0838 Part 2)** Electromagnetic compatibility (EMC) – Limit values for harmonic current emissions	1998-10

DIN EN 61000-3-3	**(VDE 0838 Part 3)** – Limit values for voltage fluctuations and flickers in low-voltage supply systems	1996-03
DIN V ENV 61000-2-2	**(VDE 0839 Part 2-2) Draft standard** – Compatibility levels for low-frequency conducted disturbances and signalling in public low-voltage power supply systems IEC 6100-2-2, EN V 6100-2-2	1994-05
DIN EN 61000-2-4	**(VDE 0839 Part 2-4)** – Compatibility levels for low-frequency conducted disturbances in industrial plants	1995-05
DIN EN 61000-2-9	**(VDE 0839 Part 2-9)** – HEMP environment, radiated disturbance – Basic EMC publication	1996-12
DIN EN 61000-2-10	**(VDE 0839 Part 2-10)** – Conducted disturbance	1999-10
DIN EN 50081-1	**(VDE 0839 Part 81-1)** – Generic emission standard, residential, commercial and light industry	1993-03
DIN EN 50081-2	**(VDE 0839 Part 81-2)** – Industrial environment	1994-03
DIN EN 61326-1	**(VDE 0843 Part 20)** Electrical equipment for control systems and laboratories, EMC requirements, general requirements	1998-01
DIN VDE 0845-1	**(VDE 0845 Part 1)** Protection of telecommunications systems against lightning, electrostatic discharges and overvoltages from power systems, provisions against overvoltages	1987-10
DIN EN 60868-0	**(VDE 0846 Part 0)** Flicker meter – Evaluation of flicker severity	1994-08
DIN VDE 0846-1	**(VDE 0846 Part 1)** Instrumentation for assessing electromagnetic compatibility – Measuring of harmonics of the main voltages and currents up to 2500 Hz	1985-08
DIN 57847-1	**(VDE 0847 Part 1)** – Method of measurements for the electromagnetic compatibility, measurement of conducted interference units	1981-11
DIN EN 61000-4-1	**(VDE 0847 Part 4-1)** Electromagnetic compatibility (EMC) – Testing and measuring techniques – Overview over immunity tests, basic EMC-publication	1995-09

DIN EN 61000-4-10	**(VDE 0847 Part 4-10)** – Damped oscillatory magnetic field immunity test, basic EMC-publication	1994-05
DIN EN 61000-4-11	**(VDE 0847 Part 4-11)** – Voltage dips, short interruptions and voltage variations immunity tests	1995-04
DIN EN 61000-4-12	**(VDE 0847 Part 4-12)** – Oscillatiory waves immunity test, basic EMC-publication	1996-03
DIN EN 61000-4-2	**(VDE 0847 Part 4-2)** – Electrostatic discharge immunity test, basic EMC-publication	1996-03
DIN EN 61000-4-24	**(VDE 0847 Part 4-24)** – Test methods for protective devices for HEMP conducted disturbances, basic EMC-publication	1997-11
DIN EN 61000-4-3	**(VDE 0847 Part 4-3)** – Radiated radio-frequency electromagnetic field immunity tests	1999-06
DIN EN 61000-4-4	**(VDE 0847 Part 4-4)** – Electrical fast transient/burst immunity test, basic EMC-publication	1996-03
DIN EN 61000-4-5	**(VDE 0847 Part 4-5)** – Surge immunity test	1996-09
DIN EN 61000-4-6	**(VDE 0847 Part 4-6)** – Immunity to conducted disturbances induced by radio-frequency fields	1997-04
DIN EN 61000-4-7	**(VDE 0847 Part 4-7)** – Guide for measuring harmonics and interharmonics and instrumentation for power supply systems	1994-08
DIN EN 61000-4-8	**(VDE 0847 Part 4-8)** – Power frequency magnetic field immunity test, basic EMC-publication	1994-05
DIN EN 61000-4-9	**(VDE 0847 Part 4-9)** – Pulse magnetic field immunity test, basic EMC-publication	1994-05
DIN EN 61000-4-15	**(VDE 0847 Part 4-15)** – Flicker meter, functional and design specifications	1998-11
DIN EN 61000-4-16	**(VDE 0847 Part 4-16)** – Test for immunity to conducted common mode disturbances in the frequency range of 0 Hz to 150 kHz	1998-08
DIN EN 61000-5-5	**(VDE 0847 Part 5-5)** – Protective devices for HEMP conducted disturbance, basic EMP-publication	1997-02

DIN VDE 0848-1	**(VDE 0848 Part 1)** Safety in electrical. magnetic and electromagnetic fields, definitions, methods for measurement and calculation	2000-08
DIN 57850	**(VDE 0850)** Coupling devices for power-line carrier systems	1980-03
DIN EN 60495	**(VDE 0850 Part 2)** Single sideband power-line carrier terminals	1995-02
DIN VDE 0851	**(VDE 0851)** Line traps for power line carrier systems (PLC), IEC 60353	1993-02
DIN VDE 0852-1	**(VDE 0852 Part 1)** Tele-protection equipment of power systems – Performance and testing – Command systems IEC 60834-1, EN 60834-1	1993-05
DIN VDE 0852-2	**(VDE 0852-2)** – Analog comparison systems IEC 60843-2, HD 543.2 S1	1995-11
DIN VDE 0873	**(VDE 0873) Appendix 1, 2 and 3** Radio interference characteristics of overhead power lines and high-voltage equipment	
Appendix 1	Physical phenomena, CISPR 18-1	1986-06
Appendix 2	Determining limit values, CISPR 18-2	1990-02
Appendix 3	Minimizing radio interference, CISPR 18-3	1991-01
DIN 57873-1	**(VDE 0873 Part 1)** Measures against radio interference from electric utility plants and electric traction systems – Radio interference from systems over 10 kV	1982-05
DIN 57873-2	**(VDE 0873 Part 2)** – Radio interference from systems under 10 kV and by electrical trains	1983-06
DIN EN 187000	**(VDE 0888 Part 100)** Generic specification: Optical fibre cables	1993-10
DIN EN 188000	**(VDE 0888 Part 101)** Generic specification: Optical fibres	1994-02
DIN EN 188100	**(VDE 0888 Part 102)** Sectional specification: Single-mode (SM) optical fibre	1996-01
DIN EN 188101	**(VDE 0888 Part 103)** Family specification: Dispersion unshifted single-mode optical fibre	1996-01

further parts: 104, 105, 106, 107, 108, 109, 110, 3, 4, 5, 6.

DIN VDE 0891-1	**(VDE 0891 Part 1)** Use of cables and insulated wires for telecommunication systems and information processing systems – General directions	1990-05
DIN VDE 0891-2	**(VDE 0891 Part 2)** – Special directions for equipment wires with solid or stranded conductors	1990-05
DIN VDE 0891-3	**(VDE 0891 Part 3)** – Special directions for switchboard cables	1990-05

further parts: 4, 5, 6, 7, 8, 9.

17.2 Application of European directives to high-voltage switchgear installations. CE mark

The CE mark based on European Directives assists the free distribution of goods on the European market. It is directed to the national standards supervising bodies. When the manufacturer applies the CE mark, this states that the legal requirements for the commercial product have been met. The CE mark is not a quality designation, a safety designation or a designation of conformity to a standard.

The following three European Union Directives may be applicable to electrical switchgear installations:

The *Machine Directive* covers most types of machines, with the exception of certain special types that are specifically excluded. The power supply companies and the manufacturers in Europe (EURELECTRIC/UNIPEDE and CAPIEL) have always been of the unanimous opinion that high-voltage equipment is not subject to the Machine Directive. The European Commission now shares this view. It should also be noted that motors, by definition, are not covered by the Machine Directive.

The *EMC Directive* is intended for application to almost all electrical equipment. However, fixed installations (which are assembled at the site of operation) have to meet the EMC protection requirements but they do not require a declaration of conformity, a CE mark nor an approval by any competent authority. This also applies to all primary and secondary devices in these installations (as components with no direct function).

The *Low Voltage Directive (LVD)* is applicable to independent low-voltage equipment which is also used in high-voltage switchgear and installations, such as control circuits, protection relays, measuring and metering devices, terminal strips, etc. This equipment must conform to the LVD and have a CE mark when purchased on the open market.

However, if control, measuring, protection and regulating equipment is a fixed component of high-voltage substations and/or switchgear, it is not covered by the Low-Voltage Directive, because by definition (as per IEC 50-441) they are considered to be high-voltage products.

In conclusion it is noted that high-voltage equipment and installations, including secondary installations, do not require a CE mark. However, they are subject to the relevant standards and regulations.

17.3 Quality in switchgear

The functional reliability of switchgear installations and hence the largely undisturbed transmission of electricity in a power network depends on the suitability and quality of the switchgear, components, systems and processes employed. Of growing importance in this regard is a forward-looking quality strategy with internationally harmonized standards and their main quality systems. The following brief review of the main international standards, terms and scope of quality assurance is intended to ease the switchgear engineer’s introduction to this complex subject.

According to the definition of the standard (DIN EN ISO 8402), quality means the totality of the characteristics of a unit with reference to its ability to meet specified and predefined requirements. With regard to the customer-supplier relationship, this means that the supplier's quality meets or exceeds the customer's requirements and meets or exceeds the statutory requirements with regard to the products and the processes.

Necessary for optimizing this attribute is a quality management system, i.e. a clearly structured organization and procedures for implementing quality assurance, together with the requisite means. Quality assurance in this sense is the sum of all the activities of quality management, quality planning and quality control (see DIN 55 350-11).

The CEN members are required to adopt the series of European standards ISO 9000 to ISO 9004, which concern the setting up of a quality system. This standard must be given the status of a national standard without any modifications. The series comprises:

DIN EN ISO 9000:	standards covering quality management and quality assurance/QM statement
DIN EN ISO 9001:	quality management systems, model for quality assurance/QM statement in design, development, production, assembly and maintenance
DIN EN ISO 9002:	quality management systems, model for quality assurance/QM statement in production, assembly and maintenance
DIN EN ISO 9003:	quality management systems, model for quality assurance/QM statement at final inspection
DIN EN ISO 9004:	quality management systems and quality management elements – guidelines

The goal of these standards is to assure the customer that the supplier meets specified minimum requirements for the quality management system. This can be done by supplying a quality management system statement to the customer or to an authorized third party. All planned, systematic, trust-building activities in this framework are termed quality assurance or quality management statement as per DIN EN ISO 8402 and include the

– establishment of a design and process organization,
– qualification of employees and equipment,
– specification of management, responsibility and authority,
– requirement for documentation of regulations and results,
– requirement for reporting to the highest level of management,
– management of risks and economics,
– preventive measures for avoiding quality problems.

17.4 Notable events and achievements in the history of ABB switchgear technology

1898	Three-phase transmission in Sweden
1900	Oil circuit-breaker with automatic overcurrent trip
1908	35 kV switchgear installation with partitions between the three phases
1908	Transformer station for 50 kV
1912	65 kV switchgear installation with partitioned phases
1917	110 kV indoor switchgear with outdoor busbars
1922	110/20 kV indoor switching station with recessed oil circuit breakers
1922	Sheet steel control panel with control switches and breaker position indicators incorporated in a mimic display
1923	First miniature circuit-breaker with thermal and magnetic trip
1924	High-speed breaker for rectifier systems
1926	110 kV outdoor switchgear mounted on lattice-type columns
1928	First delivery of oil-insulated current transformers for 110 kV
1928	Distance relays for selective disconnection of faulted parts of network
1930	Illuminated mimic display for a 110/20 kV transformer station with electrical safety interlocks
1930	First delivery of water-type circuit-breakers for medium voltage
1932	First delivery of minimum-oil convector-type circuit-breaker for 110 kV
1933	First delivery of airblast circuit-breakers for 10 to 30 kV and 250 to 500 MVA
1938	Commissioning of first transformer station for 220/110/10 kV with resonant grounding and reactive current compensation, convector-type and high-speed airblast circuit-breakers
1939	Direct current transmission at 50 kV using rectifier
1939	Service trials of airblast high-speed circuit-breakers with auto-reclosure
1939	First delivery of oil-insulated current transformers for 220 kV
1943	First outdoor high-speed airblast circuit-breaker for 110 kV, 2500 MVA
1947	Improved high-speed, surge-free synchronizer with synchronizing pulse controller
1948	Small-oil-volume circuit-breaker for 12 kV, 24 kV and 36 kV, LOS pumping-piston arc-quenching principle with current-dependent assisted arc-quenching medium flow (CALOR-EMAG)
1950	First delivery of outdoor high-speed airblast breakers for 220 kV, 2500 MVA with automatic reclosing
1952	Outdoor high-speed circuit-breakers, current transformers and surge arresters delivered to the world's first 380 kV network in Sweden

1954	Commissioning of the world's first 20 MW, 100 kV HVDC system for Gotland
1954	First high-current bus duct for 8 kA load current, open design, Al-C sections
1957	Outdoor airblast circuit-breakers of 12 000 MVA for Germany's first 380 kV transmission link from Rommerskirchen to Hoheneck
1957	Development of internal arc-resistant metal-enclosed switchboards with pressure relief, up to 36 kV (CALOR-EMAG)
1957	First electronic load-frequency control system
1958	First static audio-frequency transmitter using mercury-arc valves
1963	Network control centre with preselective control and mosaic-type illuminated display panel
1963	First delivery of oil-insulated current transformers for 550 kV
1965	High-speed airblast circuit-breakers, current transformers, voltage transformers and reactor coils for the world's first 735 kV transmission system in Canada
1966	First electronic busbar protection system for medium- and high-voltage systems
1966	First high-current bus duct in single-phase enclosure, Al-V sections
1967	First SF$_6$ gas-insulated switchgear for 123 kV (CALOR-EMAG) in Germany and 170 kV in Switzerland
1968	Germany's first telecontrol system using integrated circuits
1969	"Combiflex" modular electronic protection relay system
1970	First 245 kV SF$_6$ gas-insulated switchgear installation in Germany
1970	First delivery of 735 kV surge arresters to Canada
1972-73	Argentina's 500 kV network constructed including four turnkey outdoor switching stations and pantograph disconnectors
1972	First fully electronic ripple-control receiver
1972	World's first and biggest ripple-control system with thyristorized transmitters for a 110 kV network
1972	First power-control system with on-line state estimator program for Laufenburg, Switzerland
1973	765 kV outdoor airblast circuit-breakers and current transformers in the USA
1973	Network management / load-dispatching systems with process computer, central data processing and video terminals
1973	Airblast generator circuit-breaker for 27 kV, 160 kA and rated continuous current of 32 000 A
1974	First SF$_6$ gas-insulated switchgear installations for 420 kV and 525 kV in Switzerland and Canada

1974	420 kV outdoor switching station with tubular busbars for 3000 A
1974	Introduction of the MNS metal-enclosed modular low-voltage system
1975	SLM rail-type low-voltage fused switch disconnector
1975	420 kV SF$_6$ gas-insulated switchgear installation for Germany
1975	First residual-current protection switch
1975	First telecontrol system with adaptive signal routing
1976	Airblast generator circuit-breaker 27 kV, 250 kA and rated continuous current of 36 000 A
1976	First super-fast direction comparison protection system for high- and extra-high voltage power lines
1978	“MODURES” modular electronic relay system for medium- and high-voltage installations
1979	Network control system for a sequence of run-of-river hydro generating plants
1980	World’s biggest 123 kV SF$_6$ gas-insulated switchgear installation for the Yanbu industrial complex in Saudi Arabia, with 57 circuit-breaker branches
1980-81	Introduction of metal-oxide surge arresters and world’s first delivery to Denmark and for 735 kV to Canada
1980	World launch of the B series of modular contactors
1980	World’s biggest 525 kV SF$_6$ gas-insulated switchgear installation for the Itaipu hydroelectric power plant in Brazil, with 52 circuit-breaker branches
1980	Introduction of the vacuum-type circuit-breaker for voltages up to 36 kV (CALOR-EMAG)
1981	World’s first digital fault locator for high-voltage power lines
1981	Delivery of 18 high-current bus ducts for the Itaipu hydro-electric plant in Brazil, service currents up to 28 kA
1982	World’s first delivery of metal-oxide surge arresters for ultra-high voltage of 1600 kV to experimental facility in USA
1983	Commissioning of German Railway’s first control centre for controlling traction power supply
1983	550 MW high-voltage direct-current (HVDC) coupling at Dürnrohr (Austria) connecting the grid systems of West and East Europe
1983	Isolated-phase, force-cooled generator busduct for 20.5 kV, 36 500 A, delivered to Sweden
1983	765 kV outdoor SF$_6$ circuit-breakers delivered to the USA
1984	Delivery of world’s largest HVDC system of 6300 MW, ± 600 kV for Itaipu, Brazil
1984	Outdoor SF$_6$ circuit-breakers for 420 kV, 80 kA 4000 A
1984-89	Seven turnkey outdoor switchgear installations for the 500 kV network of Java / Indonesia

1984-85	Introduction of containerized modular high-current switchgear for gas turbine power plants
1984	Decentralized computers for transformer substations with telecontrol functions and local data processing
1985	Outdoor SF_6 circuit-breakers employing self-blast principle
1985	Introduction of gas-insulated, medium-voltage switchgear, single-phase metal-clad for up to 24 kV
1985	Introduction of gas-insulated, medium-voltage switchgear, triple-phase metal-clad (ZV2), for up to 36 kV (CALOR-EMAG)
1985	SF_6 generator circuit-breakers for 24 kV, 100 kA and rated continuous current of 12000 A
1985	First digital phase-comparison protection system for a high-voltage network
1986	Supraregional network control centres for 380 kV to 10 kV with multiple computers and complex, hierarchically structured telecontrol networks
1986	Introduction of hydraulic spring operating mechanisms for high-voltage circuit-breakers
1987	World’s first 800 kV SF_6 gas-insulated switchgear installation ready for operation in South Africa
1987	VD4 vacuum circuit-breaker series for 12 kV and 24 kV, particularly suited for compact switchboard designs (CALOR-EMAG)
1989	World’s first integrated protection and control system for power generation, transmission and distribution
1989-91	Two turnkey outdoor switchyards for Thailand’s 500 kV network
1990	1000th GIS switchgear bay ELK-O, 123 kV, delivered to Graz, Austria
1990	Delivery of the first digital distance and transformer differential protection relays
1990	World launch of EXLIM metal-oxide surge arresters for system voltages up to 800 kV
1991	Delivery of the first remote-programmable ripple-control receivers with distributed intelligence, integral clock and background switching schedules
1992	Commissioning of the first multiterminal HVDC system of 2000 MW, ± 500 kV, between Quebec and New England
1995	Commissioning of UW8 transformer substation with unified digital station control system with station-level interlocking (LON) for SF_6-insulated switchbays for 110 kV and 20 kV in Mannheim
1995	Commissioning of the first installation of gas-insulated switchbays supplied ready for operation from the factory (ZX type) with integrated digital bay control and protection system (REF 542) and plug-in technology for cable connection and busbar connection for 10 kV
1997	VM1 vacuum circuit-breaker series with electromagnetic actuating system for 12 kV and 24 kV
1998	Supply of the 20000th hydraulic spring operating mechanism