



Technical collection

# Electrical installation guide 2009

According to  
IEC international  
standards



This guide has been written for electrical Engineers who have to design, realize, inspect or maintain electrical installations in compliance with international Standards of the International Electrotechnical Commission (IEC).

“Which technical solution will guarantee that all relevant safety rules are met?” This question has been a permanent guideline for the elaboration of this document.

An international Standard such as the IEC 60364 “Electrical Installation in Buildings” specifies extensively the rules to comply with to ensure safety and predicted operational characteristics for all types of electrical installations. As the Standard must be extensive, and has to be applicable to all types of products and the technical solutions in use worldwide, the text of the IEC rules is complex, and not presented in a ready-to-use order. The Standard cannot therefore be considered as a working handbook, but only as a reference document.

The aim of the present guide is to provide a clear, practical and step-by-step explanation for the complete study of an electrical installation, according to IEC 60364 and other relevant IEC Standards. Therefore, the first chapter (B) presents the methodology to be used, and each chapter deals with one out of the eight steps of the study. The two last chapters are devoted to particular supply sources, loads and locations, and appendix provides additional information. Special attention must be paid to the EMC appendix, which is based on the broad and practical experience on electromagnetic compatibility problems.

We all hope that you, the user, will find this handbook genuinely helpful.

**Schneider Electric S.A.**

This technical guide is the result of a collective effort.

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The Electrical Installation Guide is a single document covering the techniques, regulations and standards related to electrical installations. It is intended for electrical professionals in companies, design offices, inspection organisations, etc.

This Technical Guide is aimed at professional users and is only intended to provide them guidelines for the definition of an industrial, tertiary or domestic electrical installation. Information and guidelines contained in this Guide are provided AS IS. Schneider Electric makes no warranty of any kind, whether express or implied, such as but not limited to the warranties of merchantability and fitness for a particular purpose, nor assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed in this Guide, nor represents that its use would not infringe privately owned rights. The purpose of this guide is to facilitate the implementation of International installation standards for designers & contractors, but in all cases the original text of International or local standards in force shall prevail.

This new edition has been published to take into account changes in techniques, standards and regulations, in particular electrical installation standard IEC 60364.

We thank all the readers of the previous edition of this guide for their comments that have helped improve the current edition.  
We also thank the many people and organisations, too numerous to name here, who have contributed in one way or another to the preparation of this guide.

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# Guiding tools for more efficiency in electrical distribution design

## Technical knowledge

10-30mn **eLearning** modules for individual training

Articles giving base skills about general subjects: “**Cahiers Techniques**”



## Pre-design help for budget approach

Selection criterias & method to follow in order to pre-define project specification:

- **Architecture guide**
- **ID-Spec software**



Solutions and examples with recommended architectures in **Solution guides**:

- airport
- automotive
- food
- retail
- office
- industrial buildings
- healthcare
- ...



## Design support

Practical data & methods through major design guides:

- **Electrical Installation Guide**
- Protection guide
- Industrial electrical network design guide
- ...

Product presentation of technical characteristics in all Schneider Electric product **Catalogues**

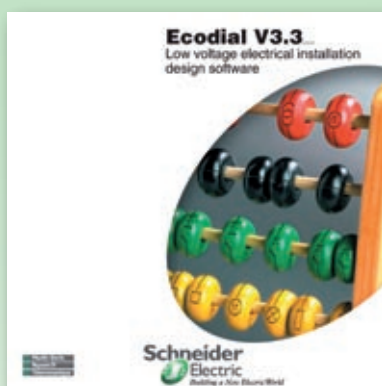
Design Software:

### ■ **My Ecodial**

Ecodial software provides a complete design package for LV installations, in accordance with IEC standards and recommendations.

Main features:

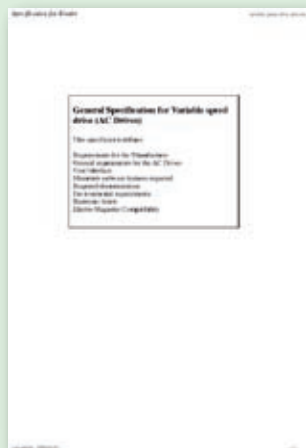
- Create diagrams
- Optimise circuit breakers curves
- Determine source power
- Follow step by step calculation
- Print the project design file
- SISPRO building
- ...



Drawing source files for connection, dimension, diagram, mounting & safety: **CAD library**

## Specification help

**Technical specification** on products & solutions for tender request



## Help in installation, use & maintenance

Product **installation data**

Product **how to use data**

Product **maintenance data**



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# Chapter A

## General rules of electrical installation design

A1

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*A - General rules of electrical installation design**B – Connection to the MV utility distribution network**C - Connection to the LV utility distribution network**D - MV & LV architecture selection guide**E - LV Distribution**F - Protection against electric shocks**G - Sizing and protection of conductors**H - LV switchgear: functions & selection*

For the best results in electrical installation design it is recommended to read all the chapters of this guide in the order in which they are presented.

### Listing of power demands

The study of a proposed electrical installation requires an adequate understanding of all governing rules and regulations.

The total power demand can be calculated from the data relative to the location and power of each load, together with the knowledge of the operating modes (steady state demand, starting conditions, non simultaneous operation, etc.)

From these data, the power required from the supply source and (where appropriate) the number of sources necessary for an adequate supply to the installation are readily obtained.

Local information regarding tariff structures is also required to allow the best choice of connection arrangement to the power-supply network, e.g. at medium voltage or low voltage level.

### Service connection

This connection can be made at:

- Medium Voltage level

A consumer-type substation will then have to be studied, built and equipped. This substation may be an outdoor or indoor installation conforming to relevant standards and regulations (the low-voltage section may be studied separately if necessary).

Metering at medium-voltage or low-voltage is possible in this case.

- Low Voltage level

The installation will be connected to the local power network and will (necessarily) be metered according to LV tariffs.

### Electrical Distribution architecture

The whole installation distribution network is studied as a complete system.

A selection guide is proposed for determination of the most suitable architecture. MV/LV main distribution and LV power distribution levels are covered.

Neutral earthing arrangements are chosen according to local regulations, constraints related to the power-supply, and to the type of loads.

The distribution equipment (panelboards, switchgears, circuit connections, ...) are determined from building plans and from the location and grouping of loads.

The type of premises and allocation can influence their immunity to external disturbances.

### Protection against electric shocks

The earthing system (TT, IT or TN) having been previously determined, then the appropriate protective devices must be implemented in order to achieve protection against hazards of direct or indirect contact.

### Circuits and switchgear

Each circuit is then studied in detail. From the rated currents of the loads, the level of short-circuit current, and the type of protective device, the cross-sectional area of circuit conductors can be determined, taking into account the nature of the cableways and their influence on the current rating of conductors.

Before adopting the conductor size indicated above, the following requirements must be satisfied:

- The voltage drop complies with the relevant standard
- Motor starting is satisfactory
- Protection against electric shock is assured

The short-circuit current  $I_{sc}$  is then determined, and the thermal and electrodynamic withstand capability of the circuit is checked.

These calculations may indicate that it is necessary to use a conductor size larger than the size originally chosen.

The performance required by the switchgear will determine its type and characteristics.

The use of cascading techniques and the discriminative operation of fuses and tripping of circuit breakers are examined.

*J – Protection against voltage surges in LV**K – Energy efficiency in electrical distribution**L - Power factor correction and harmonic filtering**M - Harmonic management**N - Characteristics of particular sources and loads**P - Residential and other special locations**Q - EMC guideline***Protection against overvoltages**

Direct or indirect lightning strokes can damage electrical equipment at a distance of several kilometers. Operating voltage surges, transient and industrial frequency over-voltage can also produce the same consequences. The effects are examined and solutions are proposed.

**Energy efficiency in electrical distribution**

Implementation of measuring devices with an adequate communication system within the electrical installation can produce high benefits for the user or owner: reduced power consumption, reduced cost of energy, better use of electrical equipment.

**Reactive energy**

The power factor correction within electrical installations is carried out locally, globally or as a combination of both methods.

**Harmonics**

Harmonics in the network affect the quality of energy and are at the origin of many disturbances as overloads, vibrations, ageing of equipment, trouble of sensitive equipment, of local area networks, telephone networks. This chapter deals with the origins and the effects of harmonics and explain how to measure them and present the solutions.

**Particular supply sources and loads**

Particular items or equipment are studied:

- Specific sources such as alternators or inverters
- Specific loads with special characteristics, such as induction motors, lighting circuits or LV/LV transformers
- Specific systems, such as direct-current networks

**Generic applications**

Certain premises and locations are subject to particularly strict regulations: the most common example being residential dwellings.

**EMC Guidelines**

Some basic rules must be followed in order to ensure Electromagnetic Compatibility. Non observance of these rules may have serious consequences in the operation of the electrical installation: disturbance of communication systems, nuisance tripping of protection devices, and even destruction of sensitive devices.

**Ecodial software**

Ecodial software<sup>(1)</sup> provides a complete design package for LV installations, in accordance with IEC standards and recommendations.

The following features are included:

- Construction of one-line diagrams
- Calculation of short-circuit currents
- Calculation of voltage drops
- Optimization of cable sizes
- Required ratings of switchgear and fusegear
- Discrimination of protective devices
- Recommendations for cascading schemes
- Verification of the protection of people
- Comprehensive print-out of the foregoing calculated design data

(1) Ecodial is a Merlin Gerin product and is available in French and English versions.

Low-voltage installations are governed by a number of regulatory and advisory texts, which may be classified as follows:

- Statutory regulations (decrees, factory acts, etc.)
- Codes of practice, regulations issued by professional institutions, job specifications
- National and international standards for installations
- National and international standards for products

## 2.1 Definition of voltage ranges

### IEC voltage standards and recommendations

Three-phase four-wire or three-wire systems		Single-phase three-wire systems
Nominal voltage (V)		Nominal voltage (V)
50 Hz	60 Hz	60 Hz
—	120/208	120/240
—	240	—
230/400 <sup>(1)</sup>	277/480	—
400/690 <sup>(1)</sup>	480	—
—	347/600	—
1000	600	—

(1) The nominal voltage of existing 220/380 V and 240/415 V systems shall evolve toward the recommended value of 230/400 V. The transition period should be as short as possible and should not exceed the year 2003. During this period, as a first step, the electricity supply authorities of countries having 220/380 V systems should bring the voltage within the range 230/400 V +6 %, -10 % and those of countries having 240/415 V systems should bring the voltage within the range 230/400 V +10 %, -6 %. At the end of this transition period, the tolerance of 230/400 V  $\pm$  10 % should have been achieved; after this the reduction of this range will be considered. All the above considerations apply also to the present 380/660 V value with respect to the recommended value 400/690 V.

**Fig. A1** : Standard voltages between 100 V and 1000 V (IEC 60038 Edition 6.2 2002-07)

Series I		Series II	
Highest voltage for equipment (kV)	Nominal system voltage (kV)	Highest voltage for equipment (kV)	Nominal system voltage (kV)
3.6 <sup>(1)</sup>	3.3 <sup>(1)</sup> 3 <sup>(1)</sup>	4.40 <sup>(1)</sup>	4.16 <sup>(1)</sup>
7.2 <sup>(1)</sup>	6.6 <sup>(1)</sup> 6 <sup>(1)</sup>	—	—
12	11 10	—	—
—	—	13.2 <sup>(2)</sup>	12.47 <sup>(2)</sup>
—	—	13.97 <sup>(2)</sup>	13.2 <sup>(2)</sup>
—	—	14.52 <sup>(1)</sup>	13.8 <sup>(1)</sup>
(17.5)	— (15)	—	—
24	22 20	—	—
—	—	26.4 <sup>(2)</sup>	24.94 <sup>(2)</sup>
36 <sup>(3)</sup>	33 <sup>(3)</sup> —	—	—
—	—	36.5	34.5
40.5 <sup>(3)</sup>	— 35 <sup>(3)</sup>	—	—

These systems are generally three-wire systems unless otherwise indicated.

The values indicated are voltages between phases.

The values indicated in parentheses should be considered as non-preferred values. It is recommended that these values should not be used for new systems to be constructed in future.

**Note 1:** It is recommended that in any one country the ratio between two adjacent nominal voltages should be not less than two.

**Note 2:** In a normal system of Series I, the highest voltage and the lowest voltage do not differ by more than approximately  $\pm 10$  % from the nominal voltage of the system. In a normal system of Series II, the highest voltage does not differ by more than +5 % and the lowest voltage by more than -10 % from the nominal voltage of the system.

(1) These values should not be used for public distribution systems.

(2) These systems are generally four-wire systems.

(3) The unification of these values is under consideration.

**Fig. A2** : Standard voltages above 1 kV and not exceeding 35 kV (IEC 60038 Edition 6.2 2002-07)



## 2.2 Regulations

In most countries, electrical installations shall comply with more than one set of regulations, issued by National Authorities or by recognized private bodies. It is essential to take into account these local constraints before starting the design.

## 2.3 Standards

This Guide is based on relevant IEC standards, in particular IEC 60364. IEC 60364 has been established by medical and engineering experts of all countries in the world comparing their experience at an international level. Currently, the safety principles of IEC 60364 and 60479-1 are the fundamentals of most electrical standards in the world (see table below and next page).

<b>IEC 60038</b>	Standard voltages
<b>IEC 60076-2</b>	Power transformers - Temperature rise
<b>IEC 60076-3</b>	Power transformers - Insulation levels, dielectric tests and external clearances in air
<b>IEC 60076-5</b>	Power transformers - Ability to withstand short-circuit
<b>IEC 60076-10</b>	Power transformers - Determination of sound levels
<b>IEC 60146</b>	Semiconductor convertors - General requirements and line commutated convertors
<b>IEC 60255</b>	Electrical relays
<b>IEC 60265-1</b>	High-voltage switches - High-voltage switches for rated voltages above 1 kV and less than 52 kV
<b>IEC 60269-1</b>	Low-voltage fuses - General requirements
<b>IEC 60269-2</b>	Low-voltage fuses - Supplementary requirements for fuses for use by unskilled persons (fuses mainly for household and similar applications)
<b>IEC 60282-1</b>	High-voltage fuses - Current-limiting fuses
<b>IEC 60287-1-1</b>	Electric cables - Calculation of the current rating - Current rating equations (100% load factor) and calculation of losses - General
<b>IEC 60364</b>	Electrical installations of buildings
<b>IEC 60364-1</b>	Electrical installations of buildings - Fundamental principles
<b>IEC 60364-4-41</b>	Electrical installations of buildings - Protection for safety - Protection against electric shock
<b>IEC 60364-4-42</b>	Electrical installations of buildings - Protection for safety - Protection against thermal effects
<b>IEC 60364-4-43</b>	Electrical installations of buildings - Protection for safety - Protection against overcurrent
<b>IEC 60364-4-44</b>	Electrical installations of buildings - Protection for safety - Protection against electromagnetic and voltage disturbance
<b>IEC 60364-5-51</b>	Electrical installations of buildings - Selection and erection of electrical equipment - Common rules
<b>IEC 60364-5-52</b>	Electrical installations of buildings - Selection and erection of electrical equipment - Wiring systems
<b>IEC 60364-5-53</b>	Electrical installations of buildings - Selection and erection of electrical equipment - Isolation, switching and control
<b>IEC 60364-5-54</b>	Electrical installations of buildings - Selection and erection of electrical equipment - Earthing arrangements
<b>IEC 60364-5-55</b>	Electrical installations of buildings - Selection and erection of electrical equipment - Other equipments
<b>IEC 60364-6-61</b>	Electrical installations of buildings - Verification and testing - Initial verification
<b>IEC 60364-7-701</b>	Electrical installations of buildings - Requirements for special installations or locations - Locations containing a bath tub or shower basin
<b>IEC 60364-7-702</b>	Electrical installations of buildings - Requirements for special installations or locations - Swimming pools and other basins
<b>IEC 60364-7-703</b>	Electrical installations of buildings - Requirements for special installations or locations - Locations containing sauna heaters
<b>IEC 60364-7-704</b>	Electrical installations of buildings - Requirements for special installations or locations - Construction and demolition site installations
<b>IEC 60364-7-705</b>	Electrical installations of buildings - Requirements for special installations or locations - Electrical installations of agricultural and horticultural premises
<b>IEC 60364-7-706</b>	Electrical installations of buildings - Requirements for special installations or locations - Restrictive conducting locations
<b>IEC 60364-7-707</b>	Electrical installations of buildings - Requirements for special installations or locations - Earthing requirements for the installation of data processing equipment
<b>IEC 60364-7-708</b>	Electrical installations of buildings - Requirements for special installations or locations - Electrical installations in caravan parks and caravans
<b>IEC 60364-7-709</b>	Electrical installations of buildings - Requirements for special installations or locations - Marinas and pleasure craft
<b>IEC 60364-7-710</b>	Electrical installations of buildings - Requirements for special installations or locations - Medical locations
<b>IEC 60364-7-711</b>	Electrical installations of buildings - Requirements for special installations or locations - Exhibitions, shows and stands
<b>IEC 60364-7-712</b>	Electrical installations of buildings - Requirements for special installations or locations - Solar photovoltaic (PV) power supply systems
<b>IEC 60364-7-713</b>	Electrical installations of buildings - Requirements for special installations or locations - Furniture
<b>IEC 60364-7-714</b>	Electrical installations of buildings - Requirements for special installations or locations - External lighting installations
<b>IEC 60364-7-715</b>	Electrical installations of buildings - Requirements for special installations or locations - Extra-low-voltage lighting installations
<b>IEC 60364-7-717</b>	Electrical installations of buildings - Requirements for special installations or locations - Mobile or transportable units
<b>IEC 60364-7-740</b>	Electrical installations of buildings - Requirements for special installations or locations - Temporary electrical installations for structures, amusement devices and booths at fairgrounds, amusement parks and circuses
<b>IEC 60427</b>	High-voltage alternating current circuit-breakers
<b>IEC 60439-1</b>	Low-voltage switchgear and controlgear assemblies - Type-tested and partially type-tested assemblies
<b>IEC 60439-2</b>	Low-voltage switchgear and controlgear assemblies - Particular requirements for busbar trunking systems (busways)
<b>IEC 60439-3</b>	Low-voltage switchgear and controlgear assemblies - Particular requirements for low-voltage switchgear and controlgear assemblies intended to be installed in places where unskilled persons have access for their use - Distribution boards
<b>IEC 60439-4</b>	Low-voltage switchgear and controlgear assemblies - Particular requirements for assemblies for construction sites (ACS)
<b>IEC 60446</b>	Basic and safety principles for man-machine interface, marking and identification - Identification of conductors by colours or numerals
<b>IEC 60439-5</b>	Low-voltage switchgear and controlgear assemblies - Particular requirements for assemblies intended to be installed outdoors in public places - Cable distribution cabinets (CDCs)
<b>IEC 60479-1</b>	Effects of current on human beings and livestock - General aspects
<b>IEC 60479-2</b>	Effects of current on human beings and livestock - Special aspects
<b>IEC 60479-3</b>	Effects of current on human beings and livestock - Effects of currents passing through the body of livestock

(Continued on next page)

IEC 60529	Degrees of protection provided by enclosures (IP code)
IEC 60644	Spécification for high-voltage fuse-links for motor circuit applications
IEC 60664	Insulation coordination for equipment within low-voltage systems
IEC 60715	Dimensions of low-voltage switchgear and controlgear. Standardized mounting on rails for mechanical support of electrical devices in switchgear and controlgear installations.
IEC 60724	Short-circuit temperature limits of electric cables with rated voltages of 1 kV ( $U_m = 1.2$ kV) and 3 kV ( $U_m = 3.6$ kV)
IEC 60755	General requirements for residual current operated protective devices
IEC 60787	Application guide for the selection of fuse-links of high-voltage fuses for transformer circuit application
IEC 60831	Shunt power capacitors of the self-healing type for AC systems having a rated voltage up to and including 1000 V - General - Performance, testing and rating - Safety requirements - Guide for installation and operation
IEC 60947-1	Low-voltage switchgear and controlgear - General rules
IEC 60947-2	Low-voltage switchgear and controlgear - Circuit-breakers
IEC 60947-3	Low-voltage switchgear and controlgear - Switches, disconnectors, switch-disconnectors and fuse-combination units
IEC 60947-4-1	Low-voltage switchgear and controlgear - Contactors and motor-starters - Electromechanical contactors and motor-starters
IEC 60947-6-1	Low-voltage switchgear and controlgear - Multiple function equipment - Automatic transfer switching equipment
IEC 61000	Electromagnetic compatibility (EMC)
IEC 61140	Protection against electric shocks - common aspects for installation and equipment
IEC 61557-1	Electrical safety in low-voltage distribution systems up to 1000 V AC and 1500 V DC - Equipment for testing, measuring or monitoring of protective measures - General requirements
IEC 61557-8	Electrical safety in low-voltage distribution systems up to 1000 V AC and 1500 V DC - Equipment for testing, measuring or monitoring of protective measures
IEC 61557-9	Electrical safety in low-voltage distribution systems up to 1000 V AC and 1500 V DC - Equipment for insulation fault location in IT systems
IEC 61557-12	Electrical safety in low-voltage distribution systems up to 1000 V AC and 1500 V DC - Equipment for testing, measuring or monitoring of protective measures. Performance measuring and monitoring devices (PMD)
IEC 61558-2-6	Safety of power transformers, power supply units and similar - Particular requirements for safety isolating transformers for general use
IEC 62271-1	Common specifications for high-voltage switchgear and controlgear standards
IEC 62271-100	High-voltage switchgear and controlgear - High-voltage alternating-current circuit-breakers
IEC 62271-102	High-voltage switchgear and controlgear - Alternating current disconnectors and earthing switches
IEC 62271-105	High-voltage switchgear and controlgear - Alternating current switch-fuse combinations
IEC 62271-200	High-voltage switchgear and controlgear - Alternating current metal-enclosed switchgear and controlgear for rated voltages above 1 kV and up to and including 52 kV
IEC 62271-202	High-voltage/low voltage prefabricated substations

(Concluded)

## 2.4 Quality and safety of an electrical installation

In so far as control procedures are respected, quality and safety will be assured only if:

- The initial checking of conformity of the electrical installation with the standard and regulation has been achieved
- The electrical equipment comply with standards
- The periodic checking of the installation recommended by the equipment manufacturer is respected.

## 2.5 Initial testing of an installation

Before a utility will connect an installation to its supply network, strict pre-commissioning electrical tests and visual inspections by the authority, or by its appointed agent, must be satisfied.

These tests are made according to local (governmental and/or institutional) regulations, which may differ slightly from one country to another. The principles of all such regulations however, are common, and are based on the observance of rigorous safety rules in the design and realization of the installation.

IEC 60364-6-61 and related standards included in this guide are based on an international consensus for such tests, intended to cover all the safety measures and approved installation practices normally required for residential, commercial and (the majority of) industrial buildings. Many industries however have additional regulations related to a particular product (petroleum, coal, natural gas, etc.). Such additional requirements are beyond the scope of this guide.

The pre-commissioning electrical tests and visual-inspection checks for installations in buildings include, typically, all of the following:

- Insulation tests of all cable and wiring conductors of the fixed installation, between phases and between phases and earth
- Continuity and conductivity tests of protective, equipotential and earth-bonding conductors
- Resistance tests of earthing electrodes with respect to remote earth
- Verification of the proper operation of the interlocks, if any
- Check of allowable number of socket-outlets per circuit

- Cross-sectional-area check of all conductors for adequacy at the short-circuit levels prevailing, taking account of the associated protective devices, materials and installation conditions (in air, conduit, etc.)
- Verification that all exposed- and extraneous metallic parts are properly earthed (where appropriate)
- Check of clearance distances in bathrooms, etc.

These tests and checks are basic (but not exhaustive) to the majority of installations, while numerous other tests and rules are included in the regulations to cover particular cases, for example: TN-, TT- or IT-earthed installations, installations based on class 2 insulation, SELV circuits, and special locations, etc.

The aim of this guide is to draw attention to the particular features of different types of installation, and to indicate the essential rules to be observed in order to achieve a satisfactory level of quality, which will ensure safe and trouble-free performance. The methods recommended in this guide, modified if necessary to comply with any possible variation imposed by a utility, are intended to satisfy all precommissioning test and inspection requirements.

## 2.6 Periodic check-testing of an installation

In many countries, all industrial and commercial-building installations, together with installations in buildings used for public gatherings, must be re-tested periodically by authorized agents.

**Figure A3** shows the frequency of testing commonly prescribed according to the kind of installation concerned.

Type of installation	Testing frequency
<b>Installations which require the protection of employees</b> <ul style="list-style-type: none"> <li>■ Locations at which a risk of degradation, fire or explosion exists</li> <li>■ Temporary installations at worksites</li> <li>■ Locations at which MV installations exist</li> <li>■ Restrictive conducting locations where mobile equipment is used</li> </ul>	Annually
Other cases	Every 3 years
<b>Installations in buildings used for public gatherings, where protection against the risks of fire and panic are required</b>	According to the type of establishment and its capacity for receiving the public
Residential	From one to three years
	According to local regulations

**Fig A3** : Frequency of check-tests commonly recommended for an electrical installation

Conformity of equipment with the relevant standards can be attested in several ways

## 2.7 Conformity (with standards and specifications) of equipment used in the installation

### Attestation of conformity

The conformity of equipment with the relevant standards can be attested:

- By an official mark of conformity granted by the certification body concerned, or
- By a certificate of conformity issued by a certification body, or
- By a declaration of conformity from the manufacturer

The first two solutions are generally not available for high voltage equipment.

### Declaration of conformity

Where the equipment is to be used by skilled or instructed persons, the manufacturer's declaration of conformity (included in the technical documentation), is generally recognized as a valid attestation. Where the competence of the manufacturer is in doubt, a certificate of conformity can reinforce the manufacturer's declaration.

**Note: CE marking**

In Europe, the European directives require the manufacturer or his authorized representative to affix the CE marking on his own responsibility. It means that:

- The product meets the legal requirements
- It is presumed to be marketable in Europe

The CE marking is neither a mark of origin nor a mark of conformity.

**Mark of conformity**

Marks of conformity are affixed on appliances and equipment generally used by ordinary non instructed people (e.g in the field of domestic appliances). A mark of conformity is delivered by certification body if the equipment meet the requirements from an applicable standard and after verification of the manufacturer's quality management system.

**Certification of Quality**

The standards define several methods of quality assurance which correspond to different situations rather than to different levels of quality.

**Assurance**

A laboratory for testing samples cannot certify the conformity of an entire production run: these tests are called type tests. In some tests for conformity to standards, the samples are destroyed (tests on fuses, for example).

Only the manufacturer can certify that the fabricated products have, in fact, the characteristics stated.

Quality assurance certification is intended to complete the initial declaration or certification of conformity.

As proof that all the necessary measures have been taken for assuring the quality of production, the manufacturer obtains certification of the quality control system which monitors the fabrication of the product concerned. These certificates are issued by organizations specializing in quality control, and are based on the international standard ISO 9001: 2000.

These standards define three model systems of quality assurance control corresponding to different situations rather than to different levels of quality:

- Model 3 defines assurance of quality by inspection and checking of final products.
- Model 2 includes, in addition to checking of the final product, verification of the manufacturing process. For example, this method is applied, to the manufacturer of fuses where performance characteristics cannot be checked without destroying the fuse.
- Model 1 corresponds to model 2, but with the additional requirement that the quality of the design process must be rigorously scrutinized; for example, where it is not intended to fabricate and test a prototype (case of a custom-built product made to specification).

**2.8 Environment**

Environmental management systems can be certified by an independent body if they meet requirements given in ISO 14001. This type of certification mainly concerns industrial settings but can also be granted to places where products are designed.

A product environmental design sometimes called "eco-design" is an approach of sustainable development with the objective of designing products/services best meeting the customers' requirements while reducing their environmental impact over their whole life cycle. The methodologies used for this purpose lead to choose equipment's architecture together with components and materials taking into account the influence of a product on the environment along its life cycle (from extraction of raw materials to scrap) i.e. production, transport, distribution, end of life etc.

In Europe two Directives have been published, they are called:

- RoHS Directive (Restriction of Hazardous Substances) coming into force on July 2006 (the coming into force was on February 13<sup>th</sup>, 2003, and the application date is July 1<sup>st</sup>, 2006) aims to eliminate from products six hazardous substances: lead, mercury, cadmium, hexavalent chromium, polybrominated biphenyls (PBB) or polybrominated diphenyl ethers (PBDE).

■ WEEE Directive (Waste of Electrical and Electronic Equipment) coming into force in August 2005 (the coming into force was on February 13<sup>th</sup>, 2003, and the application date is August 13<sup>th</sup>, 2005) in order to master the end of life and treatments for household and non household equipment.

In other parts of the world some new legislation will follow the same objectives.

In addition to manufacturers action in favour of products eco-design, the contribution of the whole electrical installation to sustainable development can be significantly improved through the design of the installation. Actually, it has been shown that an optimised design of the installation, taking into account operation conditions, MV/LV substations location and distribution structure (switchboards, busways, cables), can reduce substantially environmental impacts (raw material depletion, energy depletion, end of life)

See chapter D about location of the substation and the main LV switchboard.

## 3 Installed power loads - Characteristics

*An examination of the actual apparent-power demands of different loads: a necessary preliminary step in the design of a LV installation*

*The nominal power in kW ( $P_n$ ) of a motor indicates its rated equivalent mechanical power output.*

*The apparent power in kVA ( $P_a$ ) supplied to the motor is a function of the output, the motor efficiency and the power factor.*

$$P_a = \frac{P_n}{\eta \cos \varphi}$$

The examination of actual values of apparent-power required by each load enables the establishment of:

- A declared power demand which determines the contract for the supply of energy
- The rating of the MV/LV transformer, where applicable (allowing for expected increased load)
- Levels of load current at each distribution board

### 3.1 Induction motors

#### Current demand

The full-load current  $I_a$  supplied to the motor is given by the following formulae:

- 3-phase motor:  $I_a = P_n \times 1,000 / (\sqrt{3} \times U \times \eta \times \cos \varphi)$
- 1-phase motor:  $I_a = P_n \times 1,000 / (U \times \eta \times \cos \varphi)$

where

$I_a$ : current demand (in amps)

$P_n$ : nominal power (in kW)

$U$ : voltage between phases for 3-phase motors and voltage between the terminals for single-phase motors (in volts). A single-phase motor may be connected phase-to-neutral or phase-to-phase.

$\eta$ : per-unit efficiency, i.e. output kW / input kW

$\cos \varphi$ : power factor, i.e. kW input / kVA input

#### Subtransient current and protection setting

- Subtransient current peak value can be very high ; typical value is about 12 to 15 times the rms rated value  $I_{nm}$ . Sometimes this value can reach 25 times  $I_{nm}$ .
- Merlin Gerin circuit-breakers, Telemecanique contactors and thermal relays are designed to withstand motor starts with very high subtransient current (subtransient peak value can be up to 19 times the rms rated value  $I_{nm}$ ).
- If unexpected tripping of the overcurrent protection occurs during starting, this means the starting current exceeds the normal limits. As a result, some maximum switchgear withstands can be reached, life time can be reduced and even some devices can be destroyed. In order to avoid such a situation, oversizing of the switchgear must be considered.
- Merlin Gerin and Telemecanique switchgears are designed to ensure the protection of motor starters against short-circuits. According to the risk, tables show the combination of circuit-breaker, contactor and thermal relay to obtain type 1 or type 2 coordination (see chapter N).

#### Motor starting current

Although high efficiency motors can be found on the market, in practice their starting currents are roughly the same as some of standard motors.

The use of start-delta starter, static soft start unit or variable speed drive allows to reduce the value of the starting current (Example : 4  $I_a$  instead of 7.5  $I_a$ ).

#### Compensation of reactive-power (kvar) supplied to induction motors

It is generally advantageous for technical and financial reasons to reduce the current supplied to induction motors. This can be achieved by using capacitors without affecting the power output of the motors.

The application of this principle to the operation of induction motors is generally referred to as "power-factor improvement" or "power-factor correction".

As discussed in chapter L, the apparent power (kVA) supplied to an induction motor can be significantly reduced by the use of shunt-connected capacitors. Reduction of input kVA means a corresponding reduction of input current (since the voltage remains constant).

Compensation of reactive-power is particularly advised for motors that operate for long periods at reduced power.

As noted above  $\cos \varphi = \frac{\text{kW input}}{\text{kVA input}}$  so that a kVA input reduction will increase (i.e. improve) the value of  $\cos \varphi$ .

### 3 Installed power loads - Characteristics

The current supplied to the motor, after power-factor correction, is given by:

$$I = I_a \frac{\cos \varphi}{\cos \varphi'}$$

where  $\cos \varphi$  is the power factor before compensation and  $\cos \varphi'$  is the power factor after compensation,  $I_a$  being the original current.

**Figure A4** below shows, in function of motor rated power, standard motor current values for several voltage supplies.

kW	hp	230 V	380 - 415 V	400 V	440 - 480 V	500 V	690 V
		A	A	A	A	A	A
0.18	-	1.0	-	0.6	-	0.48	0.35
0.25	-	1.5	-	0.85	-	0.68	0.49
0.37	-	1.9	-	1.1	-	0.88	0.64
-	1/2	-	1.3	-	1.1	-	-
0.55	-	2.6	-	1.5	-	1.2	0.87
-	3/4	-	1.8	-	1.6	-	-
-	1	-	2.3	-	2.1	-	-
0.75	-	3.3	-	1.9	-	1.5	1.1
1.1	-	4.7	-	2.7	-	2.2	1.6
-	1-1/2	-	3.3	-	3.0	-	-
-	2	-	4.3	-	3.4	-	-
1.5	-	6.3	-	3.6	-	2.9	2.1
2.2	-	8.5	-	4.9	-	3.9	2.8
-	3	-	6.1	-	4.8	-	-
3.0	-	11.3	-	6.5	-	5.2	3.8
3.7	-	-	-	-	-	-	-
4	-	15	9.7	8.5	7.6	6.8	4.9
5.5	-	20	-	11.5	-	9.2	6.7
-	7-1/2	-	14.0	-	11.0	-	-
-	10	-	18.0	-	14.0	-	-
7.5	-	27	-	15.5	-	12.4	8.9
11	-	38.0	-	22.0	-	17.6	12.8
-	15	-	27.0	-	21.0	-	-
-	20	-	34.0	-	27.0	-	-
15	-	51	-	29	-	23	17
18.5	-	61	-	35	-	28	21
-	25	-	44	-	34	-	-
22	-	72	-	41	-	33	24
-	30	-	51	-	40	-	-
-	40	-	66	-	52	-	-
30	-	96	-	55	-	44	32
37	-	115	-	66	-	53	39
-	50	-	83	-	65	-	-
-	60	-	103	-	77	-	-
45	-	140	-	80	-	64	47
55	-	169	-	97	-	78	57
-	75	-	128	-	96	-	-
-	100	-	165	-	124	-	-
75	-	230	-	132	-	106	77
90	-	278	-	160	-	128	93
-	125	-	208	-	156	-	-
110	-	340	-	195	-	156	113
-	150	-	240	-	180	-	-
132	-	400	-	230	-	184	134
-	200	-	320	-	240	-	-
150	-	-	-	-	-	-	-
160	-	487	-	280	-	224	162
185	-	-	-	-	-	-	-
-	250	-	403	-	302	-	-
200	-	609	-	350	-	280	203
220	-	-	-	-	-	-	-
-	300	-	482	-	361	-	-
250	-	748	-	430	-	344	250
280	-	-	-	-	-	-	-
-	350	-	560	-	414	-	-
-	400	-	636	-	474	-	-
300	-	-	-	-	-	-	-

**Fig. A4** : Rated operational power and currents (continued on next page)



## 3 Installed power loads - Characteristics

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kW	hp	230 V A	380 - 415 V A	400 V A	440 - 480 V A	500 V A	690 V A
315	-	940	-	540	-	432	313
-	540	-	-	-	515	-	-
335	-	-	-	-	-	-	-
355	-	1061	-	610	-	488	354
-	500	-	786	-	590	-	-
375	-	-	-	-	-	-	-
400	-	1200	-	690	-	552	400
425	-	-	-	-	-	-	-
450	-	-	-	-	-	-	-
475	-	-	-	-	-	-	-
500	-	1478	-	850	-	680	493
530	-	-	-	-	-	-	-
560	-	1652	-	950	-	760	551
600	-	-	-	-	-	-	-
630	-	1844	-	1060	-	848	615
670	-	-	-	-	-	-	-
710	-	2070	-	1190	-	952	690
750	-	-	-	-	-	-	-
800	-	2340	-	1346	-	1076	780
850	-	-	-	-	-	-	-
900	-	2640	-	1518	-	1214	880
950	-	-	-	-	-	-	-
1000	-	2910	-	1673	-	1339	970

Fig. A4 : Rated operational power and currents (concluded)

### 3.2 Resistive-type heating appliances and incandescent lamps (conventional or halogen)

The current demand of a heating appliance or an incandescent lamp is easily obtained from the nominal power  $P_n$  quoted by the manufacturer (i.e.  $\cos \varphi = 1$ ) (see Fig. A5).

Nominal power (kW)	Current demand (A)			
	1-phase 127 V	1-phase 230 V	3-phase 230 V	3-phase 400 V
0.1	0.79	0.43	0.25	0.14
0.2	1.58	0.87	0.50	0.29
0.5	3.94	2.17	1.26	0.72
1	7.9	4.35	2.51	1.44
1.5	11.8	6.52	3.77	2.17
2	15.8	8.70	5.02	2.89
2.5	19.7	10.9	6.28	3.61
3	23.6	13	7.53	4.33
3.5	27.6	15.2	8.72	5.05
4	31.5	17.4	10	5.77
4.5	35.4	19.6	11.3	6.5
5	39.4	21.7	12.6	7.22
6	47.2	26.1	15.1	8.66
7	55.1	30.4	17.6	10.1
8	63	34.8	20.1	11.5
9	71	39.1	22.6	13
10	79	43.5	25.1	14.4

Fig. A5 : Current demands of resistive heating and incandescent lighting (conventional or halogen) appliances



The currents are given by:

■ 3-phase case:  $I_a = \frac{P_n^{(1)}}{\sqrt{3} U}$

■ 1-phase case:  $I_a = \frac{P_n^{(1)}}{U}$

where U is the voltage between the terminals of the equipment.

For an incandescent lamp, the use of halogen gas allows a more concentrated light source. The light output is increased and the lifetime of the lamp is doubled.

**Note:** At the instant of switching on, the cold filament gives rise to a very brief but intense peak of current.

## Fluorescent lamps and related equipment

The power  $P_n$  (watts) indicated on the tube of a fluorescent lamp does not include the power dissipated in the ballast.

The current is given by:

$$I_a = \frac{P_{\text{ballast}} + P_n}{U \cos \varphi}$$

Where U = the voltage applied to the lamp, complete with its related equipment.

If no power-loss value is indicated for the ballast, a figure of 25% of  $P_n$  may be used.

## Standard tubular fluorescent lamps

With (unless otherwise indicated):

■  $\cos \varphi = 0.6$  with no power factor (PF) correction<sup>(2)</sup> capacitor

■  $\cos \varphi = 0.86$  with PF correction<sup>(2)</sup> (single or twin tubes)

■  $\cos \varphi = 0.96$  for electronic ballast.

If no power-loss value is indicated for the ballast, a figure of 25% of  $P_n$  may be used.

**Figure A6** gives these values for different arrangements of ballast.

Arrangement of lamps, starters and ballasts	Tube power (W) <sup>(3)</sup>	Current (A) at 230 V			Tube length (cm)
		Magnetic ballast		Electronic ballast	
		Without PF correction capacitor	With PF correction capacitor		
Single tube	18	0.20	0.14	0.10	60
	36	0.33	0.23	0.18	120
	58	0.50	0.36	0.28	150
Twin tubes	2 x 18		0.28	0.18	60
	2 x 36		0.46	0.35	120
	2 x 58		0.72	0.52	150

(3) Power in watts marked on tube

**Fig. A6** : Current demands and power consumption of commonly-dimensioned fluorescent lighting tubes (at 230 V-50 Hz)

## Compact fluorescent lamps

Compact fluorescent lamps have the same characteristics of economy and long life as classical tubes. They are commonly used in public places which are permanently illuminated (for example: corridors, hallways, bars, etc.) and can be mounted in situations otherwise illuminated by incandescent lamps (see **Fig. A7** next page).

(1)  $I_a$  in amps; U in volts.  $P_n$  is in watts. If  $P_n$  is in kW, then multiply the equation by 1,000

(2) "Power-factor correction" is often referred to as "compensation" in discharge-lighting-tube terminology.  $\cos \varphi$  is approximately 0.95 (the zero values of V and I are almost in phase) but the power factor is 0.5 due to the impulsive form of the current, the peak of which occurs "late" in each half cycle

### 3 Installed power loads - Characteristics

A14

Type of lamp	Lamp power (W)	Current at 230 V (A)
Separated ballast lamp	10	0.080
	18	0.110
	26	0.150
Integrated ballast lamp	8	0.075
	11	0.095
	16	0.125
	21	0.170

Fig. A7 : Current demands and power consumption of compact fluorescent lamps (at 230 V - 50 Hz)

The power in watts indicated on the tube of a discharge lamp does not include the power dissipated in the ballast.

#### Discharge lamps

Figure A8 gives the current taken by a complete unit, including all associated ancillary equipment.

These lamps depend on the luminous electrical discharge through a gas or vapour of a metallic compound, which is contained in a hermetically-sealed transparent envelope at a pre-determined pressure. These lamps have a long start-up time, during which the current  $I_a$  is greater than the nominal current  $I_n$ . Power and current demands are given for different types of lamp (typical average values which may differ slightly from one manufacturer to another).

Type of lamp (W)	Power demand (W) at 230 V 400 V	Current In(A)		Starting	Period (mins)	Luminous efficiency (lumens per watt)	Average timelife of lamp (h)	Utilization
		PF not corrected 230 V	PF corrected 400 V	Ia/In				
High-pressure sodium vapour lamps								
50	60	0.76	0.3	1.4 to 1.6	4 to 6	80 to 120	9000	■ Lighting of large halls ■ Outdoor spaces ■ Public lighting
70	80	1	0.45					
100	115	1.2	0.65					
150	168	1.8	0.85					
250	274	3	1.4					
400	431	4.4	2.2					
1000	1055	10.45	4.9					
Low-pressure sodium vapour lamps								
26	34.5	0.45	0.17	1.1 to 1.3	7 to 15	100 to 200	8000 to 12000	■ Lighting of autoroutes ■ Security lighting, station ■ Platform, storage areas
36	46.5		0.22					
66	80.5		0.39					
91	105.5		0.49					
131	154		0.69					
Mercury vapour + metal halide (also called metal-iodide)								
70	80.5	1	0.40	1.7	3 to 5	70 to 90	6000 6000 6000 6000 2000	■ Lighting of very large areas by projectors (for example: sports stadiums, etc.)
150	172	1.80	0.88					
250	276	2.10	1.35					
400	425	3.40	2.15					
1000	1046	8.25	5.30					
2000	2092 2052	16.50 8.60	10.50 6					
Mercury vapour + fluorescent substance (fluorescent bulb)								
50	57	0.6	0.30	1.7 to 2	3 to 6	40 to 60	8000 to 12000	■ Workshops with very high ceilings (halls, hangars) ■ Outdoor lighting ■ Low light output <sup>(1)</sup>
80	90	0.8	0.45					
125	141	1.15	0.70					
250	268	2.15	1.35					
400	421	3.25	2.15					
700	731	5.4	3.85					
1000	1046	8.25	5.30					
2000	2140 2080	15	11 6.1					

(1) Replaced by sodium vapour lamps.

**Note:** these lamps are sensitive to voltage dips. They extinguish if the voltage falls to less than 50% of their nominal voltage, and will not re-ignite before cooling for approximately 4 minutes.

**Note:** Sodium vapour low-pressure lamps have a light-output efficiency which is superior to that of all other sources. However, use of these lamps is restricted by the fact that the yellow-orange colour emitted makes colour recognition practically impossible.

Fig. A8 : Current demands of discharge lamps

In order to design an installation, the actual maximum load demand likely to be imposed on the power-supply system must be assessed.

To base the design simply on the arithmetic sum of all the loads existing in the installation would be extravagantly uneconomical, and bad engineering practice.

The aim of this chapter is to show how some factors taking into account the diversity (non simultaneous operation of all appliances of a given group) and utilization (e.g. an electric motor is not generally operated at its full-load capability, etc.) of all existing and projected loads can be assessed. The values given are based on experience and on records taken from actual installations. In addition to providing basic installation-design data on individual circuits, the results will provide a global value for the installation, from which the requirements of a supply system (distribution network, MV/LV transformer, or generating set) can be specified.

### 4.1 Installed power (kW)

*The installed power is the sum of the nominal powers of all power consuming devices in the installation.*

*This is not the power to be actually supplied in practice.*

Most electrical appliances and equipments are marked to indicate their nominal power rating ( $P_n$ ).

The installed power is the sum of the nominal powers of all power-consuming devices in the installation. This is not the power to be actually supplied in practice. This is the case for electric motors, where the power rating refers to the output power at its driving shaft. The input power consumption will evidently be greater.

Fluorescent and discharge lamps associated with stabilizing ballasts, are other cases in which the nominal power indicated on the lamp is less than the power consumed by the lamp and its ballast.

Methods of assessing the actual power consumption of motors and lighting appliances are given in Section 3 of this Chapter.

The power demand (kW) is necessary to choose the rated power of a generating set or battery, and where the requirements of a prime mover have to be considered.

For a power supply from a LV public-supply network, or through a MV/LV transformer, the significant quantity is the apparent power in kVA.

### 4.2 Installed apparent power (kVA)

*The installed apparent power is commonly assumed to be the arithmetical sum of the kVA of individual loads. The maximum estimated kVA to be supplied however is not equal to the total installed kVA.*

The installed apparent power is commonly assumed to be the arithmetical sum of the kVA of individual loads. The maximum estimated kVA to be supplied however is not equal to the total installed kVA.

The apparent-power demand of a load (which might be a single appliance) is obtained from its nominal power rating (corrected if necessary, as noted above for motors, etc.) and the application of the following coefficients:

$\eta$  = the per-unit efficiency = output kW / input kW

$\cos \varphi$  = the power factor = kW / kVA

The apparent-power kVA demand of the load

$P_a = P_n / (\eta \times \cos \varphi)$

From this value, the full-load current  $I_a$  (A)<sup>(1)</sup> taken by the load will be:

$$\blacksquare I_a = \frac{P_a \times 10^3}{V}$$

for single phase-to-neutral connected load

$$\blacksquare I_a = \frac{P_a \times 10^3}{\sqrt{3} \times U}$$

for three-phase balanced load where:

$V$  = phase-to-neutral voltage (volts)

$U$  = phase-to-phase voltage (volts)

It may be noted that, strictly speaking, the total kVA of apparent power is not the arithmetical sum of the calculated kVA ratings of individual loads (unless all loads are at the same power factor).

It is common practice however, to make a simple arithmetical summation, the result of which will give a kVA value that exceeds the true value by an acceptable "design margin".

When some or all of the load characteristics are not known, the values shown in **Figure A9** next page may be used to give a very approximate estimate of VA demands (individual loads are generally too small to be expressed in kVA or kW). The estimates for lighting loads are based on floor areas of 500 m<sup>2</sup>.

(1) For greater precision, account must be taken of the factor of maximum utilization as explained below in 4.3

Fluorescent lighting (corrected to $\cos \varphi = 0.86$ )		
Type of application	Estimated (VA/m <sup>2</sup> ) fluorescent tube with industrial reflector <sup>(1)</sup>	Average lighting level (lux = lm/m <sup>2</sup> )
Roads and highways storage areas, intermittent work	7	150
Heavy-duty works: fabrication and assembly of very large work pieces	14	300
Day-to-day work: office work	24	500
Fine work: drawing offices high-precision assembly workshops	41	800
Power circuits		
Type of application	Estimated (VA/m <sup>2</sup> )	
Pumping station compressed air	3 to 6	
Ventilation of premises	23	
Electrical convection heaters:		
private houses	115 to 146	
flats and apartments	90	
Offices	25	
Dispatching workshop	50	
Assembly workshop	70	
Machine shop	300	
Painting workshop	350	
Heat-treatment plant	700	
(1) example: 65 W tube (ballast not included), flux 5,100 lumens (lm), luminous efficiency of the tube = 78.5 lm / W.		

Fig. A9 : Estimation of installed apparent power

### 4.3 Estimation of actual maximum kVA demand

All individual loads are not necessarily operating at full rated nominal power nor necessarily at the same time. Factors  $k_u$  and  $k_s$  allow the determination of the maximum power and apparent-power demands actually required to dimension the installation.

#### Factor of maximum utilization ( $k_u$ )

In normal operating conditions the power consumption of a load is sometimes less than that indicated as its nominal power rating, a fairly common occurrence that justifies the application of an utilization factor ( $k_u$ ) in the estimation of realistic values. This factor must be applied to each individual load, with particular attention to electric motors, which are very rarely operated at full load.

In an industrial installation this factor may be estimated on an average at 0.75 for motors.

For incandescent-lighting loads, the factor always equals 1.

For socket-outlet circuits, the factors depend entirely on the type of appliances being supplied from the sockets concerned.

#### Factor of simultaneity ( $k_s$ )

It is a matter of common experience that the simultaneous operation of all installed loads of a given installation never occurs in practice, i.e. there is always some degree of diversity and this fact is taken into account for estimating purposes by the use of a simultaneity factor ( $k_s$ ).

The factor  $k_s$  is applied to each group of loads (e.g. being supplied from a distribution or sub-distribution board). The determination of these factors is the responsibility of the designer, since it requires a detailed knowledge of the installation and the conditions in which the individual circuits are to be exploited. For this reason, it is not possible to give precise values for general application.

#### Factor of simultaneity for an apartment block

Some typical values for this case are given in **Figure A10** opposite page, and are applicable to domestic consumers supplied at 230/400 V (3-phase 4-wires). In the case of consumers using electrical heat-storage units for space heating, a factor of 0.8 is recommended, regardless of the number of consumers.

Number of downstream consumers	Factor of simultaneity (ks)
2 to 4	1
5 to 9	0.78
10 to 14	0.63
15 to 19	0.53
20 to 24	0.49
25 to 29	0.46
30 to 34	0.44
35 to 39	0.42
40 to 49	0.41
50 and more	0.40

Fig. A10 : Simultaneity factors in an apartment block

**Example** (see Fig. A11):

5 storeys apartment building with 25 consumers, each having 6 kVA of installed load.

The total installed load for the building is:  $36 + 24 + 30 + 36 + 24 = 150$  kVA

The apparent-power supply required for the building is:  $150 \times 0.46 = 69$  kVA

From Figure A10, it is possible to determine the magnitude of currents in different sections of the common main feeder supplying all floors. For vertical rising mains fed at ground level, the cross-sectional area of the conductors can evidently be progressively reduced from the lower floors towards the upper floors.

These changes of conductor size are conventionally spaced by at least 3-floor intervals.

In the example, the current entering the rising main at ground level is:

$$\frac{150 \times 0.46 \times 10^3}{400 \sqrt{3}} = 100 \text{ A}$$

the current entering the third floor is:

$$\frac{(36 + 24) \times 0.63 \times 10^3}{400 \sqrt{3}} = 55 \text{ A}$$

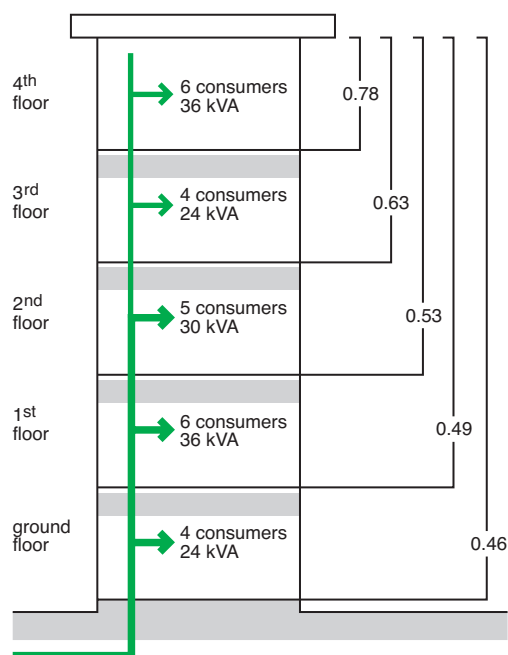


Fig. A11 : Application of the factor of simultaneity (ks) to an apartment block of 5 storeys

### Factor of simultaneity for distribution boards

**Figure A12** shows hypothetical values of  $k_s$  for a distribution board supplying a number of circuits for which there is no indication of the manner in which the total load divides between them.

If the circuits are mainly for lighting loads, it is prudent to adopt  $k_s$  values close to unity.

Number of circuits	Factor of simultaneity ( $k_s$ )
Assemblies entirely tested 2 and 3	0.9
4 and 5	0.8
6 to 9	0.7
10 and more	0.6
Assemblies partially tested in every case choose	1.0

**Fig. A12** : Factor of simultaneity for distribution boards (IEC 60439)

### Factor of simultaneity according to circuit function

$k_s$  factors which may be used for circuits supplying commonly-occurring loads, are shown in **Figure A13**.

Circuit function	Factor of simultaneity ( $k_s$ )
Lighting	1
Heating and air conditioning	1
Socket-outlets	0.1 to 0.2 <sup>(1)</sup>
Lifts and catering hoist <sup>(2)</sup>	<div> <div>■ For the most powerful motor</div> <div>■ For the second most powerful motor</div> <div>■ For all motors</div> </div>
	1 0.75 0.60

(1) In certain cases, notably in industrial installations, this factor can be higher.

(2) The current to take into consideration is equal to the nominal current of the motor, increased by a third of its starting current.

**Fig. A13** : Factor of simultaneity according to circuit function

## 4.4 Example of application of factors $k_u$ and $k_s$

An example in the estimation of actual maximum kVA demands at all levels of an installation, from each load position to the point of supply is given **Fig. A14** (opposite page).

In this example, the total installed apparent power is 126.6 kVA, which corresponds to an actual (estimated) maximum value at the LV terminals of the MV/LV transformer of 65 kVA only.

**Note:** in order to select cable sizes for the distribution circuits of an installation, the current  $I$  (in amps) through a circuit is determined from the equation:

$$I = \frac{kVA \times 10^3}{U \sqrt{3}}$$

where kVA is the actual maximum 3-phase apparent-power value shown on the diagram for the circuit concerned, and  $U$  is the phase-to-phase voltage (in volts).

## 4.5 Diversity factor

The term diversity factor, as defined in IEC standards, is identical to the factor of simultaneity ( $k_s$ ) used in this guide, as described in 4.3. In some English-speaking countries however (at the time of writing) diversity factor is the inverse of  $k_s$  i.e. it is always  $\geq 1$ .

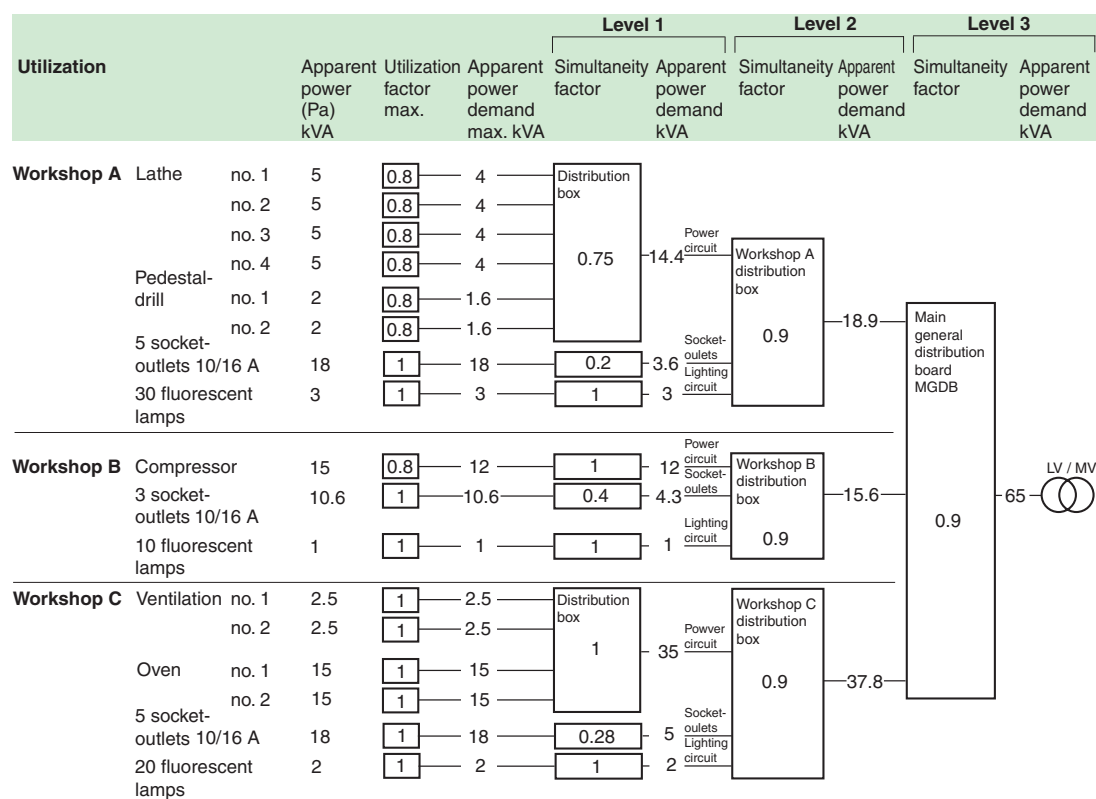


Fig A14 : An example in estimating the maximum predicted loading of an installation (the factor values used are for demonstration purposes only)

## 4.6 Choice of transformer rating

When an installation is to be supplied directly from a MV/LV transformer and the maximum apparent-power loading of the installation has been determined, a suitable rating for the transformer can be decided, taking into account the following considerations (see Fig. A15):

- The possibility of improving the power factor of the installation (see chapter L)
- Anticipated extensions to the installation
- Installation constraints (e.g. temperature)
- Standard transformer ratings

Apparent power kVA	In (A)	
	237 V	410 V
100	244	141
160	390	225
250	609	352
315	767	444
400	974	563
500	1218	704
630	1535	887
800	1949	1127
1000	2436	1408
1250	3045	1760
1600	3898	2253
2000	4872	2816
2500	6090	3520
3150	7673	4436

Fig. A15 : Standard apparent powers for MV/LV transformers and related nominal output currents

The nominal full-load current  $I_n$  on the LV side of a 3-phase transformer is given by:

$$I_n = \frac{Pa \times 10^3}{U \sqrt{3}}$$

where

- $Pa$  = kVA rating of the transformer
- $U$  = phase-to-phase voltage at no-load in volts (237 V or 410 V)
- $I_n$  is in amperes.

For a single-phase transformer:

$$I_n = \frac{Pa \times 10^3}{V}$$

where

- $V$  = voltage between LV terminals at no-load (in volts)

Simplified equation for 400 V (3-phase load)

- $I_n = \text{kVA} \times 1.4$

The IEC standard for power transformers is IEC 60076.

## 4.7 Choice of power-supply sources

The importance of maintaining a continuous supply raises the question of the use of standby-power plant. The choice and characteristics of these alternative sources are part of the architecture selection, as described in chapter D.

For the main source of supply the choice is generally between a connection to the MV or the LV network of the power-supply utility.

In practice, connection to a MV source may be necessary where the load exceeds (or is planned eventually to exceed) a certain level - generally of the order of 250 kVA, or if the quality of service required is greater than that normally available from a LV network.

Moreover, if the installation is likely to cause disturbance to neighbouring consumers, when connected to a LV network, the supply authorities may propose a MV service.

Supplies at MV can have certain advantages: in fact, a MV consumer:

- Is not disturbed by other consumers, which could be the case at LV
- Is free to choose any type of LV earthing system
- Has a wider choice of economic tariffs
- Can accept very large increases in load

It should be noted, however, that:

- The consumer is the owner of the MV/LV substation and, in some countries, he must build and equip it at his own expense. The power utility can, in certain circumstances, participate in the investment, at the level of the MV line for example
- A part of the connection costs can, for instance, often be recovered if a second consumer is connected to the MV line within a certain time following the original consumer's own connection
- The consumer has access only to the LV part of the installation, access to the MV part being reserved to the utility personnel (meter reading, operations, etc.). However, in certain countries, the MV protective circuit-breaker (or fused load-break switch) can be operated by the consumer
- The type and location of the substation are agreed between the consumer and the utility



# Chapter B

## Connection to the MV utility distribution network

B1

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# 1 Supply of power at medium voltage

B2

The main features which characterize a power-supply system include:

- The nominal voltage and related insulation levels
- The short-circuit current
- The rated normal current of items of plant and equipment
- The earthing system

The term "medium voltage" is commonly used for distribution systems with voltages above 1 kV and generally applied up to and including 52 kV (see IEC 601-01-28 Standard).

In this chapter, distribution networks which operate at voltages of 1,000 V or less are referred to as Low-Voltage systems, while systems of power distribution which require one stage of stepdown voltage transformation, in order to feed into low voltage networks, will be referred to as Medium- Voltage systems.

For economic and technical reasons the nominal voltage of medium-voltage distribution systems, as defined above, seldom exceeds 35 kV.

## 1.1 Power supply characteristics of medium voltage utility distribution network

### Nominal voltage and related insulation levels

The nominal voltage of a system or of an equipment is defined in IEC 60038 Standard as "the voltage by which a system or equipment is designated and to which certain operating characteristics are referred". Closely related to the nominal voltage is the "highest voltage for equipment" which concerns the level of insulation at normal working frequency, and to which other characteristics may be referred in relevant equipment recommendations.

The "highest voltage for equipment" is defined in IEC 60038 Standard as:

"the maximum value of voltage for which equipment may be used, that occurs under normal operating conditions at any time and at any point on the system. It excludes voltage transients, such as those due to system switching, and temporary voltage variations".

#### Notes:

- 1- The highest voltage for equipment is indicated for nominal system voltages higher than 1,000 V only. It is understood that, particularly for some categories of equipment, normal operation cannot be ensured up to this "highest voltage for equipment", having regard to voltage sensitive characteristics such as losses of capacitors, magnetizing current of transformers, etc. In such cases, IEC standards specify the limit to which the normal operation of this equipment can be ensured.
- 2- It is understood that the equipment to be used in systems having nominal voltage not exceeding 1,000 V should be specified with reference to the nominal system voltage only, both for operation and for insulation.
- 3- The definition for "highest voltage for equipment" given in IEC 60038 Standard is identical to the definition given in IEC 62271-1 Standard for "rated voltage". IEC 62271-1 Standard concerns switchgear for voltages exceeding 1,000 V.

The following values of **Figure B1**, taken from IEC 60038 Standard, list the most-commonly used standard levels of medium-voltage distribution, and relate the nominal voltages to corresponding standard values of "Highest Voltage for Equipment".

These systems are generally three-wire systems unless otherwise indicated. The values shown are voltages between phases.

The values indicated in parentheses should be considered as non-preferred values. It is recommended that these values should not be used for new systems to be constructed in future.

It is recommended that in any one country the ratio between two adjacent nominal voltages should be not less than two.

Series I (for 50 Hz and 60 Hz networks)		
Nominal system voltage		Highest voltage for equipment
(kV)	(kV)	
3.3 <sup>(1)</sup>	3 <sup>(1)</sup>	3.6 <sup>(1)</sup>
6.6 <sup>(1)</sup>	6 <sup>(1)</sup>	7.2 <sup>(1)</sup>
11	10	12
-	15	17.5
22	20	24
33 <sup>(2)</sup>	-	36 <sup>(2)</sup>
-	35 <sup>(2)</sup>	40.5 <sup>(2)</sup>

(1) These values should not be used for public distribution systems.

(2) The unification of these values is under consideration.

**Fig. B1** : Relation between nominal system voltages and highest voltages for the equipment

# 1 Supply of power at medium voltage

B3

In order to ensure adequate protection of equipment against abnormally-medium short term power-frequency overvoltages, and transient overvoltages caused by lightning, switching, and system fault conditions, etc. all MV equipment must be specified to have appropriate rated insulation levels.

A "rated insulation level" is a set of specified dielectric withstand values covering various operating conditions. For MV equipment, in addition to the "highest voltage for equipment", it includes lightning impulse withstand and short-duration power frequency withstand.

## Switchgear

**Figure B2** shown below, lists normal values of "withstand" voltage requirements from IEC 62271-1 Standard. The choice between List 1 and List 2 values of table B2 depends on the degree of exposure to lightning and switching overvoltages<sup>(1)</sup>, the type of neutral earthing, and the type of overvoltage protection devices, etc. (for further guidance reference should be made to IEC 60071).

Rated voltage U (r.m.s. value)	Rated lightning impulse withstand voltage (peak value)				Rated short-duration power-frequency withstand voltage (r.m.s. value)	
	List 1		List 2			
	To earth, between poles and across open switching device (kV)	Across the isolating distance (kV)	To earth, between poles and across open switching device (kV)	Across the isolating distance (kV)	To earth, between poles and across open switching device (kV)	Across the isolating distance (kV)
3.6	20	23	40	46	10	12
7.2	40	46	60	70	20	23
12	60	70	75	85	28	32
17.5	75	85	95	110	38	45
24	95	110	125	145	50	60
36	145	165	170	195	70	80
52	-	-	250	290	95	110
72.5	-	-	325	375	140	160

**Note:** The withstand voltage values "across the isolating distance" are valid only for the switching devices where the clearance between open contacts is designed to meet requirements specified for disconnectors (isolators).

**Fig. B2 :** Switchgear rated insulation levels

It should be noted that, at the voltage levels in question, no switching overvoltage ratings are mentioned. This is because overvoltages due to switching transients are less severe at these voltage levels than those due to lightning.

## Transformers

**Figure B3** shown below have been extracted from IEC 60076-3.

The significance of list 1 and list 2 is the same as that for the switchgear table, i.e. the choice depends on the degree of exposure to lightning, etc.

Highest voltage for equipment (r.m.s.)  (kV)	Rated short duration power frequency withstand voltage (r.m.s.) (kV)	Rated lightning impulse withstand voltage (peak)	
		List 1 (kV)	List 2 (kV)
≤ 1.1	3	-	-
3.6	10	20	40
7.2	20	40	60
12	28	60	75
17.5	38	75	95
24	50	95	125
36	70	145	170
52	95	250	
72.5	140	325	

**Fig. B3 :** Transformers rated insulation levels

(1) This means basically that List 1 generally applies to switchgear to be used on underground-cable systems while List 2 is chosen for switchgear to be used on overhead-line systems.

*The national standards of any particular country are normally rationalized to include one or two levels only of voltage, current, and fault-levels, etc.*

*A circuit-breaker (or fuse switch, over a limited voltage range) is the only form of switchgear capable of safely breaking all kinds of fault currents occurring on a power system.*

## Other components

It is evident that the insulation performance of other MV components associated with these major items, e.g. porcelain or glass insulators, MV cables, instrument transformers, etc. must be compatible with that of the switchgear and transformers noted above. Test schedules for these items are given in appropriate IEC publications.

The national standards of any particular country are normally rationalized to include one or two levels only of voltage, current, and fault-levels, etc.

## General note:

The IEC standards are intended for worldwide application and consequently embrace an extensive range of voltage and current levels. These reflect the diverse practices adopted in countries of different meteorologic, geographic and economic constraints.

## Short-circuit current

Standard values of circuit-breaker short-circuit current-breaking capability are normally given in kilo-amperes.

These values refer to a 3-phase short-circuit condition, and are expressed as the average of the r.m.s. values of the AC component of current in each of the three phases.

For circuit-breakers in the rated voltage ranges being considered in this chapter, **Figure B4** gives standard short-circuit current-breaking ratings.

kV	3.6	7.2	12	17.5	24	36	52
kA	8	8	8	8	8	8	8
(rms)	10	12.5	12.5	12.5	12.5	12.5	12.5
	16	16	16	16	16	16	20
	25	25	25	25	25	25	
	40	40	40	40	40	40	
			50				

**Fig. B4** : Standard short-circuit current-breaking ratings

## Short-circuit current calculation

The rules for calculating short-circuit currents in electrical installations are presented in IEC standard 60909.

The calculation of short-circuit currents at various points in a power system can quickly turn into an arduous task when the installation is complicated.

The use of specialized software accelerates calculations.

This general standard, applicable for all radial and meshed power systems, 50 or 60 Hz and up to 550 kV, is extremely accurate and conservative.

It may be used to handle the different types of solid short-circuit (symmetrical or dissymmetrical) that can occur in an electrical installation:

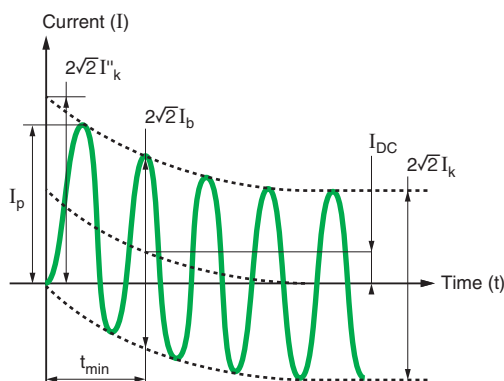
- Three-phase short-circuit (all three phases), generally the type producing the highest currents
- Two-phase short-circuit (between two phases), currents lower than three-phase faults
- Two-phase-to-earth short-circuit (between two phases and earth)
- Phase-to-earth short-circuit (between a phase and earth), the most frequent type (80% of all cases).

When a fault occurs, the transient short-circuit current is a function of time and comprises two components (see **Fig. B5**).

- An AC component, decreasing to its steady-state value, caused by the various rotating machines and a function of the combination of their time constants
- A DC component, decreasing to zero, caused by the initiation of the current and a function of the circuit impedances

Practically speaking, one must define the short-circuit values that are useful in selecting system equipment and the protection system:

- $I''_k$ : rms value of the initial symmetrical current
- $I_b$ : rms value of the symmetrical current interrupted by the switching device when the first pole opens at  $t_{min}$  (minimum delay)
- $I_k$ : rms value of the steady-state symmetrical current
- $I_p$ : maximum instantaneous value of the current at the first peak
- $I_{DC}$ : DC value of the current



**Fig. B5** : Graphic representation of short-circuit quantities as per IEC 60909

These currents are identified by subscripts 3, 2, 2E, 1, depending on the type of short-circuit, respectively three-phase, two-phase clear of earth, two-phase-to-earth, phase-to-earth.

The method, based on the Thevenin superposition theorem and decomposition into symmetrical components, consists in applying to the short-circuit point an equivalent source of voltage in view of determining the current. The calculation takes place in three steps.

- Define the equivalent source of voltage applied to the fault point. It represents the voltage existing just before the fault and is the rated voltage multiplied by a factor taking into account source variations, transformer on-load tap changers and the subtransient behavior of the machines.
- Calculate the impedances, as seen from the fault point, of each branch arriving at this point. For positive and negative-sequence systems, the calculation does not take into account line capacitances and the admittances of parallel, non-rotating loads.
- Once the voltage and impedance values are defined, calculate the characteristic minimum and maximum values of the short-circuit currents.

The various current values at the fault point are calculated using:

- The equations provided
- A summing law for the currents flowing in the branches connected to the node:
  - $I''_k$  (see **Fig. B6** for  $I''_k$  calculation, where voltage factor  $c$  is defined by the standard; geometric or algebraic summing)
  - $I_p = \kappa \times 2 \times I''_k$ , where  $\kappa$  is less than 2, depending on the R/X ratio of the positive sequence impedance for the given branch; peak summing
  - $I_b = \mu \times q \times I''_k$ , where  $\mu$  and  $q$  are less than 1, depending on the generators and motors, and the minimum current interruption delay; algebraic summing
  - $I_k = I''_k$ , when the fault is far from the generator
  - $I_k = \lambda \times I_p$ , for a generator, where  $I_r$  is the rated generator current and  $\lambda$  is a factor depending on its saturation inductance; algebraic summing.

Type of short-circuit	$I''_k$	
	General situation	Distant faults
3-phase	$\frac{c U_n}{\sqrt{3} Z_1}$	$\frac{c U_n}{\sqrt{3} Z_1}$
2-phase	$\frac{c U_n}{Z_1 + Z_2}$	$\frac{c U_n}{2Z_1}$
2-phase-to-earth	$\frac{c U_n \sqrt{3} Z_2}{Z_1 Z_2 + Z_2 Z_0 + Z_1 Z_0}$	$\frac{c U_n \sqrt{3}}{Z_1 + 2Z_0}$
Phase-to-earth	$\frac{c U_n \sqrt{3}}{Z_1 + Z_2 + Z_0}$	$\frac{c U_n \sqrt{3}}{2 Z_1 + Z_0}$

**Fig. B6** : Short-circuit currents as per IEC 60909

## Characterization

There are 2 types of system equipment, based on whether or not they react when a fault occurs.

### Passive equipment

This category comprises all equipment which, due to its function, must have the capacity to transport both normal current and short-circuit current. This equipment includes cables, lines, busbars, disconnecting switches, switches, transformers, series reactances and capacitors, instrument transformers.

For this equipment, the capacity to withstand a short-circuit without damage is defined in terms of:

- Electrodynamic withstand ("peak withstand current"; value of the peak current expressed in kA), characterizing mechanical resistance to electrodynamic stress
- Thermal withstand ("short time withstand current"; rms value expressed in kA for duration between 0,5 and 3 seconds, with a preferred value of 1 second), characterizing maximum permissible heat dissipation.

## Active equipment

This category comprises the equipment designed to clear short-circuit currents, i.e. circuit-breakers and fuses. This property is expressed by the breaking capacity and, if required, the making capacity when a fault occurs.

### ■ Breaking capacity (see Fig. B7)

This basic characteristic of a fault interrupting device is the maximum current (rms value expressed in kA) it is capable of breaking under the specific conditions defined by the standards; in the IEC 62271-100 standard, it refers to the rms value of the AC component of the short-circuit current. In some other standards, the rms value of the sum of the 2 components (AC and DC) is specified, in which case, it is the "asymmetrical current".

The breaking capacity depends on other factors such as:

- Voltage
- R/X ratio of the interrupted circuit
- Power system natural frequency
- Number of breaking operations at maximum current, for example the cycle: O - C/O - C/O (O = opening, C = closing)

The breaking capacity is a relatively complicated characteristic to define and it therefore comes as no surprise that the same device can be assigned different breaking capacities depending on the standard by which it is defined.

### ■ Short-circuit making capacity

In general, this characteristic is implicitly defined by the breaking capacity because a device should be able to close for a current that it can break.

Sometimes, the making capacity needs to be higher, for example for circuit-breakers protecting generators.

The making capacity is defined in terms of peak value (expressed in kA) because the first asymmetric peak is the most demanding from an electrodynamic point of view.

For example, according to standard IEC 62271-100, a circuit-breaker used in a 50 Hz power system must be able to handle a peak making current equal to 2.5 times the rms breaking current (2.6 times for 60 Hz systems).

Making capacity is also required for switches, and sometimes for disconnectors, even if these devices are not able to clear the fault.

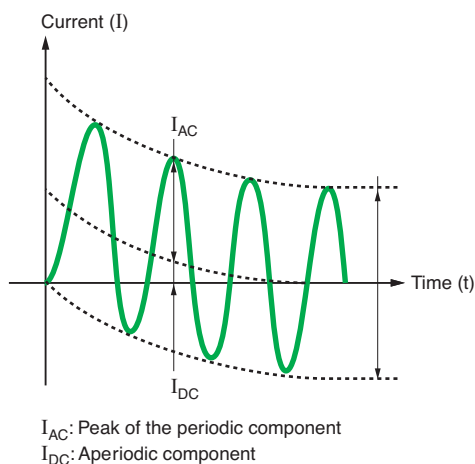
### ■ Prospective short-circuit breaking current

Some devices have the capacity to limit the fault current to be interrupted.

Their breaking capacity is defined as the maximum prospective breaking current that would develop during a solid short-circuit across the upstream terminals of the device.

## Specific device characteristics

The functions provided by various interrupting devices and their main constraints are presented in **Figure B8**.



**Fig. B7 :** Rated breaking current of a circuit-breaker subjected to a short-circuit as per IEC 60056

Device	Isolation of two active networks	Current switching conditions		Main constraints
		Normal	Fault	
Disconnector	Yes	No	No	Longitudinal input/output isolation
Switch	No	Yes	No	Making and breaking of normal load current Short-circuit making capacity
Contactor	No	Yes	No	Rated making and breaking capacities Maximum making and breaking capacities Duty and endurance characteristics
Circuit-breaker	No	Yes	Yes	Short-circuit breaking capacity Short-circuit making capacity
Fuse	No	No	Yes	Minimum short-circuit breaking capacity Maximum short-circuit breaking capacity

**Fig. B8 :** Functions provided by interrupting devices

*The most common normal current rating for general-purpose MV distribution switchgear is 400 A.*

## Rated normal current

The rated normal current is defined as "the r.m.s. value of the current which can be carried continuously at rated frequency with a temperature rise not exceeding that specified by the relevant product standard".

The rated normal current requirements for switchgear are decided at the substation design stage.

The most common normal current rating for general-purpose MV distribution switchgear is 400 A.

In industrial areas and medium-load-density urban districts, circuits rated at 630 A are sometimes required, while at bulk-supply substations which feed into MV networks,

800 A; 1,250 A; 1,600 A; 2,500 A and 4,000 A circuit-breakers are listed as standard ratings for incoming-transformer circuits, bus-section and bus-coupler CBs, etc.

For MV/LV transformer with a normal primary current up to roughly 60 A, a MV switch-fuse combination can be used. For higher primary currents, switch-fuse combination usually does not have the required performances.

There are no IEC-recommended rated current values for switch-fuse combinations.

The actual rated current of a given combination, meaning a switchgear base and defined fuses, is provided by the manufacturer of the combination as a table "fuse reference / rated current". These values of the rated current are defined by considering parameters of the combination as:

- Normal thermal current of the fuses
- Necessary derating of the fuses, due to their usage within the enclosure.

When combinations are used for protecting transformers, then further parameters are to be considered, as presented in Appendix A of the IEC 62271-105 and in the IEC 60787. They are mainly:

- The normal MV current of the transformer
- The possible need for overloading the transformer
- The inrush magnetizing current
- The MV short-circuit power
- The tapping switch adjustment range.

Manufacturers usually provide an application table "service voltage / transformer power / fuse reference" based on standard distribution network and transformer parameters, and such table should be used with care, if dealing with unusual installations.

In such a scheme, the load-break switch should be suitably fitted with a tripping device e.g. with a relay to be able to trip at low fault-current levels which must cover (by an appropriate margin) the rated minimum breaking current of the MV fuses. In this way, medium values of fault current which are beyond the breaking capability of the load-break switch will be cleared by the fuses, while low fault-current values, that cannot be correctly cleared by the fuses, will be cleared by the tripped load-break switch.

## Influence of the ambient temperature and altitude on the rated current

Normal-current ratings are assigned to all current-carrying electrical appliances, and upper limits are decided by the acceptable temperature rise caused by the  $I^2R$  (watts) dissipated in the conductors, (where  $I$  = r.m.s. current in amperes and  $R$  = the resistance of the conductor in ohms), together with the heat produced by magnetic-hysteresis and eddy-current losses in motors, transformers, steel enclosures, etc. and dielectric losses in cables and capacitors, where appropriate.

The temperature rise above the ambient temperature will depend mainly on the rate at which the heat is removed. For example, large currents can be passed through electric motor windings without causing them to overheat, simply because a cooling fan fixed to the shaft of the motor removes the heat at the same rate as it is produced, and so the temperature reaches a stable value below that which could damage the insulation and result in a burnt-out motor.

The normal-current values recommended by IEC are based on ambient-air temperatures common to temperate climates at altitudes not exceeding 1,000 metres, so that items which depend on natural cooling by radiation and air-convection will overheat if operated at rated normal current in a tropical climate and/ or at altitudes exceeding 1,000 metres. In such cases, the equipment has to be derated, i.e. be assigned a lower value of normal current rating.

The case of transformer is addressed in IEC 60076-2.



B8

Earth faults on medium-voltage systems can produce dangerous voltage levels on LV installations. LV consumers (and substation operating personnel) can be safeguarded against this danger by:

- Restricting the magnitude of MV earth-fault currents
- Reducing the substation earthing resistance to the lowest possible value
- Creating equipotential conditions at the substation and at the consumer's installation

## Earthing systems

Earthing and equipment-bonding earth connections require careful consideration, particularly regarding safety of the LV consumer during the occurrence of a short-circuit to earth on the MV system.

### Earth electrodes

In general, it is preferable, where physically possible, to separate the electrode provided for earthing exposed conductive parts of MV equipment from the electrode intended for earthing the LV neutral conductor. This is commonly practised in rural systems where the LV neutral-conductor earth electrode is installed at one or two spans of LV distribution line away from the substation.

In most cases, the limited space available in urban substations precludes this practice, i.e. there is no possibility of separating a MV electrode sufficiently from a LV electrode to avoid the transference of (possibly dangerous) voltages to the LV system.

### Earth-fault current

Earth-fault current levels at medium voltage are generally (unless deliberately restricted) comparable to those of a 3-phase short-circuit.

Such currents passing through an earth electrode will raise its voltage to a medium value with respect to "remote earth" (the earth surrounding the electrode will be raised to a medium potential; "remote earth" is at zero potential).

For example, 10,000 A of earth-fault current passing through an electrode with an (unusually low) resistance of 0.5 ohms will raise its voltage to 5,000 V.

Providing that all exposed metal in the substation is "bonded" (connected together) and then connected to the earth electrode, and the electrode is in the form of (or is connected to) a grid of conductors under the floor of the substation, then there is no danger to personnel, since this arrangement forms an equipotential "cage" in which all conductive material, including personnel, is raised to the same potential.

### Transferred potential

A danger exists however from the problem known as Transferred Potential. It will be seen in **Figure B9** that the neutral point of the LV winding of the MV/LV transformer is also connected to the common substation earth electrode, so that the neutral conductor, the LV phase windings and all phase conductors are also raised to the electrode potential.

Low-voltage distribution cables leaving the substation will transfer this potential to consumers installations. It may be noted that there will be no LV insulation failure between phases or from phase to neutral since they are all at the same potential. It is probable, however, that the insulation between phase and earth of a cable or some part of an installation would fail.

### Solutions

A first step in minimizing the obvious dangers of transferred potentials is to reduce the magnitude of MV earth-fault currents. This is commonly achieved by earthing the MV system through resistors or reactors at the star points of selected transformers<sup>(1)</sup>, located at bulk-supply substations.

A relatively medium transferred potential cannot be entirely avoided by this means, however, and so the following strategy has been adopted in some countries.

The equipotential earthing installation at a consumer's premises represents a remote earth, i.e. at zero potential. However, if this earthing installation were to be connected by a low-impedance conductor to the earth electrode at the substation, then the equipotential conditions existing in the substation would also exist at the consumer's installation.

### Low-impedance interconnection

This low-impedance interconnection is achieved simply by connecting the neutral conductor to the consumer's equipotential installation, and the result is recognized as the TN earthing system (IEC 60364) as shown in diagram A of **Figure B10** next page.

The TN system is generally associated with a Protective Multiple Earthing (PME) scheme, in which the neutral conductor is earthed at intervals along its length (every 3<sup>rd</sup> or 4<sup>th</sup> pole on a LV overhead-line distributor) and at each consumer's service position. It can be seen that the network of neutral conductors radiating from a substation, each of which is earthed at regular intervals, constitutes, together with the substation earthing, a very effective low-resistance earth electrode.

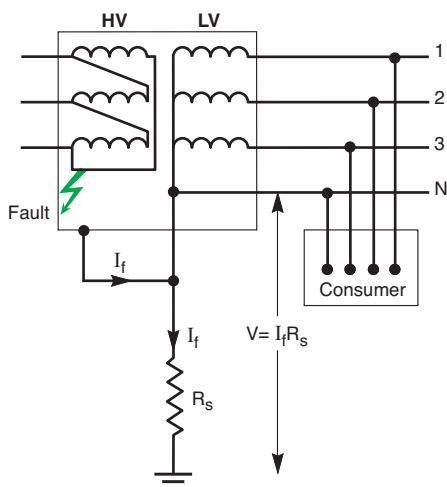
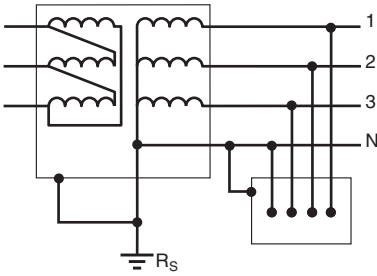
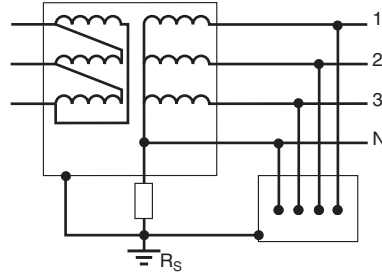
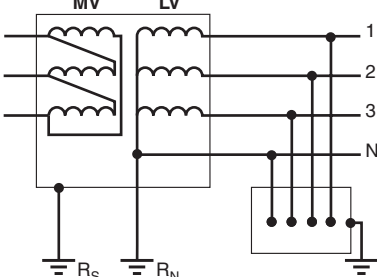
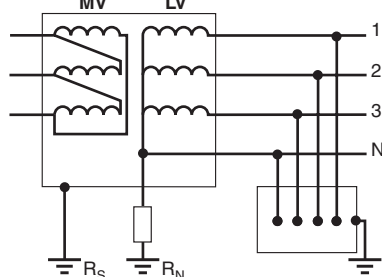
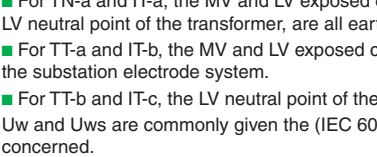
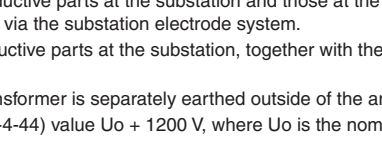


Fig. B9 : Transferred potential

(1) The others being unearthed. A particular case of earth-fault current limitation is by means of a Petersen coil.



Diagram	Rs value
<p><b>A - TN-a</b></p> 	<p><b>Cases A and B</b></p> <p>No particular resistance value for Rs is imposed in these cases</p>
<p><b>B - IT-a</b></p> 	<p><b>Cases C and D</b></p> $R_s \leq \frac{U_w - U_0}{I_m}$ <p>Where</p> <p><math>U_w</math> = the rated normal-frequency withstand voltage for low-voltage equipment at consumer installations</p> <p><math>U_0</math> = phase to neutral voltage at consumer's installations</p> <p><math>I_m</math> = maximum value of MV earth-fault current</p>
<p><b>C - TT-a</b></p> 	<p><b>Cases E and F</b></p> $R_s \leq \frac{U_{ws} - U}{I_m}$ <p>Where</p> <p><math>U_{ws}</math> = the normal-frequency withstand voltage for low-voltage equipments in the substation (since the exposed conductive parts of these equipments are earthed via Rs)</p> <p><math>U</math> = phase to neutral voltage at the substation for the TT(s) system, but the phase-to-phase voltage for the IT(s) system</p> <p><math>I_m</math> = maximum value of MV earth-fault current</p>
<p><b>D - IT-b</b></p> 	
<p><b>E - TT-b</b></p> 	
<p><b>F - IT-c</b></p> 	

In cases E and F the LV protective conductors (bonding exposed conductive parts) in the substation are earthed via the substation earth electrode, and it is therefore the substation LV equipment (only) that could be subjected to overvoltage.

#### Notes:

- For TN-a and IT-a, the MV and LV exposed conductive parts at the substation and those at the consumer's installations, together with the LV neutral point of the transformer, are all earthed via the substation electrode system.
  - For TT-a and IT-b, the MV and LV exposed conductive parts at the substation, together with the LV neutral point of the transformer are earthed via the substation electrode system.
  - For TT-b and IT-c, the LV neutral point of the transformer is separately earthed outside of the area of influence of the substation earth electrode.
- $U_w$  and  $U_{ws}$  are commonly given the (IEC 60364-4-44) value  $U_0 + 1200$  V, where  $U_0$  is the nominal phase-to-neutral voltage of the LV system concerned.

**Fig. B10** : Maximum earthing resistance  $R_s$  at a MV/LV substation to ensure safety during a short-circuit to earth fault on the medium-voltage equipment for different earthing systems

The combination of restricted earth-fault currents, equipotential installations and low resistance substation earthing, results in greatly reduced levels of overvoltage and limited stressing of phase-to-earth insulation during the type of MV earth-fault situation described above.

#### Limitation of the MV earth-fault current and earth resistance of the substation

Another widely-used earthing system is shown in diagram C of Figure B10. It will be seen that in the TT system, the consumer's earthing installation (being isolated from that of the substation) constitutes a remote earth.

This means that, although the transferred potential will not stress the phase-to-phase insulation of the consumer's equipment, the phase-to-earth insulation of all three phases will be subjected to overvoltage.

# 1 Supply of power at medium voltage

B10

The strategy in this case, is to reduce the resistance of the substation earth electrode, such that the standard value of 5-second withstand-voltage-to-earth for LV equipment and appliances will not be exceeded.

Practical values adopted by one national electrical power-supply authority, on its 20 kV distribution systems, are as follows:

- Maximum earth-fault current in the neutral connection on overhead line distribution systems, or mixed (O/H line and U/G cable) systems, is 300 A
- Maximum earth-fault current in the neutral connection on underground systems is 1,000 A

The formula required to determine the maximum value of earthing resistance  $R_s$  at the substation, to ensure that the LV withstand voltage will not be exceeded, is:

$$R_s = \frac{U_w - U_o}{I_m} \text{ in ohms (see cases C and D in Figure B10).}$$

Where

$U_w$  = the lowest standard value (in volts) of short-term (5 s) withstand voltage for the consumer's installation and appliances =  $U_o + 1200 \text{ V}$  (IEC 60364-4-44)

$U_o$  = phase to neutral voltage (in volts) at the consumer's LV service position

$I_m$  = maximum earth-fault current on the MV system (in amps). This maximum earth fault current  $I_m$  is the vectorial sum of maximum earth-fault current in the neutral connection and total unbalanced capacitive current of the network.

A third form of system earthing referred to as the "IT" system in IEC 60364 is commonly used where continuity of supply is essential, e.g. in hospitals, continuous-process manufacturing, etc. The principle depends on taking a supply from an unearthed source, usually a transformer, the secondary winding of which is unearthed, or earthed through a medium impedance ( $\geq 1,000 \text{ ohms}$ ). In these cases, an insulation failure to earth in the low-voltage circuits supplied from the secondary windings will result in zero or negligible fault-current flow, which can be allowed to persist until it is convenient to shut-down the affected circuit to carry out repair work.

## Diagrams B, D and F (Figure B10)

They show IT systems in which resistors (of approximately 1,000 ohms) are included in the neutral earthing lead.

If however, these resistors were removed, so that the system is unearthed, the following notes apply.

## Diagram B (Figure B10)

All phase wires and the neutral conductor are "floating" with respect to earth, to which they are "connected" via the (normally very medium) insulation resistances and (very small) capacitances between the live conductors and earthed metal (conduits, etc.).

Assuming perfect insulation, all LV phase and neutral conductors will be raised by electrostatic induction to a potential approaching that of the equipotential conductors.

In practice, it is more likely, because of the numerous earth-leakage paths of all live conductors in a number of installations acting in parallel, that the system will behave similarly to the case where a neutral earthing resistor is present, i.e. all conductors will be raised to the potential of the substation earth.

In these cases, the overvoltage stresses on the LV insulation are small or non-existent.

## Diagrams D and F (Figure B10)

In these cases, the medium potential of the substation (S/S) earthing system acts on the isolated LV phase and neutral conductors:

- Through the capacitance between the LV windings of the transformer and the transformer tank
- Through capacitance between the equipotential conductors in the S/S and the cores of LV distribution cables leaving the S/S
- Through current leakage paths in the insulation, in each case.

At positions outside the area of influence of the S/S earthing, system capacitances exist between the conductors and earth at zero potential (capacitances between cores are irrelevant - all cores being raised to the same potential).

The result is essentially a capacitive voltage divider, where each "capacitor" is shunted by (leakage path) resistances.

In general, LV cable and installation wiring capacitances to earth are much larger, and the insulation resistances to earth are much smaller than those of the corresponding parameters at the S/S, so that most of the voltage stresses appear at the substation between the transformer tank and the LV winding.

The rise in potential at consumers' installations is not likely therefore to be a problem where the MV earth-fault current level is restricted as previously mentioned.

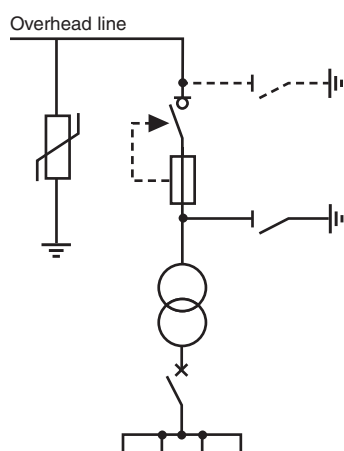


Fig. B11 : Single-line service

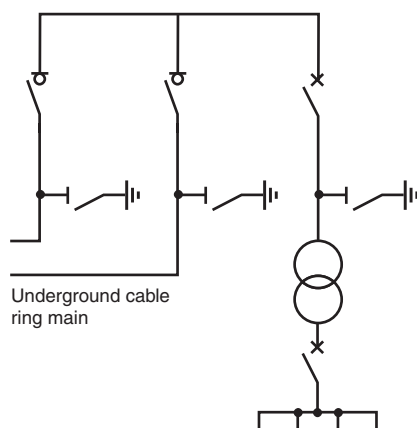


Fig. B12 : Ring-main service

(1) Copper is cathodic to most other metals and therefore resists corrosion.

(2) A ring main is a continuous distributor in the form of a closed loop, which originates and terminates on one set of busbars. Each end of the loop is controlled by its own circuit-breaker. In order to improve operational flexibility the busbars are often divided into two sections by a normally closed bus-section circuit-breaker, and each end of the ring is connected to a different section.

An interconnector is a continuous untapped feeder connecting the busbars of two substations. Each end of the interconnector is usually controlled by a circuit breaker.

An interconnector-distributor is an interconnector which supplies one or more distribution substations along its length.

All IT-earthed transformers, whether the neutral point is isolated or earthed through a medium impedance, are routinely provided with an overvoltage limiting device which will automatically connect the neutral point directly to earth if an overvoltage condition approaches the insulation-withstand level of the LV system.

In addition to the possibilities mentioned above, several other ways in which these overvoltages can occur are described in Clause 3.1.

This kind of earth-fault is very rare, and when does occur is quickly detected and cleared by the automatic tripping of a circuit-breaker in a properly designed and constructed installation.

Safety in situations of elevated potentials depends entirely on the provision of properly arranged equipotential areas, the basis of which is generally in the form of a widemeshed grid of interconnected bare copper conductors connected to vertically-driven copper-clad<sup>(1)</sup> steel rods.

The equipotential criterion to be respected is that which is mentioned in Chapter F dealing with protection against electric shock by indirect contact, namely: that the potential between any two exposed metal parts which can be touched simultaneously by any parts the body must never, under any circumstances, exceed 50 V in dry conditions, or 25 V in wet conditions.

Special care should be taken at the boundaries of equipotential areas to avoid steep potential gradients on the surface of the ground which give rise to dangerous "step potentials".

This question is closely related to the safe earthing of boundary fences and is further discussed in Sub-clause 3.1.

## 1.2 Different MV service connections

According to the type of medium-voltage network, the following supply arrangements are commonly adopted.

### Single-line service

The substation is supplied by a single circuit tee-off from a MV distributor (cable or line).

In general, the MV service is connected into a panel containing a load-break/ isolating switch-fuse combination and earthing switches, as shown in **Figure B11**.

In some countries a pole-mounted transformer with no MV switchgear or fuses (at the pole) constitutes the "substation". This type of MV service is very common in rural areas.

Protection and switching devices are remote from the transformer, and generally control a main overhead line, from which a number of these elementary service lines are tapped.

### Ring-main service

Ring-main units (RMU) are normally connected to form a MV ring main<sup>(2)</sup> or interconnector-distributor<sup>(2)</sup>, such that the RMU busbars carry the full ring-main or interconnector current (see **Fig. B12**).

The RMU consists of three units, integrated to form a single assembly, viz:

- 2 incoming units, each containing a load break/isolating switch and a circuit earthing switch
- 1 outgoing and general protection unit, containing a load-break switch and MV fuses, or a combined load-break/fuse switch, or a circuit-breaker and isolating switch, together with a circuit-earthing switch in each case.

All load-break switches and earthing switches are fully rated for short-circuit current-making duty.

This arrangement provides the user with a two-source supply, thereby reducing considerably any interruption of service due to system faults or operations by the supply authority, etc.

The main application for RMUs is in utility supply MV underground-cable networks in urban areas.

## Parallel feeders service

Where a MV supply connection to two lines or cables originating from the same busbar of a substation is possible, a similar MV switchboard to that of a RMU is commonly used (see **Fig. B13**).

The main operational difference between this arrangement and that of a RMU is that the two incoming panels are mutually interlocked, such that one incoming switch only can be closed at a time, i.e. its closure prevents the closure of the other.

On the loss of power supply, the closed incoming switch must be opened and the (formerly open) switch can then be closed.

The sequence may be carried out manually or automatically.

This type of switchboard is used particularly in networks of medium-load density and in rapidly-expanding urban areas supplied by MV underground cable systems.

## 1.3 Some operational aspects of MV distribution networks

### Overhead lines

Medium winds, ice formation, etc., can cause the conductors of overhead lines to touch each other, thereby causing a momentary (i.e. not permanent) short-circuit fault.

Insulation failure due to broken ceramic or glass insulators, caused by air-borne debris; careless use of shot-guns, etc., or again, heavily polluted insulator surfaces, can result in a short-circuit to earth.

Many of these faults are self-clearing. For example, in dry conditions, broken insulators can very often remain in service undetected, but are likely to flashover to earth (e.g. to a metal supporting structure) during a rainstorm. Moreover, polluted surfaces generally cause a flashover to earth only in damp conditions.

The passage of fault current almost invariably takes the form of an electric arc, the intense heat of which dries the current path, and to some extent, re-establishes its insulating properties. In the meantime, protective devices have usually operated to clear the fault, i.e. fuses have blown or a circuit-breaker has tripped.

Experience has shown that in the large majority of cases, restoration of supply by replacing fuses or by re-closing a circuit-breaker will be successful.

For this reason it has been possible to considerably improve the continuity of service on MV overhead-line distribution networks by the application of automatic circuit-breaker reclosing schemes at the origin of the circuits concerned.

These automatic schemes permit a number of reclosing operations if a first attempt fails, with adjustable time delays between successive attempts (to allow de-ionization of the air at the fault) before a final lock-out of the circuit-breaker occurs, after all (generally three) attempts fail.

Other improvements in service continuity are achieved by the use of remotely-controlled section switches and by automatic isolating switches which operate in conjunction with an auto-reclosing circuit-breaker.

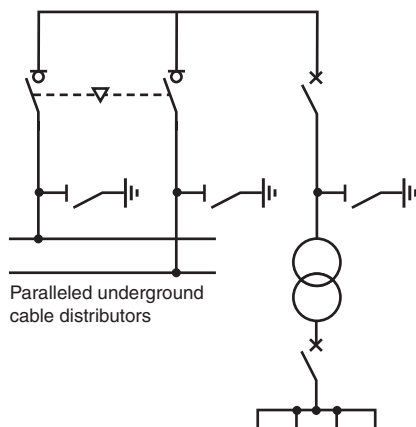
This last scheme is exemplified by the final sequence shown in **Figure B14** next page.

The principle is as follows: if, after two reclosing attempts, the circuit-breaker trips, the fault is assumed to be permanent, then there are two possibilities:

- The fault is on the section downstream the Automatic Line Switch, and while the feeder is dead the ALS opens to isolate this section of the network, before the third (and final) reclosing takes place,
- The fault is on the section upstream the ALS and the circuit-breaker will make a third reclosing attempt and thus trip and lock out.

While these measures have greatly improved the reliability of supplies from MV overhead line systems, the consumers must, where considered necessary, make their own arrangements to counter the effects of momentary interruptions to supply (between reclosures), for example:

- Uninterruptible standby emergency power
- Lighting that requires no cooling down before re-striking ("hot restrike").



**Fig. B13** : Parallel feeders service

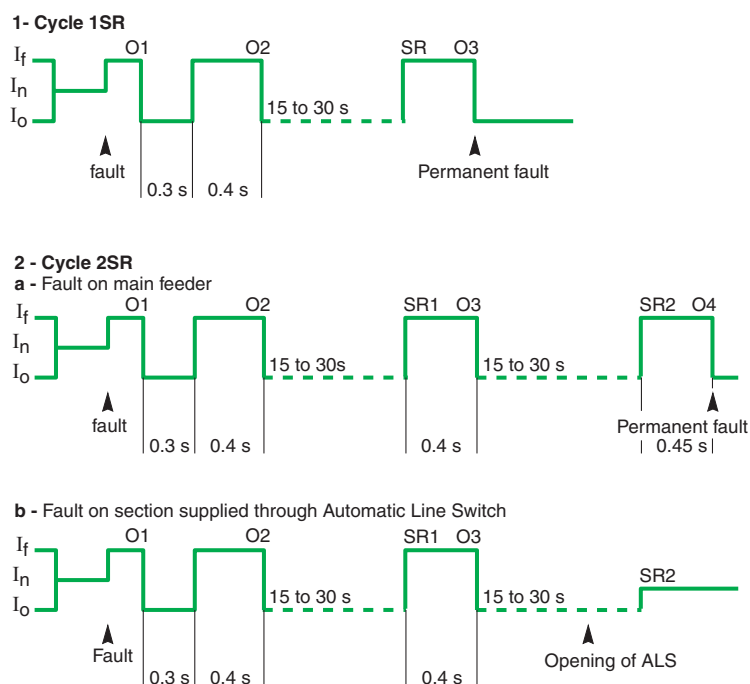


Fig. B14 : Automatic reclosing cycles of a circuit-breaker controlling a radial MV feeder

## Underground cable networks

Faults on underground cable networks are sometimes the result of careless workmanship by cable jointers or by cable laying contractors, etc., but are more commonly due to damage from tools such as pick-axes, pneumatic drills and trench excavating machines, and so on, used by other utilities.

Insulation failures sometimes occur in cable terminating boxes due to overvoltage, particularly at points in a MV system where an overhead line is connected to an underground cable. The overvoltage in such a case is generally of atmospheric origin, and electromagnetic-wave reflection effects at the joint box (where the natural impedance of the circuit changes abruptly) can result in overstressing of the cable-box insulation to the point of failure. Overvoltage protection devices, such as lightning arresters, are frequently installed at these locations.

Faults occurring in cable networks are less frequent than those on overhead (O/H) line systems, but are almost invariably permanent faults, which require more time for localization and repair than those on O/H lines.

Where a cable fault occurs on a ring, supply can be quickly restored to all consumers when the faulty section of cable has been determined.

If, however, the fault occurs on a radial feeder, the delay in locating the fault and carrying out repair work can amount to several hours, and will affect all consumers downstream of the fault position. In any case, if supply continuity is essential on all, or part of, an installation, a standby source must be provided.

*Centralized remote control, based on SCADA (Supervisory Control And Data Acquisition) systems and recent developments in IT (Information Technology) techniques, is becoming more and more common in countries in which the complexity of highly interconnected systems justifies the expenditure.*

## Remote control of MV networks

Remote control on MV feeders is useful to reduce outage durations in case of cable fault by providing an efficient and fast mean for loop configuration. This is achieved by motor operated switches implemented in some of the substations along the loop associated with relevant remote telecontrol units. Remote controlled substation will always be reenergized through telecontrolled operation when the other ones could have to wait for further manual operation.

## 2 Procedure for the establishment of a new substation

B14

Large consumers of electricity are invariably supplied at MV.

On LV systems operating at 120/208 V (3-phase 4-wires), a load of 50 kVA might be considered to be "large", while on a 240/415 V 3-phase system a "large" consumer could have a load in excess of 100 kVA. Both systems of LV distribution are common in many parts of the world.

As a matter of interest, the IEC recommends a "world" standard of 230/400 V for 3-phase 4-wire systems. This is a compromise level and will allow existing systems which operate at 220/380 V and at 240/415 V, or close to these values, to comply with the proposed standard simply by adjusting the off-circuit tapping switches of standard distribution transformers.

The distance over which the energy has to be transmitted is a further factor in considering an MV or LV service. Services to small but isolated rural consumers are obvious examples.

The decision of a MV or LV supply will depend on local circumstances and considerations such as those mentioned above, and will generally be imposed by the utility for the district concerned.

When a decision to supply power at MV has been made, there are two widely-followed methods of proceeding:

**1** - The power-supplier constructs a standard substation close to the consumer's premises, but the MV/LV transformer(s) is (are) located in transformer chamber(s) inside the premises, close to the load centre

**2** - The consumer constructs and equips his own substation on his own premises, to which the power supplier makes the MV connection

In method no. **1** the power supplier owns the substation, the cable(s) to the transformer(s), the transformer(s) and the transformer chamber(s), to which he has unrestricted access.

The transformer chamber(s) is (are) constructed by the consumer (to plans and regulations provided by the supplier) and include plinths, oil drains, fire walls and ceilings, ventilation, lighting, and earthing systems, all to be approved by the supply authority.

The tariff structure will cover an agreed part of the expenditure required to provide the service.

Whichever procedure is followed, the same principles apply in the conception and realization of the project. The following notes refer to procedure no. **2**.

*The consumer must provide certain data to the utility at the earliest stage of the project.*

### 2.1 Preliminary information

Before any negotiations or discussions can be initiated with the supply authorities, the following basic elements must be established:

#### Maximum anticipated power (kVA) demand

Determination of this parameter is described in Chapter A, and must take into account the possibility of future additional load requirements. Factors to evaluate at this stage are:

- The utilization factor (ku)
- The simultaneity factor (ks)

#### Layout plans and elevations showing location of proposed substation

Plans should indicate clearly the means of access to the proposed substation, with dimensions of possible restrictions, e.g. entrances corridors and ceiling height, together with possible load (weight) bearing limits, and so on, keeping in mind that:

- The power-supply personnel must have free and unrestricted access to the MV equipment in the substation at all times
- Only qualified and authorized consumer's personnel are allowed access to the substation
- Some supply authorities or regulations require that the part of the installation operated by the authority is located in a separated room from the part operated by the customer.

#### Degree of supply continuity required

The consumer must estimate the consequences of a supply failure in terms of its duration:

- Loss of production
- Safety of personnel and equipment



*The utility must give specific information to the prospective consumer.*

### 2.2 Project studies

From the information provided by the consumer, the power-supplier must indicate:

**The type of power supply proposed, and define:**

- The kind of power-supply system: overheadline or underground-cable network
- Service connection details: single-line service, ring-main installation, or parallel feeders, etc.
- Power (kVA) limit and fault current level

**The nominal voltage and rated voltage (Highest voltage for equipment)**

Existing or future, depending on the development of the system.

**Metering details which define:**

- The cost of connection to the power network
- Tariff details (consumption and standing charges)

*The utility must give official approval of the equipment to be installed in the substation, and of proposed methods of installation.*

### 2.3 Implementation

Before any installation work is started, the official agreement of the power-supplier must be obtained. The request for approval must include the following information, largely based on the preliminary exchanges noted above:

- Location of the proposed substation
- Single-line diagram of power circuits and connections, together with earthing-circuit proposals
- Full details of electrical equipment to be installed, including performance characteristics
- Layout of equipment and provision for metering components
- Arrangements for power-factor improvement if required
- Arrangements provided for emergency standby power plant (MV or LV) if eventually required

*After testing and checking of the installation by an independent test authority, a certificate is granted which permits the substation to be put into service.*

### 2.4 Commissioning

When required by the authority, commissioning tests must be successfully completed before authority is given to energize the installation from the power supply system. Even if no test is required by the authority it is better to do the following verification tests:

- Measurement of earth-electrode resistances
- Continuity of all equipotential earth-and safety bonding conductors
- Inspection and functional testing of all MV components
- Insulation checks of MV equipment
- Dielectric strength test of transformer oil (and switchgear oil if appropriate), if applicable
- Inspection and testing of the LV installation in the substation
- Checks on all interlocks (mechanical key and electrical) and on all automatic sequences
- Checks on correct protective-relay operation and settings

It is also imperative to check that all equipment is provided, such that any properly executed operation can be carried out in complete safety. On receipt of the certificate of conformity (if required):

- Personnel of the power-supply authority will energize the MV equipment and check for correct operation of the metering
- The installation contractor is responsible for testing and connection of the LV installation

When finally the substation is operational:

- The substation and all equipment belongs to the consumer
- The power-supply authority has operational control over all MV switchgear in the substation, e.g. the two incoming load-break switches and the transformer MV switch (or CB) in the case of a RingMainUnit, together with all associated MV earthing switches
- The power-supply personnel has unrestricted access to the MV equipment
- The consumer has independent control of the MV switch (or CB) of the transformer(s) only, the consumer is responsible for the maintenance of all substation equipment, and must request the power-supply authority to isolate and earth the switchgear to allow maintenance work to proceed. The power supplier must issue a signed permit-to-work to the consumers maintenance personnel, together with keys of locked-off isolators, etc. at which the isolation has been carried out.

The subject of protection in the electrical power industry is vast: it covers all aspects of safety for personnel, and protection against damage or destruction of property, plant, and equipment.

These different aspects of protection can be broadly classified according to the following objectives:

- Protection of personnel and animals against the dangers of overvoltages and electric shock, fire, explosions, and toxic gases, etc.
- Protection of the plant, equipment and components of a power system against the stresses of short-circuit faults, atmospheric surges (lightning) and power-system instability (loss of synchronism) etc.
- Protection of personnel and plant from the dangers of incorrect power-system operation, by the use of electrical and mechanical interlocking. All classes of switchgear (including, for example, tap-position selector switches on transformers, and so on...) have well-defined operating limits. This means that the order in which the different kinds of switching device can be safely closed or opened is vitally important. Interlocking keys and analogous electrical control circuits are frequently used to ensure strict compliance with correct operating sequences.

It is beyond the scope of a guide to describe in full technical detail the numerous schemes of protection available to power-systems engineers, but it is hoped that the following sections will prove to be useful through a discussion of general principles. While some of the protective devices mentioned are of universal application, descriptions generally will be confined to those in common use on MV and LV systems only, as defined in Sub-clause 1.1 of this Chapter.

*Protection against electric shocks and overvoltages is closely related to the achievement of efficient (low resistance) earthing and effective application of the principles of equipotential environments.*

### 3.1 Protection against electric shocks

Protective measures against electric shock are based on two common dangers:

- Contact with an active conductor, i.e. which is live with respect to earth in normal circumstances. This is referred to as a “direct contact” hazard.
- Contact with a conductive part of an apparatus which is normally dead, but which has become live due to insulation failure in the apparatus. This is referred to as an “indirect contact” hazard.

It may be noted that a third type of shock hazard can exist in the proximity of MV or LV (or mixed) earth electrodes which are passing earth-fault currents. This hazard is due to potential gradients on the surface of the ground and is referred to as a “step-voltage” hazard; shock current enters one foot and leaves by the other foot, and is particularly dangerous for four-legged animals. A variation of this danger, known as a “touch voltage” hazard can occur, for instance, when an earthed metallic part is situated in an area in which potential gradients exist.

Touching the part would cause current to pass through the hand and both feet.

Animals with a relatively long front-to-hind legs span are particularly sensitive to step-voltage hazards and cattle have been killed by the potential gradients caused by a low voltage (230/400 V) neutral earth electrode of insufficiently low resistance.

Potential-gradient problems of the kind mentioned above are not normally encountered in electrical installations of buildings, providing that equipotential conductors properly bond all exposed metal parts of equipment and all extraneous metal (i.e. not part of an electrical apparatus or the installation - for example structural steelwork, etc.) to the protective earthing conductor.

#### Direct-contact protection or basic protection

The main form of protection against direct contact hazards is to contain all live parts in housings of insulating material or in metallic earthed housings, by placing out of reach (behind insulated barriers or at the top of poles) or by means of obstacles.

Where insulated live parts are housed in a metal envelope, for example transformers, electric motors and many domestic appliances, the metal envelope is connected to the installation protective earthing system.

For MV switchgear, the IEC standard 62271-200 (Prefabricated Metal Enclosed switchgear and controlgear for voltages up to 52 kV) specifies a minimum Protection Index (IP coding) of IP2X which ensures the direct-contact protection. Furthermore, the metallic enclosure has to demonstrate an electrical continuity, then establishing a good segregation between inside and outside of the enclosure. Proper grounding of the enclosure further participates to the electrical protection of the operators under normal operating conditions.

For LV appliances this is achieved through the third pin of a 3-pin plug and socket. Total or even partial failure of insulation to the metal, can raise the voltage of the envelope to a dangerous level (depending on the ratio of the resistance of the leakage path through the insulation, to the resistance from the metal envelope to earth).



## Indirect-contact protection or fault protection

A person touching the metal envelope of an apparatus with a faulty insulation, as described above, is said to be making an indirect contact.

An indirect contact is characterized by the fact that a current path to earth exists (through the protective earthing (PE) conductor) in parallel with the shock current through the person concerned.

### Case of fault on L.V. system

Extensive tests have shown that, providing the potential of the metal envelope is not greater than 50 V with respect to earth, or to any conductive material within reaching distance, no danger exists.

### Indirect-contact hazard in the case of a MV fault

If the insulation failure in an apparatus is between a MV conductor and the metal envelope, it is not generally possible to limit the rise of voltage of the envelope to 50 V or less, simply by reducing the earthing resistance to a low value. The solution in this case is to create an equipotential situation, as described in Sub-clause 1.1 "Earthing systems".

## 3.2 Protection of transformer and circuits

### General

The electrical equipment and circuits in a substation must be protected in order to avoid or to control damage due to abnormal currents and/or voltages. All equipment normally used in power system installations have standardized short-time withstand ratings for overcurrent and overvoltage. The role of protective scheme is to ensure that this withstand limits can never be exceeded. In general, this means that fault conditions must be cleared as fast as possible without missing to ensure coordination between protective devices upstream and downstream the equipment to be protected. This means, when there is a fault in a network, generally several protective devices see the fault at the same time but only one must act.

These devices may be:

- Fuses which clear the faulty circuit directly or together with a mechanical tripping attachment, which opens an associated three-phase load-break switch
- Relays which act indirectly on the circuit-breaker coil

### Transformer protection

#### Stresses due to the supply network

Some voltage surges can occur on the network such as :

- Atmospheric voltage surges

Atmospheric voltage surges are caused by a stroke of lightning falling on or near an overhead line.

- Operating voltage surges

A sudden change in the established operating conditions in an electrical network causes transient phenomena to occur. This is generally a high frequency or damped oscillation voltage surge wave.

For both voltage surges, the overvoltage protection device generally used is a varistor (Zinc Oxide).

In most cases, voltage surges protection has no action on switchgear.

#### Stresses due to the load

Overloading is frequently due to the coincidental demand of a number of small loads, or to an increase in the apparent power (kVA) demand of the installation, due to expansion in a factory, with consequent building extensions, and so on. Load increases raise the temperature of the wirings and of the insulation material. As a result, temperature increases involve a reduction of the equipment working life. Overload protection devices can be located on primary or secondary side of the transformer.

The protection against overloading of a transformer is now provided by a digital relay which acts to trip the circuit-breaker on the secondary side of the transformer. Such relay, generally called thermal overload relay, artificially simulates the temperature, taking into account the time constant of the transformer. Some of them are able to take into account the effect of harmonic currents due to non linear loads (rectifiers, computer equipment, variable speed drives...). This type of relay is also able to predict the time before overload tripping and the waiting time after tripping. So, this information is very helpful to control load shedding operation.



Fig. B15 : Transformer with conservator tank



Fig. B16 : Totally filled transformer

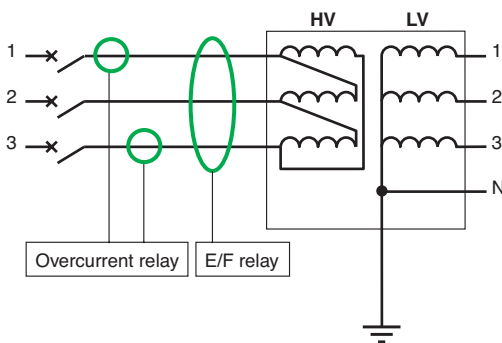


Fig. B17 : Protection against earth fault on the MV winding

In addition, larger oil-immersed transformers frequently have thermostats with two settings, one for alarm purposes and the other for tripping.

Dry-type transformers use heat sensors embedded in the hottest part of the windings insulation for alarm and tripping.

## Internal faults

The protection of transformers by transformer-mounted devices, against the effects of internal faults, is provided on transformers which are fitted with airbreathing conservator tanks by the classical Buchholz mechanical relay (see Fig. B15). These relays can detect a slow accumulation of gases which results from the arcing of incipient faults in the winding insulation or from the ingress of air due to an oil leak. This first level of detection generally gives an alarm, but if the condition deteriorates further, a second level of detection will trip the upstream circuit-breaker.

An oil-surge detection feature of the Buchholz relay will trip the upstream circuit-breaker "instantaneously" if a surge of oil occurs in the pipe connecting the main tank with the conservator tank.

Such a surge can only occur due to the displacement of oil caused by a rapidly formed bubble of gas, generated by an arc of short-circuit current in the oil.

By specially designing the cooling-oil radiator elements to perform a concerting action, "totally filled" types of transformer as large as 10 MVA are now currently available.

Expansion of the oil is accommodated without an excessive rise in pressure by the "bellows" effect of the radiator elements. A full description of these transformers is given in Sub-clause 4.4 (see Fig. B16).

Evidently the Buchholz devices mentioned above cannot be applied to this design; a modern counterpart has been developed however, which measures:

- The accumulation of gas
- Overpressure
- Overtemperature

The first two conditions trip the upstream circuit-breaker, and the third condition trips the downstream circuit-breaker of the transformer.

## Internal phase-to-phase short-circuit

Internal phase-to-phase short-circuit must be detected and cleared by:

- 3 fuses on the primary side of the transformer or
- An overcurrent relay that trips a circuit-breaker upstream of the transformer

## Internal phase-to-earth short-circuit

This is the most common type of internal fault. It must be detected by an earth fault relay. Earth fault current can be calculated with the sum of the 3 primary phase currents (if 3 current transformers are used) or by a specific core current transformer. If a great sensitivity is needed, specific core current transformer will be preferred. In such a case, a two current transformers set is sufficient (see Fig. B17).

## Protection of circuits

The protection of the circuits downstream of the transformer must comply with the IEC 60364 requirements.

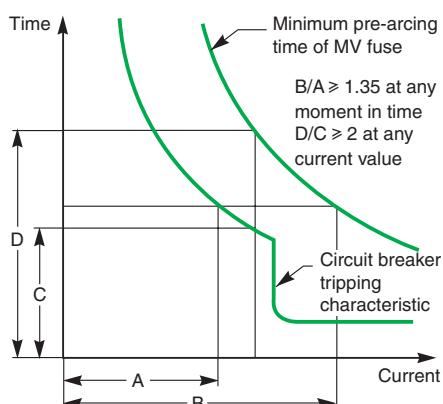
## Discrimination between the protective devices upstream and downstream of the transformer

The consumer-type substation with LV metering requires discriminative operation between the MV fuses or MV circuit-breaker and the LV circuit-breaker or fuses. The rating of the MV fuses will be chosen according to the characteristics of the transformer.

The tripping characteristics of the LV circuit-breaker must be such that, for an overload or short-circuit condition downstream of its location, the breaker will trip sufficiently quickly to ensure that the MV fuses or the MV circuit-breaker will not be adversely affected by the passage of overcurrent through them.

The tripping performance curves for MV fuses or MV circuit-breaker and LV circuit-breakers are given by graphs of time-to-operate against current passing through them. Both curves have the general inverse-time/current form (with an abrupt discontinuity in the CB curve at the current value above which "instantaneous" tripping occurs).

These curves are shown typically in Figure B18.



**Fig. B18** : Discrimination between MV fuse operation and LV circuit-breaker tripping, for transformer protection



**Fig. B19** : MV fuse and LV circuit-breaker configuration

■ In order to achieve discrimination:

All parts of the fuse or MV circuit-breaker curve must be above and to the right of the CB curve.

■ In order to leave the fuses unaffected (i.e. undamaged):

All parts of the minimum pre-arcing fuse curve must be located to the right of the CB curve by a factor of 1.35 or more (e.g. where, at time T, the CB curve passes through a point corresponding to 100 A, the fuse curve at the same time T must pass through a point corresponding to 135 A, or more, and so on...) and, all parts of the fuse curve must be above the CB curve by a factor of 2 or more (e.g. where, at a current level I the CB curve passes through a point corresponding to 1.5 seconds, the fuse curve at the same current level I must pass through a point corresponding to 3 seconds, or more, etc.).

The factors 1.35 and 2 are based on standard maximum manufacturing tolerances for MV fuses and LV circuit-breakers.

In order to compare the two curves, the MV currents must be converted to the equivalent LV currents, or vice-versa.

Where a LV fuse-switch is used, similar separation of the characteristic curves of the MV and LV fuses must be respected.

■ In order to leave the MV circuit-breaker protection untripped:

All parts of the minimum pre-arcing fuse curve must be located to the right of the CB curve by a factor of 1.35 or more (e.g. where, at time T, the LV CB curve passes through a point corresponding to 100 A, the MV CB curve at the same time T must pass through a point corresponding to 135 A, or more, and so on...) and, all parts of the MV CB curve must be above the LV CB curve (time of LV CB curve must be less or equal than MV CB curves minus 0.3 s)

The factors 1.35 and 0.3 s are based on standard maximum manufacturing tolerances for MV current transformers, MV protection relay and LV circuit-breakers.

In order to compare the two curves, the MV currents must be converted to the equivalent LV currents, or vice-versa.

## Choice of protective device on the primary side of the transformer

As explained before, for low reference current, the protection may be by fuses or by circuit-breaker.

When the reference current is high, the protection will be achieved by circuit-breaker.

Protection by circuit-breaker provides a more sensitive transformer protection compared with fuses. The implementation of additional protections (earth fault protection, thermal overload protection) is easier with circuit-breakers.

## 3.3 Interlocks and conditioned operations

Mechanical and electrical interlocks are included on mechanisms and in the control circuits of apparatus installed in substations, as a measure of protection against an incorrect sequence of manoeuvres by operating personnel.

Mechanical protection between functions located on separate equipment (e.g. switchboard and transformer) is provided by key-transfer interlocking.

An interlocking scheme is intended to prevent any abnormal operational manoeuvre. Some of such operations would expose operating personnel to danger, some others would only lead to an electrical incident.

### Basic interlocking

Basic interlocking functions can be introduced in one given functional unit; some of these functions are made mandatory by the IEC 62271-200, for metal-enclosed MV switchgear, but some others are the result of a choice from the user.

Considering access to a MV panel, it requires a certain number of operations which shall be carried out in a pre-determined order. It is necessary to carry out operations in the reverse order to restore the system to its former condition. Either proper procedures, or dedicated interlocks, can ensure that the required operations are performed in the right sequence. Then such accessible compartment will be classified as "accessible and interlocked" or "accessible by procedure". Even for users with proper rigorous procedures, use of interlocks can provide a further help for safety of the operators.

## Key interlocking

Beyond the interlocks available within a given functional unit (see also 4.2), the most widely-used form of locking/interlocking depends on the principle of key transfer.

The principle is based on the possibility of freeing or trapping one or several keys, according to whether or not the required conditions are satisfied.

These conditions can be combined in unique and obligatory sequences, thereby guaranteeing the safety of personnel and installation by the avoidance of an incorrect operational procedure.

Non-observance of the correct sequence of operations in either case may have extremely serious consequences for the operating personnel, as well as for the equipment concerned.

**Note:** It is important to provide for a scheme of interlocking in the basic design stage of planning a MV/LV substation. In this way, the apparatuses concerned will be equipped during manufacture in a coherent manner, with assured compatibility of keys and locking devices.

## Service continuity

For a given MV switchboard, the definition of the accessible compartments as well as their access conditions provide the basis of the "Loss of Service Continuity" classification defined in the standard IEC 62271-200. Use of interlocks or only proper procedure does not have any influence on the service continuity. Only the request for accessing a given part of the switchboard, under normal operation conditions, results in limiting conditions which can be more or less severe regarding the continuity of the electrical distribution process.

## Interlocks in substations

In a MV/LV distribution substation which includes:

- A single incoming MV panel or two incoming panels (from parallel feeders) or two incoming/outgoing ring-main panels
- A transformer switchgear-and-protection panel, which can include a load-break/disconnecting switch with MV fuses and an earthing switch, or a circuit-breaker and line disconnecting switch together with an earthing switch
- A transformer compartment

Interlocks allow manœuvres and access to different panels in the following conditions:

### Basic interlocks, embedded in single functional units

- Operation of the load-break/isolating switch
  - If the panel door is closed and the associated earthing switch is open
- Operation of the line-disconnecting switch of the transformer switchgear - and - protection panel
  - If the door of the panel is closed, and
  - If the circuit-breaker is open, and the earthing switch(es) is (are) open
- Closure of an earthing switch
  - If the associated isolating switch(es) is (are) open<sup>(1)</sup>
- Access to an accessible compartment of each panel, if interlocks have been specified
  - If the isolating switch for the compartment is open and the earthing switch(es) for the compartment is (are) closed
- Closure of the door of each accessible compartment, if interlocks have been specified
  - If the earthing switch(es) for the compartment is (are) closed

### Functional interlocks involving several functional units or separate equipment

- Access to the terminals of a MV/LV transformer
    - If the tee-off functional unit has its switch open and its earthing switch closed.
- According to the possibility of back-feed from the LV side, a condition on the LV main breaker can be necessary.

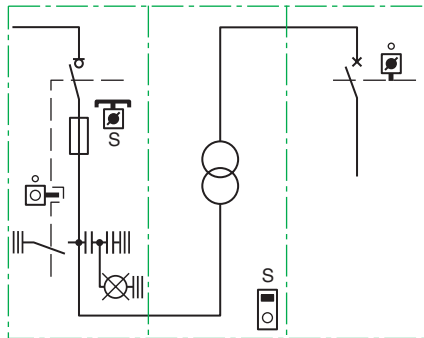
## Practical example

In a consumer-type substation with LV metering, the interlocking scheme most commonly used is MV/LV/TR (high voltage/ low voltage/transformer).

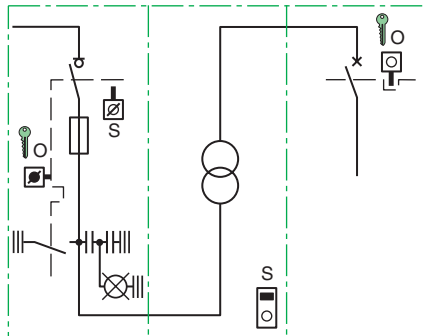
The aim of the interlocking is:

- To prevent access to the transformer compartment if the earthing switch has not been previously closed
- To prevent the closure of the earthing switch in a transformer switchgear-and-protection panel, if the LV circuit-breaker of the transformer has not been previously locked "open" or "withdrawn"

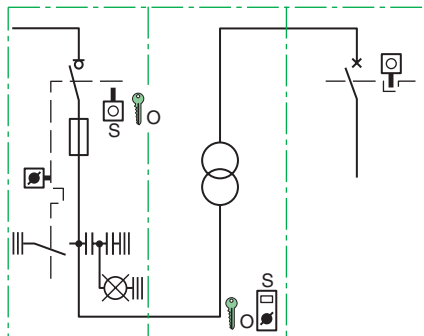
(1) If the earthing switch is on an incoming circuit, the associated isolating switches are those at both ends of the circuit, and these should be suitably interlocked. In such situation, the interlocking function becomes a multi-units key interlock.



MV switch and LV CB closed



MV fuses accessible



Transformer MV terminals accessible

## Legend

- Key absent
- Key free
- Key trapped
- Panel or door

Fig. B20 : Example of MV/LV/TR interlocking

Access to the MV or LV terminals of a transformer, (protected upstream by a MV switchgear-and-protection panel, containing a MV load-break / isolating switch, MV fuses, and a MV earthing switch) must comply with the strict procedure described below, and is illustrated by the diagrams of **Figure B20**.

**Note:** The transformer in this example is provided with plug-in type MV terminal connectors which can only be removed by unlocking a retaining device common to all three phase connectors<sup>(1)</sup>.

The MV load-break / disconnecting switch is mechanically linked with the MV earthing switch such that only one of the switches can be closed, i.e. closure of one switch automatically locks the closure of the other.

## Procedure for the isolation and earthing of the power transformer, and removal of the MV plug-type shrouded terminal connections (or protective cover)

### Initial conditions

- MV load-break/disconnection switch and LV circuit-breaker are closed
- MV earthing switch locked in the open position by key "O"
- Key "O" is trapped in the LV circuit-breaker as long as that circuit-breaker is closed

### Step 1

- Open LV CB and lock it open with key "O"
- Key "O" is then released

### Step 2

- Open the MV switch
- Check that the "voltage presence" indicators extinguish when the MV switch is opened

### Step 3

- Unlock the MV earthing switch with key "O" and close the earthing switch
- Key "O" is now trapped

### Step 4

The access panel to the MV fuses can now be removed (i.e. is released by closure of the MV earthing switch). Key "S" is located in this panel, and is trapped when the MV switch is closed

- Turn key "S" to lock the MV switch in the open position
- Key "S" is now released

### Step 5

Key "S" allows removal of the common locking device of the plug-type MV terminal connectors on the transformer or of the common protective cover over the terminals, as the case may be.

In either case, exposure of one or more terminals will trap key "S" in the interlock.

The result of the foregoing procedure is that:

- The MV switch is locked in the open position by key "S".
- Key "S" is trapped at the transformer terminals interlock as long as the terminals are exposed.
- The MV earthing switch is in the closed position but not locked, i.e. may be opened or closed. When carrying out maintenance work, a padlock is generally used to lock the earthing switch in the closed position, the key of the padlock being held by the engineer supervizing the work.
- The LV CB is locked open by key "O", which is trapped by the closed MV earthing switch. The transformer is therefore safely isolated and earthed.

It may be noted that the upstream terminal of the load-break disconnecting switch may remain live in the procedure described as the terminals in question are located in a separate non accessible compartment in the particular switchgear under discussion. Any other technical solution with exposed terminals in the accessed compartment would need further de-energisation and interlocks.

(1) Or may be provided with a common protective cover over the three terminals.

## 4 The consumer substation with LV metering

B22

### 4.1 General

A consumer substation with LV metering is an electrical installation connected to a utility supply system at a nominal voltage of 1 kV - 35 kV, and includes a single MV/LV transformer generally not exceeding 1,250 kVA.

#### Functions

##### The substation

All component parts of the substation are located in one room, either in an existing building, or in the form of a prefabricated housing exterior to the building.

##### Connection to the MV network

Connection at MV can be:

- Either by a single service cable or overhead line, or
- Via two mechanically interlocked load-break switches with two service cables from duplicate supply feeders, or
- Via two load-break switches of a ring-main unit

##### The transformer

Since the use of PCB<sup>(1)</sup>-filled transformers is prohibited in most countries, the preferred available technologies are:

- Oil-immersed transformers for substations located outside premises
- Dry-type, vacuum-cast-resin transformers for locations inside premises, e.g. multistoreyed buildings, buildings receiving the public, and so on...

##### Metering

Metering at low voltage allows the use of small metering transformers at modest cost. Most tariff structures take account of MV/LV transformer losses.

##### LV installation circuits

A low-voltage circuit-breaker, suitable for isolation duty and locking off facilities, to:

- Supply a distribution board
- Protect the transformer against overloading and the downstream circuits against short-circuit faults.

##### One-line diagrams

The diagrams on the following page (see **Fig. B21**) represent the different methods of MV service connection, which may be one of four types:

- Single-line service
- Single-line service (equipped for extension to form a ring main)
- Duplicate supply service
- Ring main service

### 4.2 Choice of MV switchgear

#### Standards and specifications

The switchgear and equipment described below are rated for 1 kV - 24 kV systems and comply with the following international standards:

IEC 62271-1, 62271-200, 60265-1, 62271-102, 62271-100, 62271-105

Local regulations can also require compliance with national standards as:

- France: UTE
- United Kingdom: BS
- Germany: VDE
- United States of America: ANSI

#### Type of equipment

In addition of Ring Main Units discussed in section 1.2, all kinds of switchgear arrangements are possible when using modular switchgear, and provisions for later extensions are easily realized.



## 4 The consumer substation with LV metering

B23

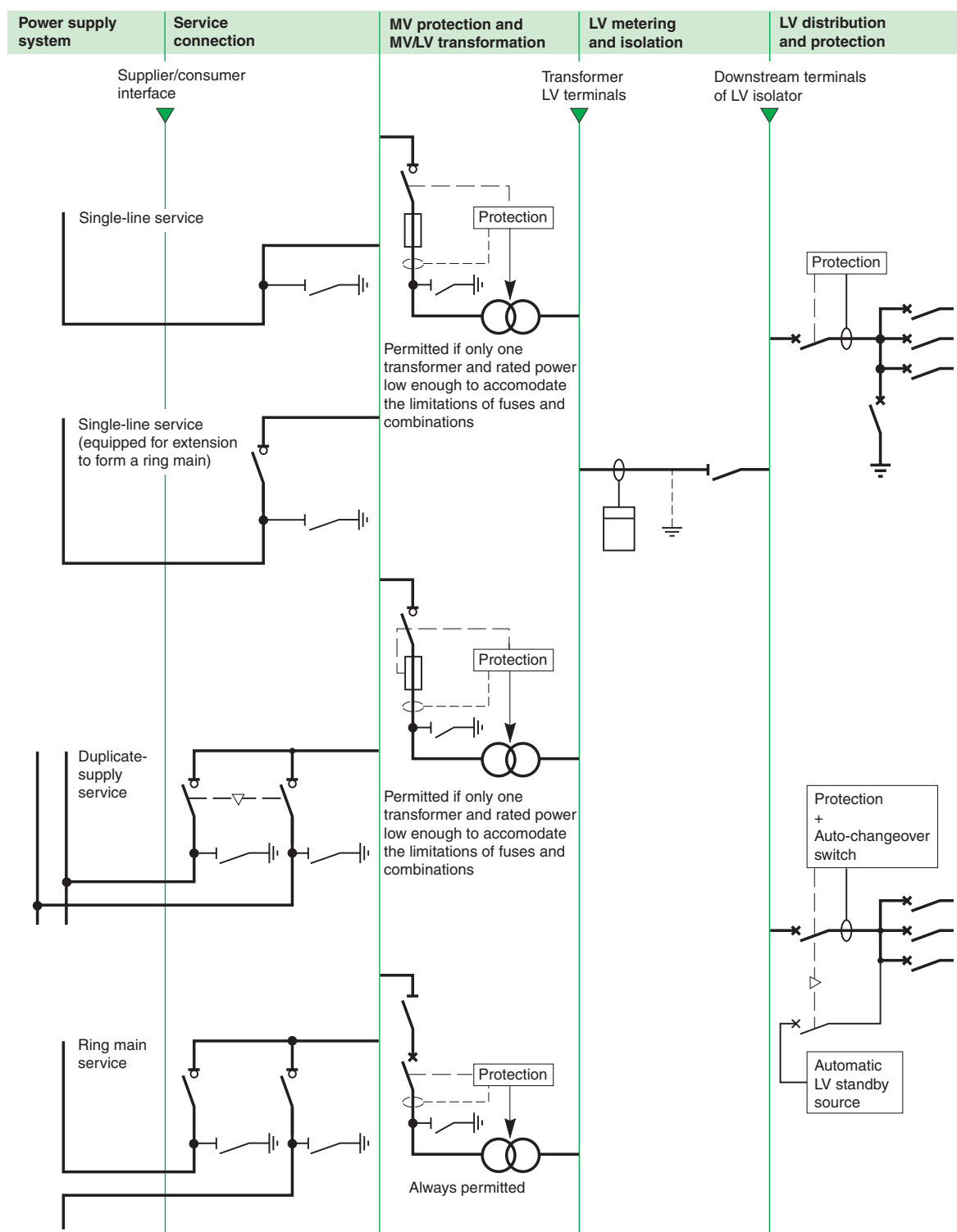


Fig. B21 : Consumer substation with LV metering

### Operational safety of metal enclosed switchgear

#### Description

The following notes describe a “state-of-the art” load-break / disconnecting-switch panel (see **Fig. B22**) incorporating the most modern developments for ensuring:

- Operational safety
- Minimum space requirements
- Extendibility and flexibility
- Minimum maintenance requirements

Each panel includes 3 compartments:

- Switchgear: the load-break disconnecting switch is incorporated in an hermetically sealed (for life) molded epoxy-resin unit
- Connections: by cable at terminals located on the molded switch unit
- Busbars: modular, such that any number of panels may be assembled side-by-side to form a continuous switchboard, and for control and indication a low voltage cabinet which can accommodate automatic control and relaying equipment. An additional cabinet may be mounted above the existing one if further space is required.

Cable connections are provided inside a cable-terminating compartment at the front of the unit, to which access is gained by removal of the front panel of the compartment.

The units are connected electrically by means of prefabricated sections of busbars.

Site erection is effected by following the assembly instructions.

Operation of the switchgear is simplified by the grouping of all controls and indications on a control panel at the front of each unit.

The technology of these switchgear units is essentially based on operational safety, ease of installation and low maintenance requirements.

#### Switchgear internal safety measures

- The load-break/disconnecting switch fully satisfies the requirement of “reliable position indicating device” as defined in IEC 62271-102 (disconnectors and earthing switches)
- The functional unit incorporates the basic interlocks specified by the IEC 62271-200 (prefabricated metal enclosed switchgear and controlgear):
  - Closure of the switch is not possible unless the earth switch is open
  - Closure of the earthing switch is only possible if the load break/isolating switch is open
- Access to the cable compartment, which is the only user-accessible compartment during operation, is secured by further interlocks:
  - Opening of the access panel to the cable terminations compartment<sup>(1)</sup> is only possible if the earthing switch is closed
  - The load-break/disconnecting switch is locked in the open position when the above-mentioned access panel is open. Opening of the earthing switch is then possible, for instance to allow a dielectric test on the cables.

With such features, the switchboard can be operated with live busbars and cables, except for the unit where the access to cables is made. It complies then with the Loss of Service Continuity class LSB2A, as defined in the IEC 62271-200.

Apart from the interlocks noted above, each switchgear panel includes:

- Built-in padlocking facilities on the operation levers
- 5 predrilled sets of fixing holes for possible future interlocking locks

#### Operations

- Operating handles, levers, etc. required for switching operations are grouped together on a clearly illustrated panel
- All closing-operation levers are identical on all units (except those containing a circuit-breaker)
- Operation of a closing lever requires very little effort
- Opening or closing of a load-break/disconnecting switch can be by lever or by push-button for automatic switches
- Conditions of switches (Open, Closed, Spring-charged), are clearly indicated



**Fig. B22 :** Metal enclosed MV load break disconnecting switch

(1) Where MV fuses are used they are located in this compartment.



## 4.3 Choice of MV switchgear panel for a transformer circuit

Three types of MV switchgear panel are generally available:

- Load-break switch and separate MV fuses in the panel
- Load-break switch/MV fuses combination
- Circuit-breaker

Seven parameters influence the optimum choice:

- The primary current of the transformer
- The insulating medium of the transformer
- The position of the substation with respect to the load centre
- The kVA rating of the transformer
- The distance from switchgear to the transformer
- The use of separate protection relays (as opposed to direct-acting trip coils).

**Note:** The fuses used in the load-break/switch fuses combination have striker-pins which ensure tripping of the 3-pole switch on the operation of one (or more) fuse(s).

## 4.4 Choice of MV/LV transformer

### Characteristic parameters of a transformer

A transformer is characterized in part by its electrical parameters, but also by its technology and its conditions of use.

#### Electrical characteristics

- Rated power (P<sub>n</sub>): the conventional apparent-power in kVA on which other design-parameter values and the construction of the transformer are based. Manufacturing tests and guarantees are referred to this rating
- Frequency: for power distribution systems of the kind discussed in this guide, the frequency will be 50 Hz or 60 Hz
- Rated primary and secondary voltages: For a primary winding capable of operating at more than one voltage level, a kVA rating corresponding to each level must be given. The secondary rated voltage is its open circuit value
- Rated insulation levels are given by overvoltage-withstand test values at power frequency, and by high voltage impulse tests values which simulate lightning discharges. At the voltage levels discussed in this guide, overvoltages caused by MV switching operations are generally less severe than those due to lightning, so that no separate tests for switching-surge withstand capability are made
- Off-circuit tap-selector switch generally allows a choice of up to  $\pm 2.5\%$  and  $\pm 5\%$  level about the rated voltage of the highest voltage winding. The transformer must be de-energized before this switch is operated
- Winding configurations are indicated in diagrammatic form by standard symbols for star, delta and inter-connected-star windings; (and combinations of these for special duty, e.g. six-or twelve-phase rectifier transformers, etc.) and in an IEC-recommended alphanumeric code. This code is read from left-to-right, the first letter refers to the highest voltage winding, the second letter to the next highest, and so on:
  - Capital letters refer to the highest voltage winding
  - D** = delta
  - Y** = star
  - Z** = interconnected-star (or zigzag)
  - N** = neutral connection brought out to a terminal
  - Lower-case letters are used for tertiary and secondary windings
  - d** = delta
  - y** = star
  - z** = interconnected-star (or zigzag)
  - n** = neutral connection brought out to a terminal
  - A number from 0 to 11, corresponding to those, on a clock dial ("0" is used instead of "12") follows any pair of letters to indicate the phase change (if any) which occurs during the transformation.

A very common winding configuration used for distribution transformers is that of a Dyn 11 transformer, which has a delta MV winding with a star-connected secondary winding the neutral point of which is brought out to a terminal. The phase change through the transformer is +30 degrees, i.e. phase 1 secondary voltage is at "11 o'clock" when phase 1 of the primary voltage is at "12 o'clock", as shown in Figure B31 page B34. All combinations of delta, star and zigzag windings produce a phase change which (if not zero) is either 30 degrees or a multiple of 30 degrees. IEC 60076-4 describes the "clock code" in detail.

### Characteristics related to the technology and utilization of the transformer

This list is not exhaustive:

- Choice of technology
- The insulating medium is:
  - Liquid (mineral oil) or
  - Solid (epoxy resin and air)
- For indoor or outdoor installation
- Altitude ( $\leq 1,000$  m is standard)
- Temperature (IEC 60076-2)
  - Maximum ambient air: 40 °C
  - Daily maximum average ambient air: 30 °C
  - Annual maximum average ambient air: 20 °C

For non-standard operating conditions, refer to “Influence of the Ambient temperature and altitude on the rated current” on page B7.

### Description of insulation techniques

There are two basic classes of distribution transformer presently available:

- Dry type (cast in resin)
- Liquid filled (oil-immersed)

#### Dry type transformers

The windings of these transformers are insulated by resin between turns and by resin and air to other windings and to frame. The resin is usually cast under vacuum process (which is patented by major manufacturers).

It is recommended that the transformer be chosen according to the IEC 60076-11, as follows:

- Environment class E2 (frequent condensation and/or high level of pollution)
- Climatic conditions class B2 (utilization, transport and stockage down to -25 °C)
- Fire resistance (transformers exposed to fire risk with low flammability and self extinguishing in a given time)

The following description refers to the process developed by a leading European manufacturer in this field.

The encapsulation of a winding uses three components:

- Epoxy-resin based on biphenol A with a viscosity that ensures complete impregnation of the windings
- Anhydride hardener modified to introduce a degree of resilience in the moulding, essential to avoid the development of cracks during the temperature cycles occurring in normal operation
- Pulverulent additive composed of trihydrated alumina  $Al(OH)_3$  and silica which enhances its mechanical and thermal properties, as well as giving exceptional intrinsic qualities to the insulation in the presence of heat.

This three-component system of encapsulation gives Class F insulation ( $\Delta\theta = 100$  K) with excellent fire-resisting qualities and immediate self-extinction. These transformers are therefore classified as nonflammable.

The mouldings of the windings contain no halogen compounds (chlorine, bromine, etc.) or other compounds capable of producing corrosive or toxic pollutants, thereby guaranteeing a high degree of safety to personnel in emergency situations, notably in the event of a fire.

It also performs exceptionally well in hostile industrial atmospheres of dust, humidity, etc. (see Fig. B23).

#### Liquid-filled transformers

The most common insulating/cooling liquid used in transformers is mineral oil. Mineral oils are specified in IEC 60296. Being flammable, safety measures are obligatory in many countries, especially for indoor substations. The DGPT unit (Detection of Gas, Pressure and Temperature) ensures the protection of oil-filled transformers. In the event of an anomaly, the DGPT causes the MV supply to the transformer to be cut off very rapidly, before the situation becomes dangerous.

Mineral oil is bio-degradable and does not contain PCB (polychlorinated biphenyl), which was the reason for banning askerel, i.e. Pyralène, Pyrolio, Pyroline...

On request, mineral oil can be replaced by an alternative insulating liquid, by adapting the transformer, as required, and taking appropriate additional precautions if necessary.

The insulating fluid also acts as a cooling medium; it expands as the load and/or the ambient temperature increases, so that all liquid-filled transformers must be designed to accommodate the extra volume of liquid without the pressure in the tank becoming excessive.



Fig. B23 : Dry-type transformer



Fig. B24 : Hermetically-sealed totally-filled tank



Fig. B25 : Air-breathing conservator-type tank at atmosphere pressure

There are two ways in which this pressure limitation is commonly achieved:

- Hermetically-sealed totally-filled tank (up to 10 MVA at the present time)  
Developed by a leading French manufacturer in 1963, this method was adopted by the national utility in 1972, and is now in world-wide service (see Fig. B24).  
Expansion of the liquid is compensated by the elastic deformation of the oil-cooling passages attached to the tank.
- The “total-fill” technique has many important advantages over other methods:
  - Oxydation of the dielectric liquid (with atmospheric oxygen) is entirely precluded
  - No need for an air-drying device, and so no consequent maintenance (inspection and changing of saturated dessicant)
  - No need for dielectric-strength test of the liquid for at least 10 years
  - Simplified protection against internal faults by means of a DGPT device is possible
  - Simplicity of installation: lighter and lower profile (than tanks with a conservator) and access to the MV and LV terminals is unobstructed
  - Immediate detection of (even small) oil leaks; water cannot enter the tank

■ Air-breathing conservator-type tank at atmospheric pressure  
Expansion of the insulating liquid is taken up by a change in the level of liquid in an expansion (conservator) tank, mounted above the transformer main tank, as shown in Figure B25. The space above the liquid in the conservator may be filled with air which is drawn in when the level of liquid falls, and is partially expelled when the level rises. When the air is drawn in from the surrounding atmosphere it is admitted through an oil seal, before passing through a dessicating device (generally containing silica-gel crystals) before entering the conservator. In some designs of larger transformers the space above the oil is occupied by an impermeable air bag so that the insulation liquid is never in contact with the atmosphere. The air enters and exits from the deformable bag through an oil seal and dessicator, as previously described. A conservator expansion tank is obligatory for transformers rated above 10 MVA (which is presently the upper limit for “total-fill” type transformers).

## Choice of technology

As discussed above, the choice of transformer is between liquid-filled or dry type. For ratings up to 10 MVA, totally-filled units are available as an alternative to conservator-type transformers.

A choice depends on a number of considerations, including:

- Safety of persons in proximity to the transformer. Local regulations and official recommendations may have to be respected
- Economic considerations, taking account of the relative advantages of each technique

The regulations affecting the choice are:

- Dry-type transformer:
  - In some countries a dry-type transformer is obligatory in high apartment blocks
  - Dry-type transformers impose no constraints in other situations
- Transformers with liquid insulation:
  - This type of transformer is generally forbidden in high apartment blocks
  - For different kinds of insulation liquids, installation restrictions, or minimum protection against fire risk, vary according to the class of insulation used
  - Some countries in which the use of liquid dielectrics is highly developed, classify the several categories of liquid according to their fire performance. This latter is assessed according to two criteria: the flash-point temperature, and the minimum calorific power. The principal categories are shown in Figure B26 in which a classification code is used for convenience.

As an example, French standard defines the conditions for the installation of liquid-filled transformers. No equivalent IEC standard has yet been established.

The French standard is aimed at ensuring the safety of persons and property and recommends, notably, the minimum measures to be taken against the risk of fire.

Code	Dielectric fluid	Flash-point (°C)	Minimum calorific power (MJ/kg)
O1	Mineral oil	< 300	-
K1	High-density hydrocarbons	> 300	48
K2	Esters	> 300	34 - 37
K3	Silicones	> 300	27 - 28
L3	Insulating halogen liquids	-	12

Fig. B26 : Categories of dielectric fluids

The main precautions to observe are indicated in **Figure B27**.

- For liquid dielectrics of class L3 there are no special measures to be taken
- For dielectrics of classes O1 and K1 the measures indicated are applicable only if there are more than 25 litres of dielectric liquid in the transformer
- For dielectrics of classes K2 and K3 the measures indicated are applicable only if there are more than 50 litres of dielectric liquid in the transformer.

Class of dielectric fluid	No. of litres above which measures must be taken	Locations					
		Chamber or enclosed area reserved to qualified and authorized personnel, and separated from any other building by a distance D			Reserved to trained personnel and isolated from work areas by fire-proof walls (2 hours rating)		Other chambers or locations <sup>(2)</sup>
		D > 8 m	4 m < D < 8 m	D < 4 m <sup>(1)</sup> in the direction of occupied areas	No openings	With opening(s)	
O1	25	No special measures	Interposition of a fire-proof screen (1 hour rating)	Fire-proof wall (2 hour rating) against adjoining building	Measures (1 + 2) or 3 or 4	Measures (1 + 2 + 5) or 3 or (4 + 5)	Measures (1A + 2 + 4) <sup>(3)</sup> or 3
K1							
K2	50	No special measures		Interposition of a fire-proof screen (1 hour rating)	No special measures	Measures 1A or 3 or 4	Measures 1 or 3 or 4
K3							
L3		No special measures					

**Measure 1:** Arrangements such that if the dielectric escapes from the transformer, it will be completely contained (in a sump, by sills around the transformer, and by blocking of cable trenches, ducts and so on, during construction).

**Measure 1A:** In addition to measure 1, arrange that, in the event of liquid ignition there is no possibility of the fire spreading (any combustible material must be moved to a distance of at least 4 metres from the transformer, or at least 2 metres from it if a fire-proof screen [of 1 hour rating] is interposed).

**Measure 2:** Arrange that burning liquid will extinguish rapidly and naturally (by providing a pebble bed in the containment sump).

**Measure 3:** An automatic device (gas, pressure & thermal relay, or Buchholz) for cutting off the primary power supply, and giving an alarm, if gas appears in the transformer tank.

**Measure 4:** Automatic fire-detection devices in close proximity to the transformer, for cutting off primary power supply, and giving an alarm.

**Measure 5:** Automatic closure by fire-proof panels (1/2 hour minimum rating) of all openings (ventilation louvres, etc.) in the walls and ceiling of the substation chamber.

**Notes:**

(1) A fire-proof door (rated at 2 hours) is not considered to be an opening.

(2) Transformer chamber adjoining a workshop and separated from it by walls, the fire-proof characteristics of which are not rated for 2 hours. Areas situated in the middle of workshops the material being placed (or not) in a protective container.

(3) It is indispensable that the equipment be enclosed in a chamber, the walls of which are solid, the only orifices being those necessary for ventilation purposes.

**Fig. B27 :** Safety measures recommended in electrical installations using dielectric liquids of classes O1, K1, K2 or K3

## The determination of optimal power

### Oversizing a transformer

It results in:

- Excessive investment and unnecessarily high no-load losses, but
- Lower on-load losses

### Undersizing a transformer

It causes:

- A reduced efficiency when fully loaded, (the highest efficiency is attained in the range 50% - 70% full load) so that the optimum loading is not achieved
- On long-term overload, serious consequences for
  - The transformer, owing to the premature ageing of the windings insulation, and in extreme cases, resulting in failure of insulation and loss of the transformer
  - The installation, if overheating of the transformer causes protective relays to trip the controlling circuit-breaker.

### Definition of optimal power

In order to select an optimal power (kVA) rating for a transformer, the following factors must be taken into account:

- List the power of installed power-consuming equipment as described in Chapter A
- Decide the utilization (or demand) factor for each individual item of load
- Determine the load cycle of the installation, noting the duration of loads and overloads
- Arrange for power-factor correction, if justified, in order to:
  - Reduce cost penalties in tariffs based, in part, on maximum kVA demand
  - Reduce the value of declared load ( $P(\text{kVA}) = P(\text{kW})/\cos \varphi$ )
- Select, among the range of standard transformer ratings available, taking into account all possible future extensions to the installation.

It is important to ensure that cooling arrangements for the transformer are adequate.



Fig. B28 : SM6 metal enclosed indoor MV equipment

### 4.5 Instructions for use of MV equipment

The purpose of this chapter is to provide general guidelines on how to avoid or greatly reduce MV equipment degradation on sites exposed to humidity and pollution.

#### Normal service conditions for indoor MV equipment

All MV equipments comply with specific standards and with the IEC 62271-1 standard “Common specifications for high-voltage switchgear and controlgear”, which defines the normal conditions for the installation and use of such equipment. For instance, regarding humidity, the standard mentions:

The conditions of humidity are as follows:

- The average value of the relative humidity, measured over a period of 24 h does not exceed 90%;
- The average value of the water vapour pressure, over a period of 24 h does not exceed 2.2 kPa;
- The average value of the relative humidity, over a period of one month does not exceed 90%;
- The average value of water vapour pressure, over a period of one month does not exceed 1.8 kPa;

Under these conditions, condensation may occasionally occur.

**NOTE 1:** Condensation can be expected where sudden temperature changes occur in period of high humidity.

**NOTE 2:** To withstand the effects of high humidity and condensation, such as a breakdown of insulation or corrosion of metallic parts, switchgear designed for such conditions and tested accordingly should be used.

**NOTE 3:** Condensation may be prevented by special design of the building or housing, by suitable ventilation and heating of the station or by use of dehumidifying equipment.

As indicated in the standard, condensation may occasionally occur even under normal conditions. The standard goes on to indicate special measures concerning the substation premises that can be implemented to prevent condensation.

#### Use under severe conditions

Under certain severe conditions concerning humidity and pollution, largely beyond the normal conditions of use mentioned above, correctly designed electrical equipment can be subject to damage by rapid corrosion of metal parts and surface degradation of insulating parts.

#### Remedial measures for condensation problems

- Carefully design or adapt substation ventilation.
- Avoid temperature variations.
- Eliminate sources of humidity in the substation environment.
- Install an air conditioning system.
- Make sure cabling is in accordance with applicable rules.

#### Remedial measures for pollution problems

- Equip substation ventilation openings with chevron-type baffles to reduce entry of dust and pollution.
- Keep substation ventilation to the minimum required for evacuation of transformer heat to reduce entry of pollution and dust.
- Use MV cubicles with a sufficiently high degree of protection (IP).
- Use air conditioning systems with filters to restrict entry of pollution and dust.
- Regularly clean all traces of pollution from metal and insulating parts.

#### Ventilation

Substation ventilation is generally required to dissipate the heat produced by transformers and to allow drying after particularly wet or humid periods. However, a number of studies have shown that excessive ventilation can drastically increase condensation.

Ventilation should therefore be kept to the minimum level required.

Furthermore, ventilation should never generate sudden temperature variations that can cause the dew point to be reached.

For this reason:

Natural ventilation should be used whenever possible. If forced ventilation is necessary, the fans should operate continuously to avoid temperature fluctuations.

Guidelines for sizing the air entry and exit openings of substations are presented hereafter.



## Calculation methods

A number of calculation methods are available to estimate the required size of substation ventilation openings, either for the design of new substations or the adaptation of existing substations for which condensation problems have occurred. The basic method is based on transformer dissipation. The required ventilation opening surface areas  $S$  and  $S'$  can be estimated using the following formulas:

$$S = \frac{1.8 \times 10^{-4} P}{\sqrt{H}} \text{ and } S' = 1.10 \times S$$

where:

$S$  = Lower (air entry) ventilation opening area [ $\text{m}^2$ ] (grid surface deducted)

$S'$  = Upper (air exit) ventilation opening area [ $\text{m}^2$ ] (grid surface deducted)

$P$  = Total dissipated power [W]

$P$  is the sum of the power dissipated by:

- The transformer (dissipation at no load and due to load)
  - The LV switchgear
  - The MV switchgear
- $H$  = Height between ventilation opening mid-points [m]  
See Fig. B29

### Note:

This formula is valid for a yearly average temperature of 20 °C and a maximum altitude of 1,000 m.

It must be noted that these formulae are able to determine only one order of magnitude of the sections  $S$  and  $S'$ , which are qualified as thermal section, i.e. fully open and just necessary to evacuate the thermal energy generated inside the MV/LV substation.

The practical sections are of course larger according to the adopted technological solution.

Indeed, the real air flow is strongly dependant:

- on the openings shape and solutions adopted to ensure the cubicle protection index (IP): metal grid, stamped holes, chevron louvers,...
- on internal components size and their position compared to the openings: transformer and/or retention oil box position and dimensions, flow channel between the components, ...
- and on some physical and environmental parameters: outside ambient temperature, altitude, magnitude of the resulting temperature rise.

The understanding and the optimization of the attached physical phenomena are subject to precise flow studies, based on the fluid dynamics laws, and realized with specific analytic software.

### Example:

Transformer dissipation = 7,970 W

LV switchgear dissipation = 750 W

MV switchgear dissipation = 300 W

The height between ventilation opening mid-points is 1.5 m.

Calculation:

Dissipated Power  $P = 7,970 + 750 + 300 = 9,020$  W

$$S = \frac{1.8 \times 10^{-4} P}{\sqrt{1.5}} = 1.32 \text{ m}^2 \text{ and } S' = 1.1 \times 1.32 = 1.46 \text{ m}^2$$

## Ventilation opening locations

To favour evacuation of the heat produced by the transformer via natural convection, ventilation openings should be located at the top and bottom of the wall near the transformer. The heat dissipated by the MV switchboard is negligible.

To avoid condensation problems, the substation ventilation openings should be located as far as possible from the switchboard (see Fig. B 30).

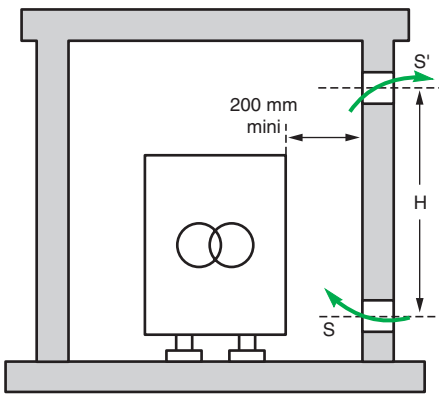


Fig. B29 : Natural ventilation

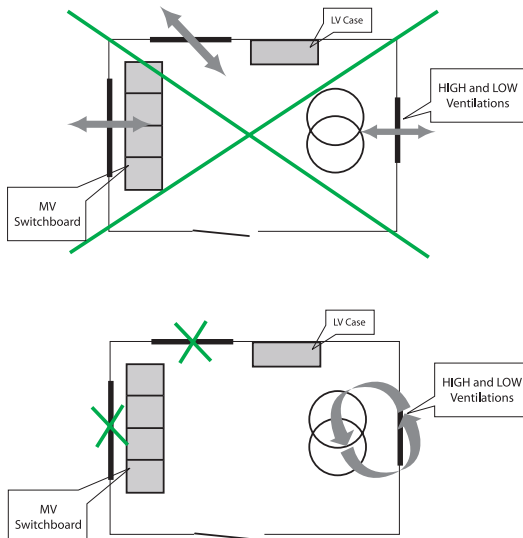


Fig. B30 : Ventilation opening locations

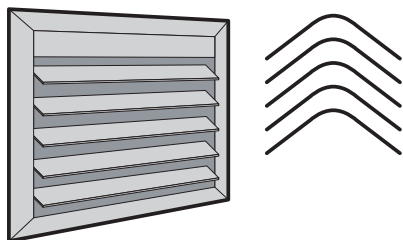


Fig. B31 : Chevron-blade baffles

### Type of ventilation openings

To reduce the entry of dust, pollution, mist, etc., the substation ventilation openings should be equipped with chevron-blade baffles.

Always make sure the baffles are oriented in the right direction (see Fig. B31).

### Temperature variations inside cubicles

To reduce temperature variations, always install anti-condensation heaters inside MV cubicles if the average relative humidity can remain high over a long period of time. The heaters must operate continuously, 24 hours a day all year long.

Never connect them to a temperature control or regulation system as this could lead to temperature variations and condensation as well as a shorter service life for the heating elements. Make sure the heaters offer an adequate service life (standard versions are generally sufficient).

### Temperature variations inside the substation

The following measures can be taken to reduce temperature variations inside the substation:

- Improve the thermal insulation of the substation to reduce the effects of outdoor temperature variations on the temperature inside the substation.
- Avoid substation heating if possible. If heating is required, make sure the regulation system and/or thermostat are sufficiently accurate and designed to avoid excessive temperature swings (e.g. no greater than 1 °C).

If a sufficiently accurate temperature regulation system is not available, leave the heating on continuously, 24 hours a day all year long.

- Eliminate cold air drafts from cable trenches under cubicles or from openings in the substation (under doors, roof joints, etc.).

### Substation environment and humidity

Various factors outside the substation can affect the humidity inside.

- Plants

Avoid excessive plant growth around the substation.

- Substation waterproofing

The substation roof must not leak. Avoid flat roofs for which waterproofing is difficult to implement and maintain.

- Humidity from cable trenches

Make sure cable trenches are dry under all conditions.

A partial solution is to add sand to the bottom of the cable trench.

### Pollution protection and cleaning

Excessive pollution favours leakage current, tracking and flashover on insulators.

To prevent MV equipment degradation by pollution, it is possible to either protect the equipment against pollution or regularly clean the resulting contamination.

### Protection

Indoor MV switchgear can be protected by enclosures providing a sufficiently high degree of protection (IP).

### Cleaning

If not fully protected, MV equipment must be cleaned regularly to prevent degradation by contamination from pollution.

Cleaning is a critical process. The use of unsuitable products can irreversibly damage the equipment.

For cleaning procedures, please contact your Schneider Electric correspondent.

## 5 The consumer substation with MV metering

B32

*A consumer substation with MV metering is an electrical installation connected to a utility supply system at a nominal voltage of 1 kV - 35 kV and generally includes a single MV/LV transformer which exceeds 1,250 kVA, or several smaller transformers. The rated current of the MV switchgear does not normally exceed 400 A.*

### 5.1 General

#### Functions

##### The substation

According to the complexity of the installation and the manner in which the load is divided, the substation:

- Might include one room containing the MV switchboard and metering panel(s), together with the transformer(s) and low-voltage main distribution board(s),
- Or might supply one or more transformer rooms, which include local LV distribution boards, supplied at MV from switchgear in a main substation, similar to that described above.

These substations may be installed, either:

- Inside a building, or
- Outdoors in prefabricated housings.

##### Connection to the MV network

Connection at MV can be:

- Either by a single service cable or overhead line, or
- Via two mechanically interlocked load-break switches with two service cables from duplicate supply feeders, or
- Via two load-break switches of a ring-main unit.

##### Metering

Before the installation project begins, the agreement of the power-supply utility regarding metering arrangements must be obtained.

A metering panel will be incorporated in the MV switchboard. Voltage transformers and current transformers, having the necessary metering accuracy, may be included in the main incoming circuit-breaker panel or (in the case of the voltage transformer) may be installed separately in the metering panel.

##### Transformer rooms

If the installation includes a number of transformer rooms, MV supplies from the main substation may be by simple radial feeders connected directly to the transformers, or by duplicate feeders to each room, or again, by a ring-main, according to the degree of supply availability desired.

In the two latter cases, 3-panel ring-main units will be required at each transformer room.

##### Local emergency generators

Emergency standby generators are intended to maintain a power supply to essential loads, in the event of failure of the power supply system.

##### Capacitors

Capacitors will be installed, according to requirements:

- In stepped MV banks at the main substation, or
- At LV in transformer rooms.

##### Transformers

For additional supply-security reasons, transformers may be arranged for automatic changeover operation, or for parallel operation.

#### One-line diagrams

The diagrams shown in **Figure B32** next page represent:

- The different methods of MV service connection, which may be one of four types:
  - Single-line service
  - Single-line service (equipped for extension to form a ring main)
  - Duplicate supply service
  - Ring main service
- General protection at MV, and MV metering functions
- Protection of outgoing MV circuits
- Protection of LV distribution circuits



## 5 The consumer substation with MV metering

B33

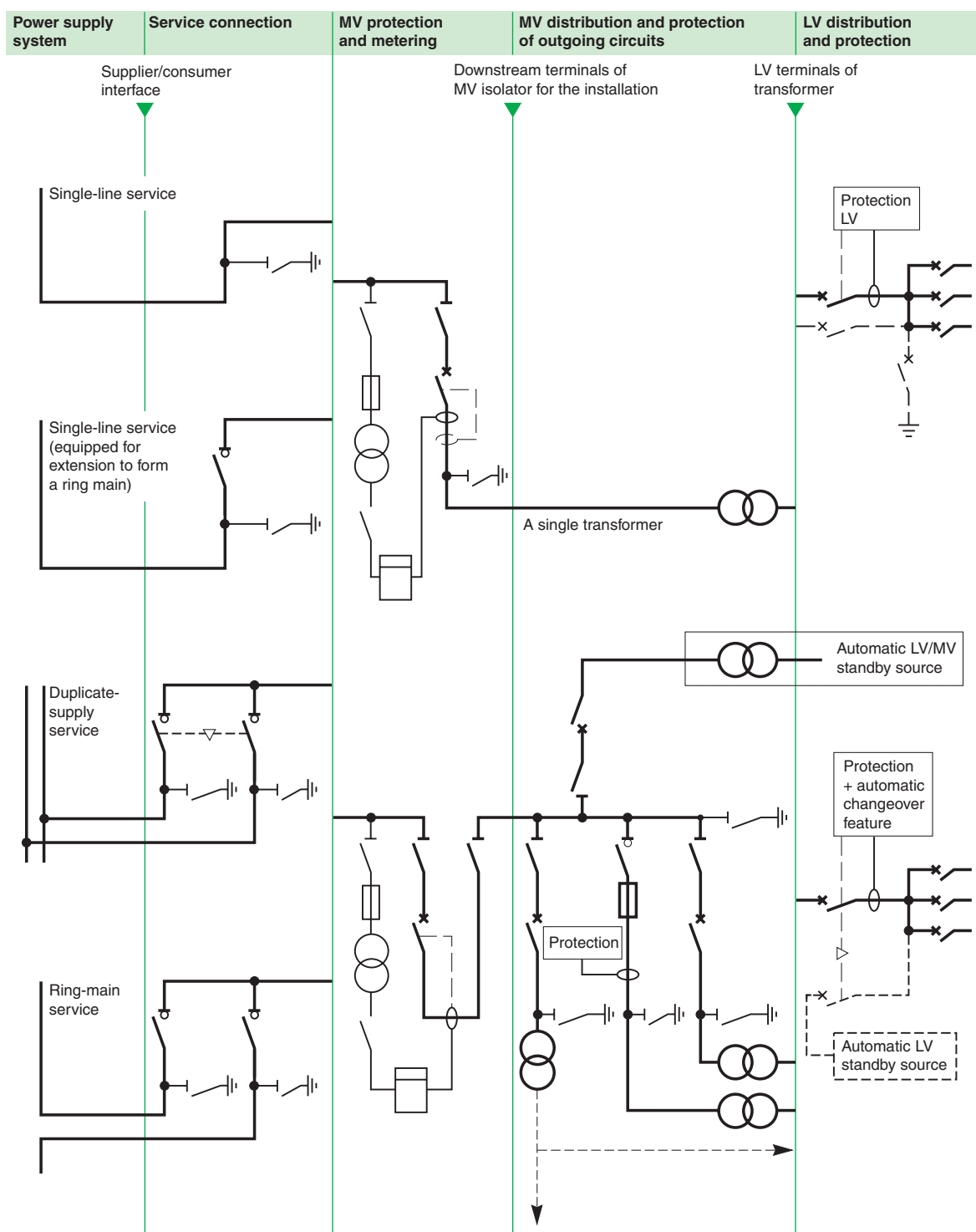


Fig. B32 : Consumer substation with MV metering

## 5.2 Choice of panels

A substation with MV metering includes, in addition to the panels described in 4.2, panels specifically designed for metering and, if required, for automatic or manual changeover from one source to another.

### Metering and general protection

These two functions are achieved by the association of two panels:

- One panel containing the VT
- The main MV circuit-breaker panel containing the CTs for measurement and protection

The general protection is usually against overcurrent (overload and short-circuit) and earth faults. Both schemes use protective relays which are sealed by the power-supply utility.

### Substation including generators

#### Generator in stand alone operation

If the installation needs great power supply availability, a MV standby generator set can be used. In such a case, the installation must include an automatic changeover. In order to avoid any possibility of parallel operation of the generator with the power supply network, a specific panel with automatic changeover is needed (see **Fig. B33**).

##### ■ Protection

Specific protective devices are intended to protect the generator itself. It must be noted that, due to the very low short-circuit power of the generator comparing with the power supply network, a great attention must be paid to protection discrimination.

##### ■ Control

A voltage regulator controlling an alternator is generally arranged to respond to a reduction of voltage at its terminals by automatically increasing the excitation current of the alternator, until the voltage is restored to normal. When it is intended that the alternator should operate in parallel with others, the AVR (Automatic Voltage Regulator) is switched to "parallel operation" in which the AVR control circuit is slightly modified (compounded) to ensure satisfactory sharing of kvars with the other parallel machines.

When a number of alternators are operating in parallel under AVR control, an increase in the excitation current of one of them (for example, carried out manually after switching its AVR to Manual control) will have practically no effect on the voltage level. In fact, the alternator in question will simply operate at a lower power factor (more kVA, and therefore more current) than before.

The power factor of all the other machines will automatically improve, such that the load power factor requirements are satisfied, as before.

#### Generator operating in parallel with the utility supply network

To connect a generator set on the network, the agreement of the power supply utility is usually required. Generally the equipment (panels, protection relays) must be approved by the utility.

The following notes indicate some basic consideration to be taken into account for protection and control.

##### ■ Protection

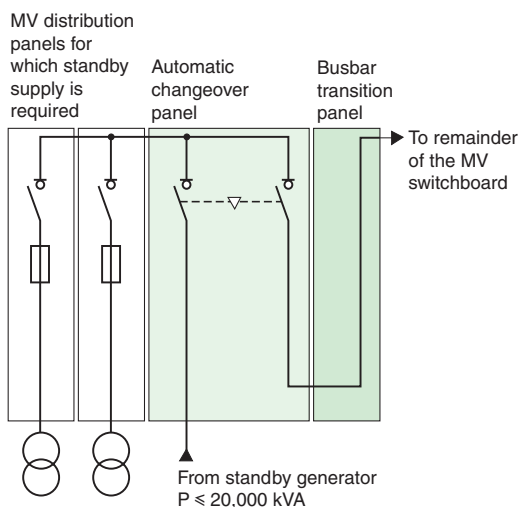
To study the connection of generator set, the power supply utility needs some data as follows :

- Power injected on the network
- Connection mode
- Short-circuit current of the generator set
- Voltage unbalance of the generator
- etc.

Depending on the connection mode, dedicated uncoupling protection functions are required :

- Under-voltage and over-voltage protection
- Under-frequency and over-frequency protection
- Zero sequence overvoltage protection
- Maximum time of coupling (for momentary coupling)
- Reverse real power

For safety reasons, the switchgear used for uncoupling must also be provided with the characteristics of a disconnector (i.e total isolation of all active conductors between the generator set and the power supply network).



**Fig. B33** : Section of MV switchboard including standby supply panel

## ■ Control

When generators at a consumer's substation operate in parallel with all the generation of the utility power supply system, supposing the power system voltage is reduced for operational reasons (it is common to operate MV systems within a range of  $\pm 5\%$  of nominal voltage, or even more, where load-flow patterns require it), an AVR set to maintain the voltage within  $\pm 3\%$  (for example) will immediately attempt to raise the voltage by increasing the excitation current of the alternator.

Instead of raising the voltage, the alternator will simply operate at a lower power factor than before, thereby increasing its current output, and will continue to do so, until it is eventually tripped out by its overcurrent protective relays. This is a well-known problem and is usually overcome by the provision of a "constant power-factor" control switch on the AVR unit.

By making this selection, the AVR will automatically adjust the excitation current to match whatever voltage exists on the power system, while at the same time maintaining the power factor of the alternator constant at the pre-set value (selected on the AVR control unit).

In the event that the alternator becomes decoupled from the power system, the AVR must be automatically (rapidly) switched back to "constant-voltage" control.

## 5.3 Parallel operation of transformers

The need for operation of two or more transformers in parallel often arises due to:

- Load growth, which exceeds the capacity of an existing transformer
- Lack of space (height) for one large transformer
- A measure of security (the probability of two transformers failing at the same time is very small)
- The adoption of a standard size of transformer throughout an installation

### Total power (kVA)

The total power (kVA) available when two or more transformers of the same kVA rating are connected in parallel, is equal to the sum of the individual ratings, providing that the percentage impedances are all equal and the voltage ratios are identical.

Transformers of unequal kVA ratings will share a load practically (but not exactly) in proportion to their ratings, providing that the voltage ratios are identical and the percentage impedances (at their own kVA rating) are identical, or very nearly so. In these cases, a total of more than 90% of the sum of the two ratings is normally available.

It is recommended that transformers, the kVA ratings of which differ by more than 2:1, should not be operated permanently in parallel.

### Conditions necessary for parallel operation

All paralleled units must be supplied from the same network.

The inevitable circulating currents exchanged between the secondary circuits of paralleled transformers will be negligibly small providing that:

- Secondary cabling from the transformers to the point of paralleling have approximately equal lengths and characteristics
- The transformer manufacturer is fully informed of the duty intended for the transformers, so that:
  - The winding configurations (star, delta, zigzag star) of the several transformers have the same phase change between primary and secondary voltages
  - The short-circuit impedances are equal, or differ by less than 10%
  - Voltage differences between corresponding phases must not exceed 0.4%
  - All possible information on the conditions of use, expected load cycles, etc. should be given to the manufacturer with a view to optimizing load and no-load losses

## 5 The consumer substation with MV metering

B36

### Common winding arrangements

As described in 4.4 "Electrical characteristics-winding configurations" the relationships between primary, secondary, and tertiary windings depend on:

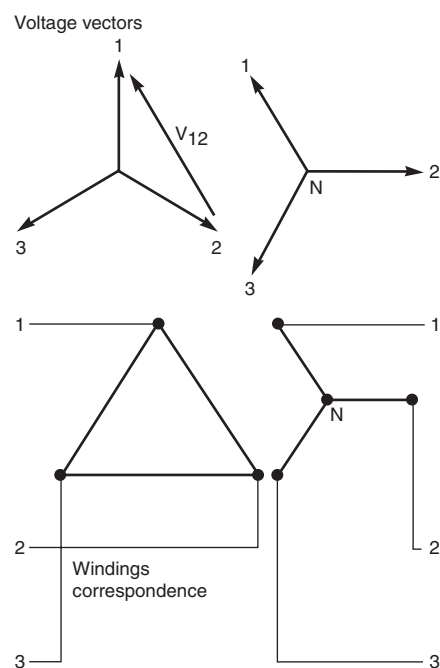
- Type of windings (delta, star, zigzag)
- Connection of the phase windings

Depending on which ends of the windings form the star point (for example), a star winding will produce voltages which are  $180^\circ$  displaced with respect to those produced if the opposite ends had been joined to form the star point. Similar  $180^\circ$  changes occur in the two possible ways of connecting phase-to-phase coils to form delta windings, while four different combinations of zigzag connections are possible.

- The phase displacement of the secondary phase voltages with respect to the corresponding primary phase voltages.

As previously noted, this displacement (if not zero) will always be a multiple of  $30^\circ$  and will depend on the two factors mentioned above, viz type of windings and connection (i.e. polarity) of the phase windings.

By far the most common type of distribution transformer winding configuration is the Dyn 11 connection (see **Fig. B34**).



$V_{12}$  on the primary winding produces  $V_{1N}$  in the secondary winding and so on ...

**Fig. B34** : Phase change through a Dyn 11 transformer

## 6 Constitution of MV/LV distribution substations

B37

MV/LV substations are constructed according to the magnitude of the load and the kind of power system in question.

Substations may be built in public places, such as parks, residential districts, etc. or on private premises, in which case the power supply authority must have unrestricted access. This is normally assured by locating the substation, such that one of its walls, which includes an access door, coincides with the boundary of the consumers premises and the public way.

### 6.1 Different types of substation

Substations may be classified according to metering arrangements (MV or LV) and type of supply (overhead line or underground cable).

The substations may be installed:

- Either indoors in room specially built for the purpose, within a building, or
- An outdoor installation which could be :
  - Installed in a dedicated enclosure prefabricated or not, with indoor equipment (switchgear and transformer)
  - Ground mounted with outdoor equipment (switchgear and transformers)
  - Pole mounted with dedicated outdoor equipment (switchgear and transformers)

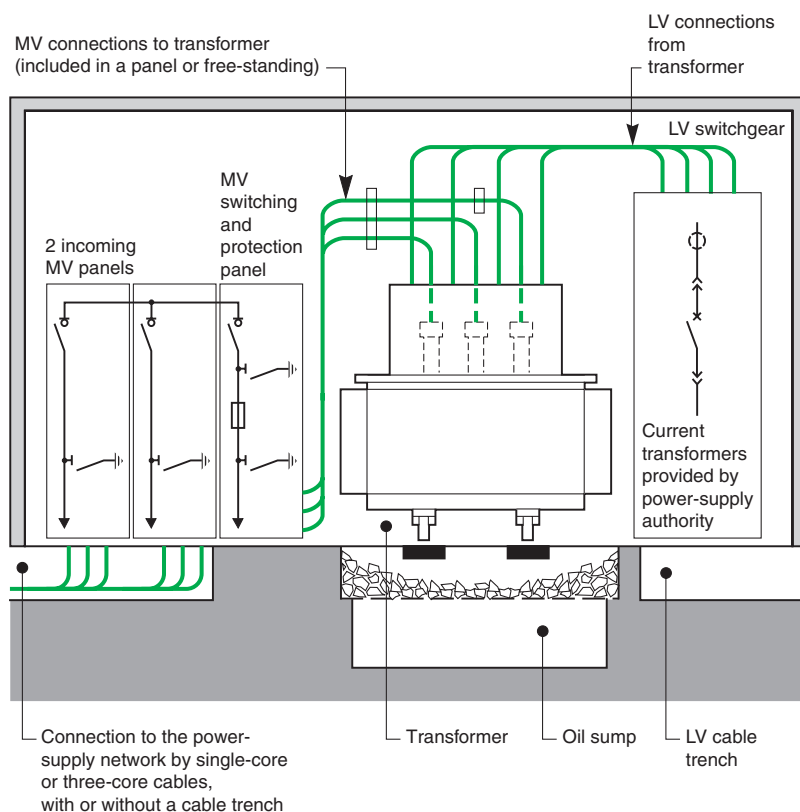
Prefabricated substations provide a particularly simple, rapid and competitive choice.

### 6.2 Indoor substation

#### Conception

**Figure B35** shows a typical equipment layout recommended for a LV metering substation.

Remark: the use of a cast-resin dry-type transformer does not need a fireprotection oil sump. However, periodic cleaning is needed.



**Fig. B35 :** Typical arrangement of switchgear panels for LV metering

## 6 Constitution of MV/LV distribution substations

B38

### Service connections and equipment interconnections

#### At high voltage

- Connections to the MV system are made by, and are the responsibility of the utility
- Connections between the MV switchgear and the transformers may be:
  - By short copper bars where the transformer is housed in a panel forming part of the MV switchboard
  - By single-core screened cables with synthetic insulation, with possible use of plug-in type terminals at the transformer

#### At low voltage

- Connections between the LV terminals of the transformer and the LV switchgear may be:
  - Single-core cables
  - Solid copper bars (circular or rectangular section) with heat-shrinkable insulation

#### Metering (see Fig. B36)

- Metering current transformers are generally installed in the protective cover of the power transformer LV terminals, the cover being sealed by the supply utility
- Alternatively, the current transformers are installed in a sealed compartment within the main LV distribution cabinet
- The meters are mounted on a panel which is completely free from vibrations
- Placed as close to the current transformers as possible, and
- Are accessible only to the utility

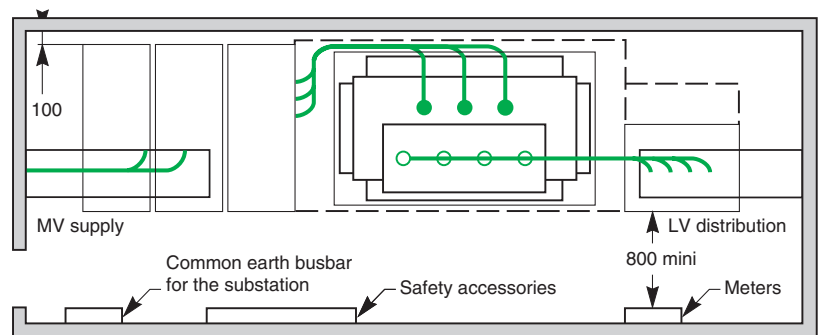


Fig. B36 : Plan view of typical substation with LV metering

### Earthing circuits

The substation must include:

- An earth electrode for all exposed conductive parts of electrical equipment in the substation and exposed extraneous metal including:
  - Protective metal screens
  - Reinforcing rods in the concrete base of the substation

### Substation lighting

Supply to the lighting circuits can be taken from a point upstream or downstream of the main incoming LV circuit-breaker. In either case, appropriate overcurrent protection must be provided. A separate automatic circuit (or circuits) is (are) recommended for emergency lighting purposes.

Operating switches, pushbuttons, etc. are normally located immediately adjacent to entrances.

Lighting fittings are arranged such that:

- Switchgear operating handles and position indication markings are adequately illuminated
- All metering dials and instruction plaques and so on, can be easily read

## Materials for operation and safety

According to local safety rules, generally, the substation is provided with:

- Materials for assuring safe exploitation of the equipment including:
  - Insulating stool and/or an insulating mat (rubber or synthetic)
  - A pair of insulated gloves stored in an envelope provided for the purpose
  - A voltage-detecting device for use on the MV equipment
  - Earthing attachments (according to type of switchgear)
- Fire-extinguishing devices of the powder or CO2 type
- Warning signs, notices and safety alarms:
  - On the external face of all access doors, a DANGER warning plaque and prohibition of entry notice, together with instructions for first-aid care for victims of electrical accidents.

## 6.3 Outdoor substations

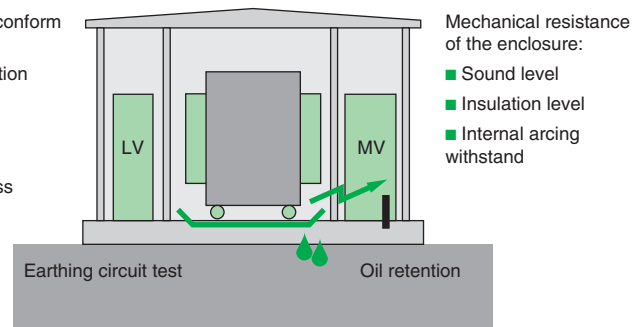
### Outdoor substation with prefabricated enclosures

A prefabricated MV/LV substation complying with IEC 62271-202 standard includes :

- equipment in accordance with IEC standards
- a type tested enclosure, which means during its design, it has undergone a battery of tests (see **Fig. B37**):
  - Degree of protection
  - Functional tests
  - Temperature class
  - Non-flammable materials
  - Mechanical resistance of the enclosure
  - Sound level
  - Insulation level
  - Internal arc withstand
  - Earthing circuit test
  - Oil retention,...

Use of equipment conform to IEC standards:

- Degree of protection
- Electromagnetic compatibility
- Functional tests
- Temperature class
- Non-flammable materials



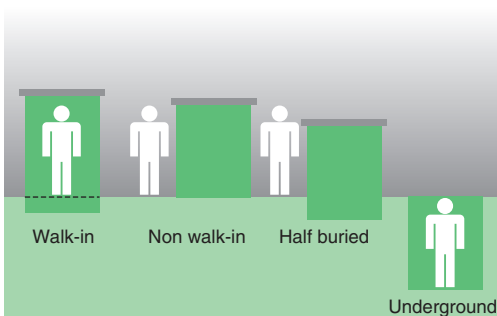
**Fig. B37** : Type tested substation according to IEC 62271-202 standard

### Main benefits are :

- Safety:
  - For public and operators thanks to a high reproducible quality level
- Cost effective:
  - Manufactured, equipped and tested in the factory
  - Delivery time
  - Delivered ready to be connected.

**IEC 62271-202 standard includes four main designs** (see **Fig. B38**)

- Walk-in type substation :
  - Operation protected from bad weather conditions
- Non walk-in substation
  - Ground space savings, and outdoors operations
- Half buried substation
  - Limited visual impact
- Underground substation
  - Blends completely into the environment.



a -



b -



**Fig. B38** : The four designs according to IEC 62271-202 standard and two pictures **[a]** walk-in type MV/LV substation; **[b]** half buried type MV/LV substation

## 6 Constitution of MV/LV distribution substations

B40

### Outdoor substations without enclosures (see Fig. B39)

These kinds of outdoor substation are common in some countries, based on weatherproof equipment exposed to the elements.

These substations comprise a fenced area in which three or more concrete plinths are installed for:

- A ring-main unit, or one or more switch-fuse or circuit-breaker unit(s)
- One or more transformer(s), and
- One or more LV distribution panel(s).

### Pole mounted substations

#### Field of application

These substations are mainly used to supply isolated rural consumers from MV overhead line distribution systems.

#### Constitution

In this type of substation, most often, the MV transformer protection is provided by fuses.

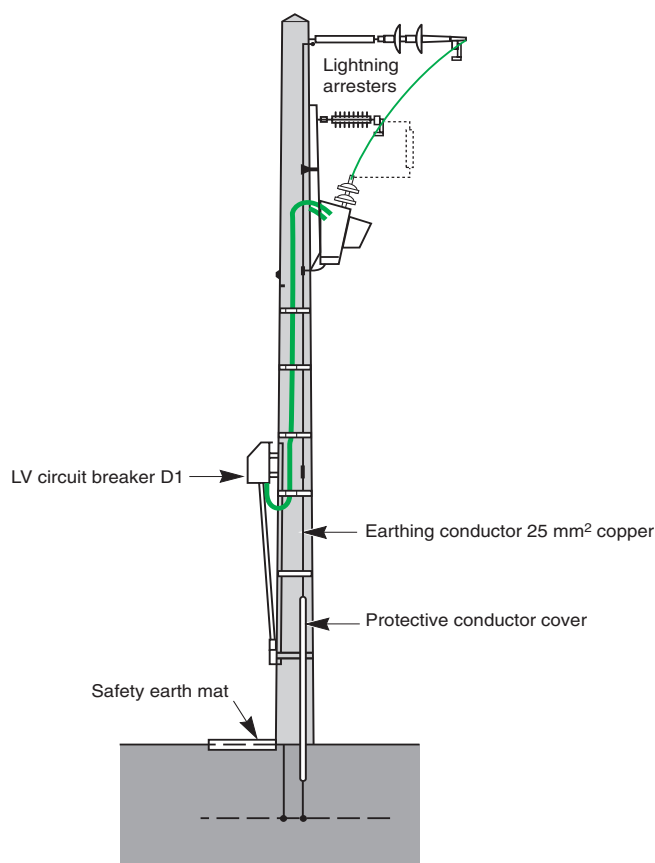
Lightning arresters are provided, however, to protect the transformer and consumers as shown in **Figure B40**.

#### General arrangement of equipment

As previously noted the location of the substation must allow easy access, not only for personnel but for equipment handling (raising the transformer, for example) and the manœuvring of heavy vehicles.



**Fig. B39** : Outdoor substations without enclosures



**Fig. B40** : Pole-mounted transformer substation



# Chapter C

## Connection to the LV utility distribution network

### Contents

1	<b>Low-voltage utility distribution networks</b>	<b>C2</b>
	1.1 Low-voltage consumers	C2
	1.2 Low-voltage distribution networks	C10
	1.3 The consumer service connection	C11
	1.4 Quality of supply voltage	C15
2	<b>Tariffs and metering</b>	<b>C16</b>

C1

# 1 Low-voltage utility distribution networks

C2

The most-common LV supplies are within the range 120 V single phase to 240/415 V 3-phase 4-wires.

Loads up to 250 kVA can be supplied at LV, but power-supply organizations generally propose a MV service at load levels for which their LV networks are marginally adequate.

An international voltage standard for 3-phase 4-wire LV systems is recommended by the IEC 60038 to be 230/400 V

## 1.1 Low-voltage consumers

In Europe, the transition period on the voltage tolerance to “230V/400V + 10% / - 10%” has been extended for another 5 years up to the year 2008.

Low-voltage consumers are, by definition, those consumers whose loads can be satisfactorily supplied from the low-voltage system in their locality.

The voltage of the local LV network may be 120/208 V or 240/415 V, i.e. the lower or upper extremes of the most common 3-phase levels in general use, or at some intermediate level, as shown in **Figure C1**.

An international voltage standard for 3-phase 4-wire LV systems is recommended by the IEC 60038 to be 230/400 V.

Loads up to 250 kVA can be supplied at LV, but power-supply organizations generally propose a MV service at load levels for which their LV networks are marginally adequate.

Country	Frequency & tolerance (Hz & %)	Domestic (V)	Commercial (V)	Industrial (V)
Afghanistan	50 220 (k)	380/220 (a)	380/220 (a)	380/220 (a)
Algeria	50 ± 1.5	220/127 (e) 220 (k)	380/220 (a) 220/127 (a)	10,000 5,500 6,600 380/220 (a)
Angola	50	380/220 (a) 220 (k)	380/220 (a)	380/220 (a)
Antigua and Barbuda	60	240 (k) 120 (k)	400/230 (a) 120/208 (a)	400/230 (a) 120/208 (a)
Argentina	50 ± 2	380/220 (a) 220 (k)	380/220 (a) 220 (k)	
Armenia	50 ± 5	380/220 (a) 220 (k)	380/220 (a) 220 (k)	380/220 (a)
Australia	50 ± 0.1	415/240 (a) 240 (k)	415/240 (a) 440/250 (a) 440 (m)	22,000 11,000 6,600 415/240 440/250
Austria	50 ± 0.1	230 (k)	380/230 (a) (b) 230 (k)	5,000 380/220 (a)
Azerbaijan	50 ± 0.1	208/120 (a) 240/120 (k)	208/120 (a) 240/120 (k)	
Bahrain	50 ± 0.1	415/240 (a) 240 (k)	415/240 (a) 240 (k)	11,000 415/240 (a) 240 (k)
Bangladesh	50 ± 2	410/220 (a) 220 (k)	410/220 (a)	11,000 410/220 (a)
Barbados	50 ± 6	230/115 (j) 115 (k)	230/115 (j) 200/115 (a) 220/115 (a)	230/400 (g) 230/155 (j)
Belarus	50	380/220 (a) 220 (k) 220/127 (a) 127 (k)	380/220 (a) 220 (k)	380/220 (a)
Belgium	50 ± 5	230 (k) 230 (a) 3N, 400	230 (k) 230 (a) 3N, 400	6,600 10,000 11,000 15,000
Bolivia	50 ± 0.5	230 (k)	400/230 (a) 230 (k)	400/230 (a)
Botswana	50 ± 3	220 (k)	380/220 (a)	380/220 (a)
Brazil	60	220 (k) 127 (k)	220/380 (a) 127/220 (a)	13,800 11,200 220/380 (a) 127/220 (a)
Brunei	50 ± 2	230	230	11,000 68,000
Bulgaria	50 ± 0.1	220	220/240	1,000 690 380

Fig. C1 : Voltage of local LV network and their associated circuit diagrams (continued on next page)

# 1 Low-voltage utility distribution networks

Country	Frequency & tolerance (Hz & %)	Domestic (V)	Commercial (V)	Industrial (V)
Cambodia	50 ± 1	220 (k)	220/300	220/380
Cameroon	50 ± 1	220/260 (k)	220/260 (k)	220/380 (a)
Canada	60 ± 0.02	120/240 (j)	347/600 (a) 480 (f) 240 (f) 120/240 (j) 120/208 (a)	7,200/12,500 347/600 (a) 120/208 600 (f) 480 (f) 240 (f)
Cape Verde		220	220	380/400
Chad	50 ± 1	220 (k)	220 (k)	380/220 (a)
Chile	50 ± 1	220 (k)	380/220 (a)	380/220 (a)
China	50 ± 0.5	220 (k)	380/220 (a) 220 (k)	380/220 (a) 220 (k)
Colombia	60 ± 1	120/240 (g) 120 (k)	120/240 (g) 120 (k)	13,200 120/240 (g)
Congo	50	220 (k)	240/120 (j) 120 (k)	380/220 (a)
Croatia	50	400/230 (a) 230 (k)	400/230 (a) 230 (k)	400/230 (a)
Cyprus	50 ± 0.1	240 (k)	415/240	11,000 415/240
Czech Republic	50 ± 1	230	500 230/400	400,000 220,000 110,000 35,000 22,000 10,000 6,000 3,000
Denmark	50 ± 1	400/230 (a)	400/230 (a)	400/230 (a)
Djibouti	50		400/230 (a)	400/230 (a)
Dominica	50	230 (k)	400/230 (a)	400/230 (a)
Egypt	50 ± 0.5	380/220 (a) 220 (k)	380/220 (a) 220 (k)	66,000 33,000 20,000 11,000 6,600 380/220 (a)
Estonia	50 ± 1	380/220 (a) 220 (k)	380/220 (a) 220 (k)	380/220 (a)
Ethiopia	50 ± 2.5	220 (k)	380/231 (a)	15 000 380/231 (a)
Falkland Islands	50 ± 3	230 (k)	415/230 (a)	415/230 (a)
Fidji Islands	50 ± 2	415/240 (a) 240 (k)	415/240 (a) 240 (k)	11,000 415/240 (a)
Finland	50 ± 0.1	230 (k)	400/230 (a)	690/400 (a) 400/230 (a)
France	50 ± 1	400/230 (a) 230 (a)	400/230 690/400 590/100	20,000 10,000 230/400
Gambia	50	220 (k)	220/380	380
Georgia	50 ± 0.5	380/220 (a) 220 (k)	380/220 (a) 220 (k)	380/220 (a)
Germany	50 ± 0.3	400/230 (a) 230 (k)	400/230 (a) 230 (k)	20,000 10,000 6,000 690/400 400/230
Ghana	50 ± 5	220/240	220/240	415/240 (a)
Gibraltar	50 ± 1	415/240 (a)	415/240 (a)	415/240 (a)
Greece	50	220 (k) 230	6,000 380/220 (a)	22,000 20,000 15,000 6,600
Granada	50	230 (k)	400/230 (a)	400/230 (a)
Hong Kong	50 ± 2	220 (k)	380/220 (a) 220 (k)	11,000 386/220 (a)
Hungary	50 ± 5	220	220	220/380
Iceland	50 ± 0.1	230	230/400	230/400

Fig. C1 : Voltage of local LV network and their associated circuit diagrams (continued on next page)

# 1 Low-voltage utility distribution networks

C4

Country	Frequency & tolerance (Hz & %)	Domestic (V)	Commercial (V)	Industrial (V)
India	50 ± 1.5	440/250 (a) 230 (k)	440/250 (a) 230 (k)	11,000 400/230 (a) 440/250 (a)
Indonesia	50 ± 2	220 (k)	380/220 (a)	150,000 20,000 380/220 (a)
Iran	50 ± 5	220 (k)	380/220 (a)	20,000 11,000 400/231 (a) 380/220 (a)
Iraq	50	220 (k)	380/220 (a)	11,000 6,600 3,000 380/220 (a)
Ireland	50 ± 2	230 (k)	400/230 (a)	20,000 10,000 400/230 (a)
Israel	50 ± 0.2	400/230 (a) 230 (k)	400/230 (a) 230 (k)	22,000 12,600 6,300 400/230 (a)
Italy	50 ± 0.4	400/230 (a) 230 (k)	400/230 (a)	20,000 15,000 10,000 400/230 (a)
Jamaica	50 ± 1	220/110 (g) (j)	220/110 (g) (j)	4,000 2,300 220/110 (g)
Japan (east)	+ 0.1 - 0.3	200/100 (h)	200/100 (h) (up to 50 kW)	140,000 60,000 20,000 6,000 200/100 (h)
Jordan	50	380/220 (a) 400/230 (k)	380/220 (a)	400 (a)
Kazakhstan	50	380/220 (a) 220 (k) 220/127 (a) 127 (k)	380/220 (a) 220 (k)	380/220 (a)
Kenya	50	240 (k)	415/240 (a)	415/240 (a)
Kirghizia	50	380/220 (a) 220 (k) 220/127 (a) 127 (k)	380/220 (a) 220 (k)	380/220 (a)
Korea (North)	60 +0, -5	220 (k)	220/380 (a)	13,600 6,800
Korea (South)	60	100 (k)	100/200 (j)	
Kuwait	50 ± 3	240 (k)	415/240 (a)	415/240 (a)
Laos	50 ± 8	380/220 (a)	380/220 (a)	380/220 (a)
Lesotho		220 (k)	380/220 (a)	380/220 (a)
Latvia	50 ± 0.4	380/220 (a) 220 (k)	380/220 (a) 220 (k)	380/220 (a)
Lebanon	50	220 (k)	380/220 (a)	380/220 (a)
Libya	50	230 (k) 127 (k)	400/230 (a) 220/127 (a) 230 (k) 127 (k)	400/230 (a) 220/127 (a)
Lithuania	50 ± 0.5	380/220 (a) 220 (k)	380/220 (a) 220 (k)	380/220 (a)
Luxembourg	50 ± 0.5	380/220 (a)	380/220 (a)	20,000 15,000 5,000
Macedonia	50	380/220 (a) 220 (k)	380/220 (a) 220 (k)	10,000 6,600 380/220 (a)
Madagascar	50	220/110 (k)	380/220 (a)	35,000 5,000 380/220

Fig. C1 : Voltage of local LV network and their associated circuit diagrams (continued on next page)

# 1 Low-voltage utility distribution networks

C5

Country	Frequency & tolerance (Hz & %)	Domestic (V)	Commercial (V)	Industrial (V)
Malaysia	50 ± 1	240 (k) 415 (a)	415/240 (a)	415/240 (a)
Malawi	50 ± 2.5	230 (k)	400 (a) 230 (k)	400 (a)
Mali	50	220 (k) 127 (k)	380/220 (a) 220/127 (a) 220 (k) 127 (k)	380/220 (a) 220/127 (a)
Malta	50 ± 2	240 (k)	415/240 (a)	415/240 (a)
Martinique	50	127 (k)	220/127 (a) 127 (k)	220/127 (a)
Mauritania	50 ± 1	230 (k)	400/230 (a)	400/230 (a)
Mexico	60 ± 0.2	127/220 (a) 220 (k) 120 (l)	127/220 (a) 220 (k) 120 (l)	13,800 13,200 277/480 (a) 127/220 (b)
Moldavia	50	380/220 (a) 220 (k) 220/127 (a) 127 (k)	380/220 (a) 220 (k)	380/220 (a)
Morocco	50 ± 5	380/220 (a) 220/110 (a)	380/220 (a)	225,000 150,000 60,000 22,000 20,000
Mozambique	50	380/220 (a)	380/220 (a)	6,000 10,000
Nepal	50 ± 1	220 (k)	440/220 (a) 220 (k)	11,000 440/220 (a)
Netherlands	50 ± 0.4	230/400 (a) 230 (k)	230/400 (a)	25,000 20,000 12,000 10,000 230/400
New Zealand	50 ± 1.5	400/230 (e) (a) 230 (k) 460/230 (e)	400/230 (e) (a) 230 (k)	11,000 400/230 (a)
Niger	50 ± 1	230 (k)	380/220 (a)	15,000 380/220 (a)
Nigeria	50 ± 1	230 (k) 220 (k)	400/230 (a) 380/220 (a)	15,000 11,000 400/230 (a) 380/220 (a)
Norway	50 ± 2	230/400	230/400	230/400 690
Oman	50	240 (k)	415/240 (a) 240 (k)	415/240 (a)
Pakistan	50	230 (k)	400/230 (a) 230 (k)	400/230 (a)
Papua New Guinea	50 ± 2	240 (k)	415/240 (a) 240 (k)	22,000 11,000 415/240 (a)
Paraguay	50 ± 0.5	220 (k)	380/220 (a) 220 (k)	22,000 380/220 (a)
Philippines (Rep of the)	60 ± 0.16	110/220 (j)	13,800 4,160 2,400 110/220 (h)	13,800 4,160 2,400 440 (b) 110/220 (h)
Poland	50 ± 0.1	230 (k)	400/230 (a)	1,000 690/400 400/230 (a)
Portugal	50 ± 1	380/220 (a) 220 (k)	15,000 5,000 380/220 (a) 220 (k)	15,000 5,000 380/220 (a)
Qatar	50 ± 0.1	415/240 (k)	415/240 (a)	11,000 415/240 (a)

Fig. C1 : Voltage of local LV network and their associated circuit diagrams (continued on next page)

# 1 Low-voltage utility distribution networks

C6

Country	Frequency & tolerance (Hz & %)	Domestic (V)	Commercial (V)	Industrial (V)
Romania	50 ± 0.5	220 (k) 220/380 (a)	220/380 (a)	20,000 10,000 6,000 220/380 (a)
Russia	50 ± 0.2	380/220 (a) 220 (k)	380/220 (a) 220 (k)	380/220 (a)
Rwanda	50 ± 1	220 (k)	380/220 (a)	15,000 6,600 380/220 (a)
Saint Lucia	50 ± 3	240 (k)	415/240 (a)	11,000 415/240 (a)
Samoa		400/230		
San Marino	50 ± 1	230/220	380	15,000 380
Saudi Arabia	60	220/127 (a)	220/127 (a) 380/220 (a)	11,000 7,200 380/220 (a)
The Solomon Islands	50 ± 2	240	415/240	415/240
Senegal	50 ± 5	220 (a) 127 (k)	380/220 (a) 220/127 (k)	90,000 30,000 6,600
Serbia and Montenegro	50	380/220 (a) 220 (k)	380/220 (a) 220 (k)	10,000 6,600 380/220 (a)
Seychelles	50 ± 1	400/230 (a)	400/230 (a)	11,000 400/230 (a)
Sierra Leone	50 ± 5	230 (k)	400/230 (a) 230 (k)	11,000 400
Singapore	50	400/230 (a) 230 (k)	400/230 (a)	22,000 6,600 400/230 (a)
Slovakia	50 ± 0.5	230	230	230/400
Slovenia	50 ± 0.1	220 (k)	380/220 (a)	10,000 6,600 380/220 (a)
Somalia	50	230 (k) 220 (k) 110 (k)	440/220 (j) 220/110 (j) 230 (k)	440/220 (g) 220/110 (g)
South Africa	50 ± 2.5	433/250 (a) 400/230 (a) 380/220 (a) 220 (k)	11,000 6,600 3,300 433/250 (a) 400/230 (a) 380/220 (a)	11,000 6,600 3,300 500 (b) 380/220 (a)
Spain	50 ± 3	380/220 (a) (e) 220 (k) 220/127 (a) 127 (k)	380/220 (a) 220/127 (a) (e)	15,000 11,000 380/220 (a)
Sri Lanka	50 ± 2	230 (k)	400/230 (a) 230 (k)	11,000 400/230 (a)
Sudan	50	240 (k)	415/240 (a) 240 (k)	415/240 (a)
Swaziland	50 ± 2.5	230 (k)	400/230 (a) 230 (k)	11,000 400/230 (a)
Sweden	50 ± 0.5	400/230 (a) 230 (k)	400/230 (a) 230 (k)	6,000 400/230 (a)
Switzerland	50 ± 2	400/230 (a)	400/230 (a)	20,000 10,000 3,000 1,000 690/500
Syria	50	220 (k) 115 (k)	380/220 (a) 220 (k) 200/115 (a)	380/220 (a)
Tadzhikistan	50	380/220 (a) 220 (k) 220/127 (a) 127 (k)	380/220 (a) 220 (k)	380/220 (a)

Fig. C1 : Voltage of local LV network and their associated circuit diagrams (continued on next page)

Country	Frequency & tolerance (Hz & %)	Domestic (V)	Commercial (V)	Industrial (V)
Tanzania	50	400/230 (a)	400/230 (a)	11,000 400/230 (a)
Thailand	50	220 (k)	380/220 (a) 220 (k)	380/220 (a)
Togo	50	220 (k)	380/220 (a)	20,000 5,500 380/220 (a)
Tunisia	50 ± 2	380/220 (a) 220 (k)	380/220 (a) 220 (k)	30,000 15,000 10,000 380/220 (a)
Turkmenistan	50	380/220 (a) 220 (k) 220/127 (a) 127 (k)	380/220 (a) 220 (k)	380/220 (a)
Turkey	50 ± 1	380/220 (a)	380/220 (a)	15,000 6,300 380/220 (a)
Uganda	+ 0.1	240 (k)	415/240 (a)	11,000 415/240 (a)
Ukraine	+ 0.2 / - 1.5	380/220 (a) 220 (k)	380/220 (a) 220 (k)	380/220 (a) 220 (k)
United Arab Emirates	50 ± 1	220 (k)	415/240 (a) 380/220 (a) 220 (k)	6,600 415/210 (a) 380/220 (a)
United Kingdom (except Northern Ireland)	50 ± 1	230 (k)	400/230 (a)	22,000 11,000 6,600 3,300 400/230 (a)
United Kingdom (Including Northern Ireland)	50 ± 0.4	230 (k) 220 (k)	400/230 (a) 380/220 (a)	400/230 (a) 380/220 (a)
United States of America Charlotte (North Carolina)	60 ± 0.06	120/240 (j) 120/208 (a)	265/460 (a) 120/240 (j) 120/208 (a)	14,400 7,200 2,400 575 (f) 460 (f) 240 (f) 265/460 (a) 120/240 (j) 120/208 (a)
United States of America Detroit (Michigan)	60 ± 0.2	120/240 (j) 120/208 (a)	480 (f) 120/240 (h) 120/208 (a)	13,200 4,800 4,160 480 (f) 120/240 (h) 120/208 (a)
United States of America Los Angeles (California)	60 ± 0.2	120/240 (j)	4,800 120/240 (g)	4,800 120/240 (g)
United States of America Miami (Florida)	60 ± 0.3	120/240 (j) 120/208 (a)	120/240 (j) 120/240 (h) 120/208 (a)	13,200 2,400 480/277 (a) 120/240 (h)
United States of America New York (New York)	60	120/240 (j) 120/208 (a)	120/240 (j) 120/208 (a) 240 (f)	12,470 4,160 277/480 (a) 480 (f)
United States of America Pittsburg (Pennsylvania)	60 ± 0.03	120/240 (j)	265/460 (a) 120/240 (j) 120/208 (a) 460 (f) 230 (f)	13,200 11,500 2,400 265/460 (a) 120/208 (a) 460 (f) 230 (f)

Fig. C1 : Voltage of local LV network and their associated circuit diagrams (continued on next page)

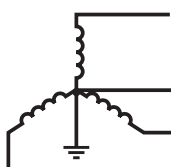


# 1 Low-voltage utility distribution networks

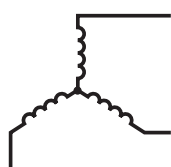
C8

Country	Frequency & tolerance (Hz & %)	Domestic (V)	Commercial (V)	Industrial (V)
United States of America Portland (Oregon)	60	120/240 (j)	227/480 (a) 120/240 (j) 120/208 (a) 480 (f) 240 (f)	19,900 12,000 7,200 2,400 277/480 (a) 120/208 (a) 480 (f) 240 (f)
United States of America San Francisco (California)	60 ± 0.08	120/240 (j)	277/480 (a) 120/240 (j)	20,800 12,000 4,160 277/480 (a) 120/240 (g)
United States of America Toledo (Ohio)	60 ± 0.08	120/240 (j) 120/208 (a)	277/480 (c) 120/240(h) 120/208 (j)	12,470 7,200 4,800 4,160 480 (f) 277/480 (a) 120/208 (a)
Uruguay	50 ± 1	220 (b) (k)	220 (b) (k)	15,000 6,000 220 (b)
Vietnam	50 ± 0.1	220 (k)	380/220 (a)	35,000 15,000 10,000 6,000
Yemen	50	250 (k)	440/250 (a)	440/250 (a)
Zambia	50 ± 2.5	220 (k)	380/220 (a)	380 (a)
Zimbabwe	50	225 (k)	390/225 (a)	11,000 390/225 (a)

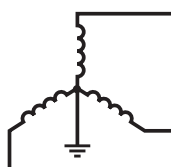
## Circuit diagrams



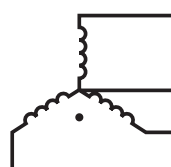
(a) Three-phase star;  
Four-wire:  
Earthed neutral



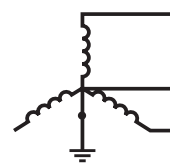
(b) Three-phase star;  
Three-wire



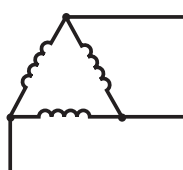
(c) Three-phase star;  
Three-wire:  
Earthed neutral



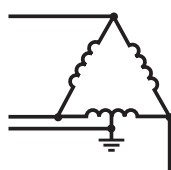
(d) Three-phase star;  
Four-wire:  
Non-earthed neutral



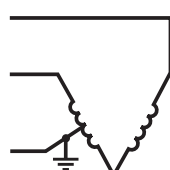
(e) Two-phase star;  
Three-wire  
Earthed neutral



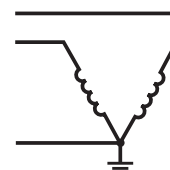
(f) Three-phase delta;  
Three-wire



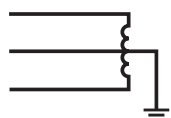
(g) Three-phase delta;  
Four-wire:  
Earthed mid point of  
one phase



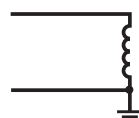
(h) Three-phase open delta;  
Four-wire:  
Earthed mid point of one  
phase



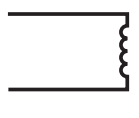
(i) Three-phase  
open delta:  
Earthed junction  
of phases



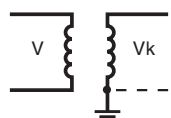
(j) Single-phase;  
Three-wire:  
Earthed mid point



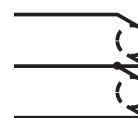
(k) Single-phase;  
Two-wire:  
Earthed end of phase



(l) Single-phase;  
Two-wire  
Unearthed



(m) Single-wire:  
Earthed return (swr)



(n) DC:  
Three-wire:  
Unearthed

Fig. C1 : Voltage of local LV network and their associated circuit diagrams (concluded)

## Residential and commercial consumers

The function of a LV “mains” distributor is to provide service connections (underground cable or overhead line) to a number of consumers along its route.

The current-rating requirements of distributors are estimated from the number of consumers to be connected and an average demand per consumer.

The two principal limiting parameters of a distributor are:

- The maximum current which it is capable of carrying indefinitely, and
- The maximum length of cable which, when carrying its maximum current, will not exceed the statutory voltage-drop limit

These constraints mean that the magnitude of loads which utilities are willing to connect to their LV distribution mains, is necessarily restricted.

For the range of LV systems mentioned in the second paragraph of this sub-clause (1.1) viz: 120 V single phase to 240/415 V 3-phase, typical maximum permitted loads connected to a LV distributor might<sup>(1)</sup> be (see **Fig. C2**):

System	Assumed max. permitted current per consumer service	kVA
120 V 1-phase 2-wire	60 A	7.2
120/240 V 1-phase 3-wire	60 A	14.4
120/208 V 3-phase 4-wire	60 A	22
220/380 V 3-phase 4-wire	120 A	80
230/400 V 3-phase 4-wire	120 A	83
240/415 V 3-phase 4-wire	120 A	86

**Fig. C2** : Typical maximum permitted loads connected to a LV distributor

Practices vary considerably from one power supply organization to another, and no “standardized” values can be given.

Factors to be considered include:

- The size of an existing distribution network to which the new load is to be connected
- The total load already connected to the distribution network
- The location along the distribution network of the proposed new load, i.e. close to the substation, or near the remote end of the distribution network, etc

In short, each case must be examined individually.

The load levels listed above are adequate for all normal residential consumers, and will be sufficient for the installations of many administrative, commercial and similar buildings.

## Medium-size and small industrial consumers (with dedicated LV lines direct from a utility supply MV/LV substation)

Medium and small industrial consumers can also be satisfactorily supplied at low-voltage.

For loads which exceed the maximum permitted limit for a service from a distributor, a dedicated cable can usually be provided from the LV distribution fuse- (or switch-) board, in the power utility substation.

Generally, the upper load limit which can be supplied by this means is restricted only by the available spare transformer capacity in the substation.

In practice, however:

- Large loads (e.g. > 300 kVA) require correspondingly large cables, so that, unless the load centre is close to the substation, this method can be economically unfavourable
- Many utilities prefer to supply loads exceeding 200 kVA (this figure varies with different suppliers) at medium voltage

For these reasons, dedicated supply lines at LV are generally applied (at 220/380 V to 240/415 V) to a load range of 80 kVA to 250 kVA.

Consumers normally supplied at low voltage include:

- Residential dwellings
- Shops and commercial buildings
- Small factories, workshops and filling stations
- Restaurants
- Farms, etc

(1) The Figure C2 values shown are indicative only, being (arbitrarily) based on 60 A maximum service currents for the first three systems, since smaller voltage drops are allowed at these lower voltages, for a given percentage statutory limit. The second group of systems is (again, arbitrarily) based on a maximum permitted service current of 120 A.

*In cities and large towns, standardized LV distribution cables form a network through link boxes. Some links are removed, so that each (fused) distributor leaving a substation forms a branched open-ended radial system, as shown in **Figure C3***

## 1.2 LV distribution networks

In European countries the standard 3-phase 4-wire distribution voltage level is 230/400 V. Many countries are currently converting their LV systems to the latest IEC standard of 230/400 V nominal (IEC 60038). Medium to large-sized towns and cities have underground cable distribution systems. MV/LV distribution substations, mutually spaced at approximately 500-600 metres, are typically equipped with:

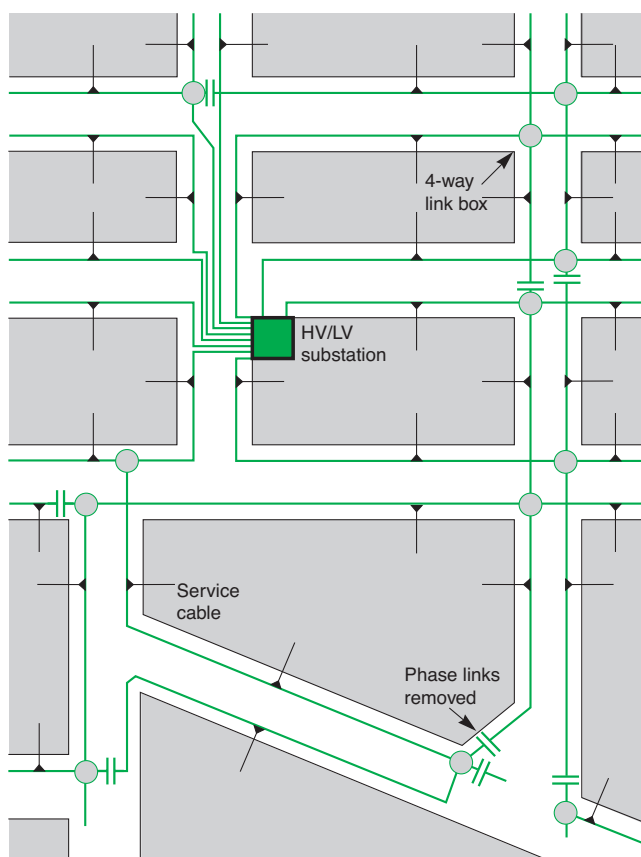
- A 3-or 4-way MV switchboard, often made up of incoming and outgoing load-break switches forming part of a ring main, and one or two MV circuit-breakers or combined fuse/ load-break switches for the transformer circuits
- One or two 1,000 kVA MV/LV transformers
- One or two (coupled) 6-or 8-way LV 3-phase 4-wire distribution fuse boards, or moulded-case circuit-breaker boards, control and protect outgoing 4-core distribution cables, generally referred to as “distributors”

The output from a transformer is connected to the LV busbars via a load-break switch, or simply through isolating links.

In densely-loaded areas, a standard size of distributor is laid to form a network, with (generally) one cable along each pavement and 4-way link boxes located in manholes at street corners, where two cables cross.

Recent trends are towards weather-proof cabinets above ground level, either against a wall, or where possible, flush-mounted in the wall.

Links are inserted in such a way that distributors form radial circuits from the substation with open-ended branches (see Fig. C3). Where a link box unites a distributor from one substation with that from a neighbouring substation, the phase links are omitted or replaced by fuses, but the neutral link remains in place.



**Fig. C3 :** Showing one of several ways in which a LV distribution network may be arranged for radial branched-distributor operation, by removing (phase) links

*In less-densely loaded urban areas a more-economic system of tapered radial distribution is commonly used, in which conductors of reduced size are installed as the distance from a substation increases*

*Improved methods using insulated twisted conductors to form a pole mounted aerial cable are now standard practice in many countries*

*In Europe, each utility-supply distribution substation is able to supply at LV an area corresponding to a radius of approximately 300 metres from the substation. North and Central American systems of distribution consist of a MV network from which numerous (small) MV/LV transformers each supply one or several consumers, by direct service cable (or line) from the transformer location*

*Service components and metering equipment were formerly installed inside a consumer's building. The modern tendency is to locate these items outside in a weatherproof cabinet*

This arrangement provides a very flexible system in which a complete substation can be taken out of service, while the area normally supplied from it is fed from link boxes of the surrounding substations.

Moreover, short lengths of distributor (between two link boxes) can be isolated for fault-location and repair.

Where the load density requires it, the substations are more closely spaced, and transformers up to 1,500 kVA are sometimes necessary.

Other forms of urban LV network, based on free-standing LV distribution pillars, placed above ground at strategic points in the network, are widely used in areas of lower load density. This scheme exploits the principle of tapered radial distributors in which the distribution cable conductor size is reduced as the number of consumers downstream diminish with distance from the substation.

In this scheme a number of large-sectioned LV radial feeders from the distribution board in the substation supply the busbars of a distribution pillar, from which smaller distributors supply consumers immediately surrounding the pillar.

Distribution in market towns, villages and rural areas generally has, for many years, been based on bare copper conductors supported on wooden, concrete or steel poles, and supplied from pole-mounted or ground-mounted transformers.

In recent years, LV insulated conductors, twisted to form a two-core or 4-core self supporting cable for overhead use, have been developed, and are considered to be safer and visually more acceptable than bare copper lines.

This is particularly so when the conductors are fixed to walls (e.g. under-eaves wiring) where they are hardly noticeable.

As a matter of interest, similar principles have been applied at higher voltages, and self supporting "bundled" insulated conductors for MV overhead installations are now available for operation at 24 kV.

Where more than one substation supplies a village, arrangements are made at poles on which the LV lines from different substations meet, to interconnect corresponding phases.

North and Central American practice differs fundamentally from that in Europe, in that LV networks are practically nonexistent, and 3-phase supplies to premises in residential areas are rare.

The distribution is effectively carried out at medium voltage in a way, which again differs from standard European practices. The MV system is, in fact, a 3-phase 4-wire system from which single-phase distribution networks (phase and neutral conductors) supply numerous single-phase transformers, the secondary windings of which are centre-tapped to produce 120/240 V single-phase 3-wire supplies. The central conductors provide the LV neutrals, which, together with the MV neutral conductors, are solidly earthed at intervals along their lengths.

Each MV/LV transformer normally supplies one or several premises directly from the transformer position by radial service cable(s) or by overhead line(s).

Many other systems exist in these countries, but the one described appears to be the most common.

**Figure C4** (next page) shows the main features of the two systems.

## 1.3 The consumer-service connection

In the past, an underground cable service or the wall-mounted insulated conductors from an overhead line service, invariably terminated inside the consumer's premises, where the cable-end sealing box, the utility fuses (inaccessible to the consumer) and meters were installed.

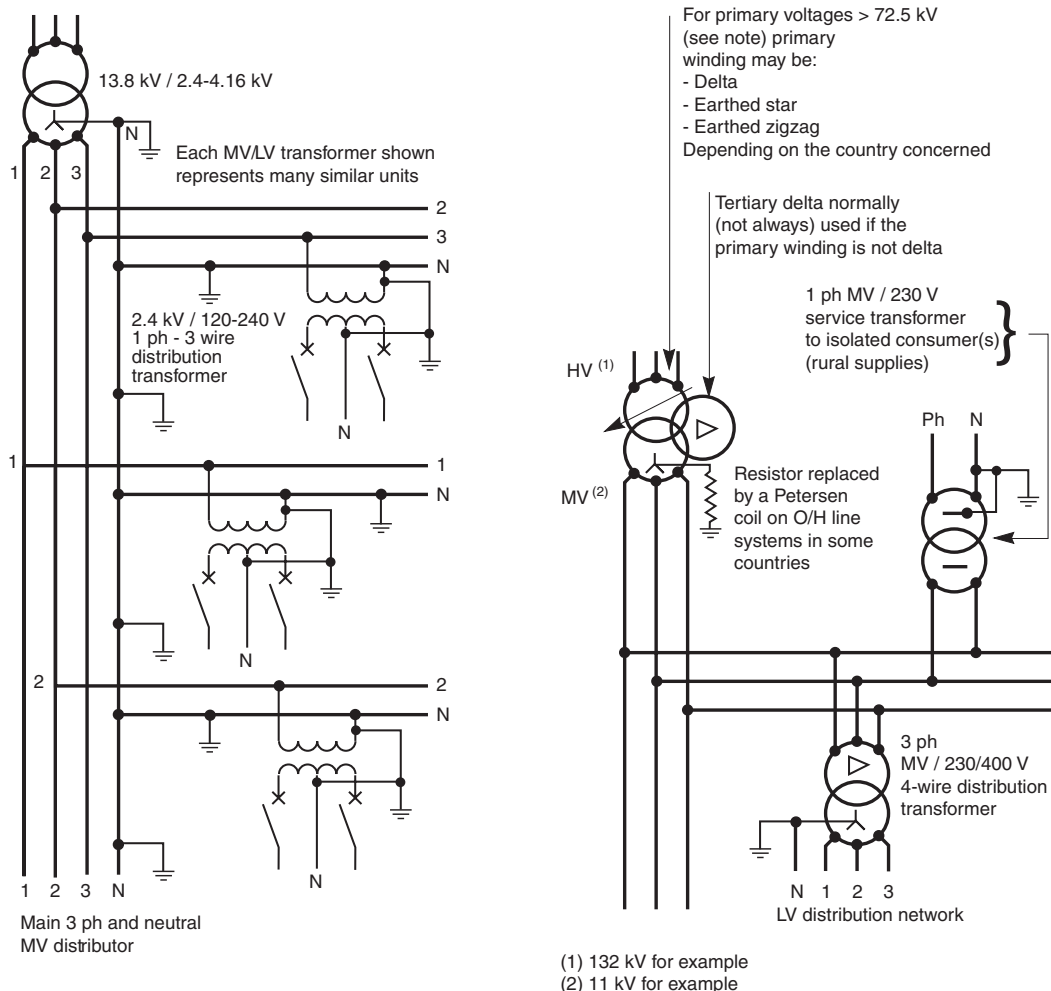
A more recent trend is (as far as possible) to locate these service components in a weatherproof housing outside the building.

The utility/consumer interface is often at the outgoing terminals of the meter(s) or, in some cases, at the outgoing terminals of the installation main circuit-breaker (depending on local practices) to which connection is made by utility staff, following a satisfactory test and inspection of the installation.

A typical arrangement is shown in **Figure C5** (next page).

# 1 Low-voltage utility distribution networks

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**Note:** At primary voltages greater than 72.5 kV in bulk-supply substations, it is common practice in some European countries to use an earthed-star primary winding and a delta secondary winding. The neutral point on the secondary side is then provided by a zigzag earthing reactor, the star point of which is connected to earth through a resistor. Frequently, the earthing reactor has a secondary winding to provide LV 3-phase supplies for the substation. It is then referred to as an "earthing transformer".

Fig. C4 : Widely-used American and European-type systems

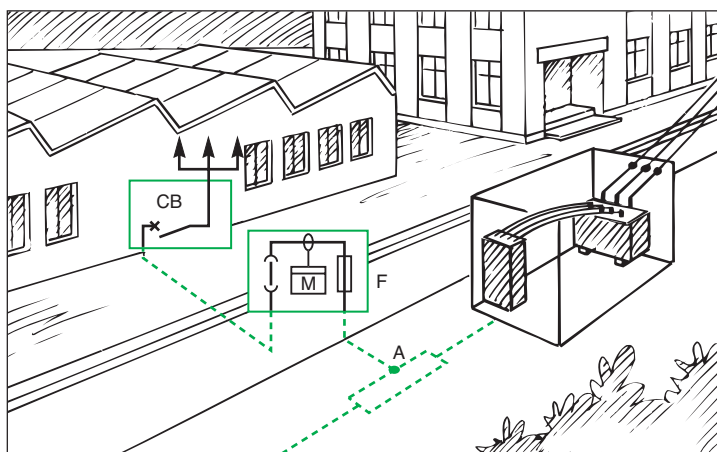


Fig. C5 : Typical service arrangement for TT-earthed systems

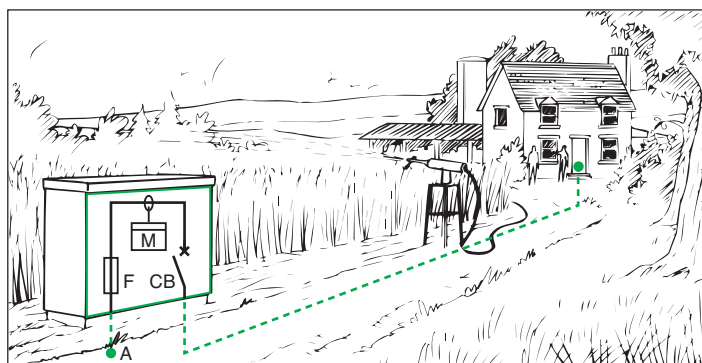
*LV consumers are normally supplied according to the TN or TT system, as described in chapters F and G. The installation main circuit-breaker for a TT supply must include a residual current earth-leakage protective device. For a TN service, overcurrent protection by circuit-breaker or switch-fuse is required*

A MCCB -moulded case circuit-breaker- which incorporates a sensitive residual-current earth-fault protective feature is mandatory at the origin of any LV installation forming part of a TT earthing system. The reason for this feature and related leakage-current tripping levels are discussed in Clause 3 of Chapter G.

A further reason for this MCCB is that the consumer cannot exceed his (contractual) declared maximum load, since the overload trip setting, which is sealed by the supply authority, will cut off supply above the declared value. Closing and tripping of the MCCB is freely available to the consumer, so that if the MCCB is inadvertently tripped on overload, or due to an appliance fault, supplies can be quickly restored following correction of the anomaly.

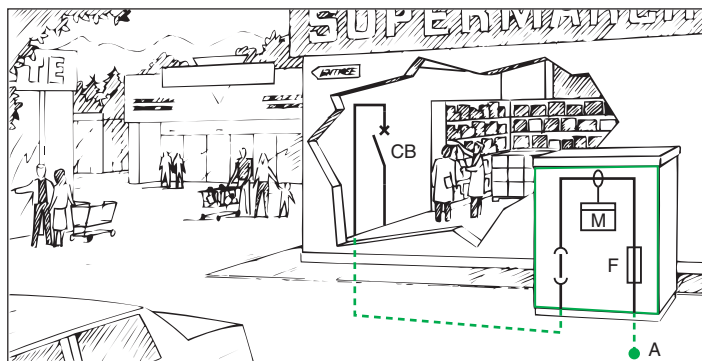
In view of the inconvenience to both the meter reader and consumer, the location of meters is nowadays generally outside the premises, either:

- In a free-standing pillar-type housing as shown in **Figures C6 and C7**
- In a space inside a building, but with cable termination and supply authority's fuses located in a flush-mounted weatherproof cabinet accessible from the public way, as shown in **Figure C8** next page
- For private residential consumers, the equipment shown in the cabinet in Figure C5 is installed in a weatherproof cabinet mounted vertically on a metal frame in the front garden, or flush-mounted in the boundary wall, and accessible to authorized personnel from the pavement. **Figure C9** (next page) shows the general arrangement, in which removable fuse links provide the means of isolation



In this kind of installation it is often necessary to place the main installation circuit-breaker some distance from the point of utilization, e.g. saw-mills, pumping stations, etc.

**Fig. C6 :** Typical rural-type installation

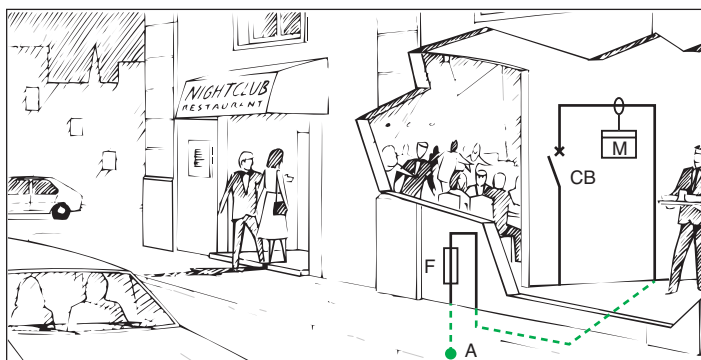


The main installation CB is located in the consumer's premises in cases where it is set to trip if the declared kVA load demand is exceeded.

**Fig. C7 :** Semi-urban installations (shopping precincts, etc.)

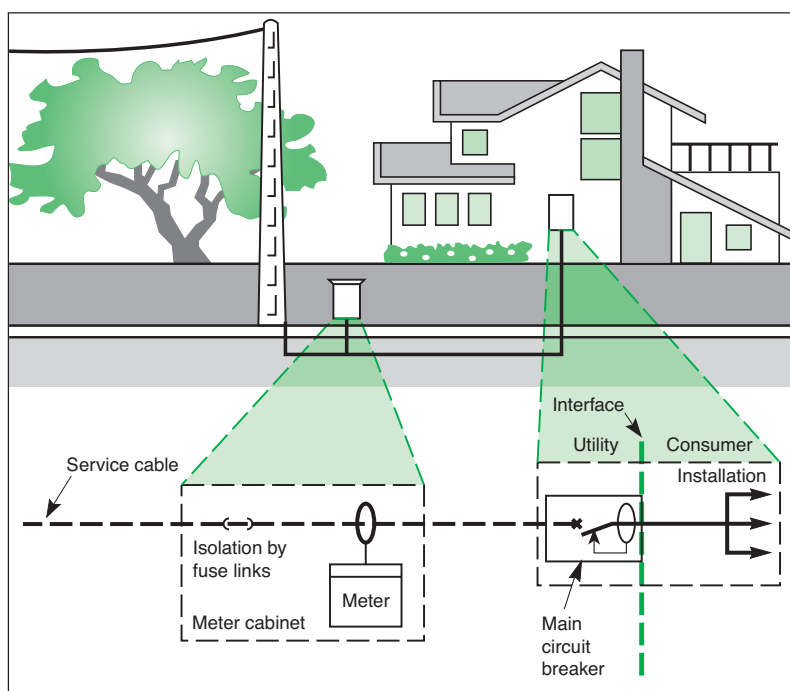
# 1 Low-voltage utility distribution networks

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The service cable terminates in a flushmounted wall cabinet which contains the isolating fuse links, accessible from the public way. This method is preferred for esthetic reasons, when the consumer can provide a suitable metering and main-switch location.

*Fig. C8 : Town centre installations*



*Fig. C9 : Typical LV service arrangement for residential consumers*

In the field of electronic metering, techniques have developed which make their use attractive by utilities either for electricity metering and for billing purposes, the liberalisation of the electricity market having increased the needs for more data collection to be returned from the meters. For example electronic metering can also help utilities to understand their customers' consumption profiles. In the same way, they will be useful for more and more power line communication and radio-frequency applications as well.

In this area, prepayment systems are also more and more employed when economically justified. They are based on the fact that for instance consumers having made their payment at vending stations, generate tokens to pass the information concerning this payment on to the meters. For these systems the key issues are security and inter-operability which seem to have been addressed successfully now. The attractiveness of these systems is due to the fact they not only replace the meters but also the billing systems, the reading of meters and the administration of the revenue collection.



*An adequate level of voltage at the consumers supply-service terminals is essential for satisfactory operation of equipment and appliances. Practical values of current, and resulting voltage drops in a typical LV system, show the importance of maintaining a high Power Factor as a means of reducing voltage drop.*

## 1.4 Quality of supply voltage

The quality of the LV network supply voltage in its widest sense implies:

- Compliance with statutory limits of magnitude and frequency
- Freedom from continual fluctuation within those limits
- Uninterrupted power supply, except for scheduled maintenance shutdowns, or as a result of system faults or other emergencies
- Preservation of a near-sinusoidal wave form

In this Sub-clause the maintenance of voltage magnitude only will be discussed.

In most countries, power-supply authorities have a statutory obligation to maintain the level of voltage at the service position of consumers within the limits of  $\pm 5\%$  (or in some cases  $\pm 6\%$  or more-see table C1) of the declared nominal value.

Again, IEC and most national standards recommend that LV appliances be designed and tested to perform satisfactorily within the limits of  $\pm 10\%$  of nominal voltage. This leaves a margin, under the worst conditions (of minus 5% at the service position, for example) of 5% allowable voltage drop in the installation wiring.

The voltage drops in a typical distribution system occur as follows: the voltage at the MV terminals of a MV/LV transformer is normally maintained within a  $\pm 2\%$  band by the action of automatic on-load tapchangers of the transformers at bulk-supply substations, which feed the MV network from a higher-voltage subtransmission system.

If the MV/LV transformer is in a location close to a bulk-supply substation, the  $\pm 2\%$  voltage band may be centered on a voltage level which is higher than the nominal MV value. For example, the voltage could be  $20.5 \text{ kV} \pm 2\%$  on a 20 kV system. In this case, the MV/LV distribution transformer should have its MV off-circuit tapping switch selected to the + 2.5% tap position.

Conversely, at locations remote from bulk supply substations a value of  $19.5 \text{ kV} \pm 2\%$  is possible, in which case the off-circuit tapping switch should be selected to the - 5% position.

The different levels of voltage in a system are normal, and depend on the system powerflow pattern. Moreover, these voltage differences are the reason for the term "nominal" when referring to the system voltage.

### Practical application

With the MV/LV transformer correctly selected at its off-circuit tapping switch, an unloaded transformer output voltage will be held within a band of  $\pm 2\%$  of its no-load voltage output.

To ensure that the transformer can maintain the necessary voltage level when fully loaded, the output voltage at no-load must be as high as possible without exceeding the upper + 5% limit (adopted for this example). In present-day practice, the winding ratios generally give an output voltage of about 104% at no-load<sup>(1)</sup>, when nominal voltage is applied at MV, or is corrected by the tapping switch, as described above. This would result in a voltage band of 102% to 106% in the present case.

A typical LV distribution transformer has a short-circuit reactance voltage of 5%. If it is assumed that its resistance voltage is one tenth of this value, then the voltage drop within the transformer when supplying full load at 0.8 power factor lagging, will be:

$$\begin{aligned} \text{V\% drop} &= R\% \cos \varphi + X\% \sin \varphi \\ &= 0.5 \times 0.8 + 5 \times 0.6 \\ &= 0.4 + 3 = 3.4\% \end{aligned}$$

The voltage band at the output terminals of the fully-loaded transformer will therefore be  $(102 - 3.4) = 98.6\%$  to  $(106 - 3.4) = 102.6\%$ .

The maximum allowable voltage drop along a distributor is therefore  $98.6 - 95 = 3.6\%$ .

This means, in practical terms, that a medium-sized 230/400 V 3-phase 4-wire distribution cable of 240 mm<sup>2</sup> copper conductors would be able to supply a total load of 292 kVA at 0.8 PF lagging, distributed evenly over 306 metres of the distributor. Alternatively, the same load at the premises of a single consumer could be supplied at a distance of 153 metres from the transformer, for the same volt-drop, and so on...

As a matter of interest, the maximum rating of the cable, based on calculations derived from IEC 60287 (1982) is 290 kVA, and so the 3.6% voltage margin is not unduly restrictive, i.e. the cable can be fully loaded for distances normally required in LV distribution systems.

Furthermore, 0.8 PF lagging is appropriate to industrial loads. In mixed semi-industrial areas 0.85 is a more common value, while 0.9 is generally used for calculations concerning residential areas, so that the volt-drop noted above may be considered as a "worst case" example.

(1) Transformers designed for the 230/400 V IEC standard will have a no-load output of 420 V, i.e. 105% of the nominal voltage

No attempt will be made in this guide to discuss particular tariffs, since there appears to be as many different tariff structures around the world as there are utilities.

Some tariffs are very complicated in detail but certain elements are basic to all of them and are aimed at encouraging consumers to manage their power consumption in a way which reduces the cost of generation, transmission and distribution.

The two predominant ways in which the cost of supplying power to consumers can be reduced, are:

- Reduction of power losses in the generation, transmission and distribution of electrical energy. In principle the lowest losses in a power system are attained when all parts of the system operate at unity power factor
- Reduction of the peak power demand, while increasing the demand at low-load periods, thereby exploiting the generating plant more fully, and minimizing plant redundancy

### Reduction of losses

Although the ideal condition noted in the first possibility mentioned above cannot be realized in practice, many tariff structures are based partly on kVA demand, as well as on kWh consumed. Since, for a given kW loading, the minimum value of kVA occurs at unity power factor, the consumer can minimize billing costs by taking steps to improve the power factor of the load (as discussed in Chapter L). The kVA demand generally used for tariff purposes is the maximum average kVA demand occurring during each billing period, and is based on average kVA demands, over fixed periods (generally 10, 30 or 60 minute periods) and selecting the highest of these values. The principle is described below in "principle of kVA maximum-demand metering".

### Reduction of peak power demand

The second aim, i.e. that of reducing peak power demands, while increasing demand at low-load periods, has resulted in tariffs which offer substantial reduction in the cost of energy at:

- Certain hours during the 24-hour day
- Certain periods of the year

The simplest example is that of a residential consumer with a storage-type water heater (or storage-type space heater, etc.). The meter has two digital registers, one of which operates during the day and the other (switched over by a timing device) operates during the night. A contactor, operated by the same timing device, closes the circuit of the water heater, the consumption of which is then indicated on the register to which the cheaper rate applies. The heater can be switched on and off at any time during the day if required, but will then be metered at the normal rate. Large industrial consumers may have 3 or 4 rates which apply at different periods during a 24-hour interval, and a similar number for different periods of the year. In such schemes the ratio of cost per kWh during a period of peak demand for the year, and that for the lowest-load period of the year, may be as much as 10: 1.

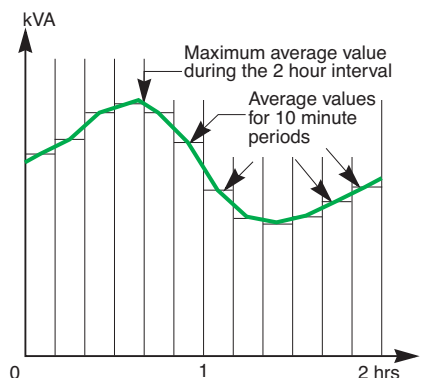
### Meters

It will be appreciated that high-quality instruments and devices are necessary to implement this kind of metering, when using classical electro-mechanical equipment. Recent developments in electronic metering and micro-processors, together with remote ripple-control<sup>(1)</sup> from an utility control centre (to change peak-period timing throughout the year, etc.) are now operational, and facilitate considerably the application of the principles discussed.

In most countries, some tariffs, as noted above, are partly based on kVA demand, in addition to the kWh consumption, during the billing periods (often 3-monthly intervals). The maximum demand registered by the meter to be described, is, in fact, a maximum (i.e. the highest) average kVA demand registered for succeeding periods during the billing interval.

(1) Ripple control is a system of signalling in which a voice frequency current (commonly at 175 Hz) is injected into the LV mains at appropriate substations. The signal is injected as coded impulses, and relays which are tuned to the signal frequency and which recognize the particular code will operate to initiate a required function. In this way, up to 960 discrete control signals are available.

**Figure C10** shows a typical kVA demand curve over a period of two hours divided into succeeding periods of 10 minutes. The meter measures the average value of kVA during each of these 10 minute periods.



**Fig. C10 :** Maximum average value of kVA over an interval of 2 hours

### Principle of kVA maximum demand metering

A kVAh meter is similar in all essentials to a kWh meter but the current and voltage phase relationship has been modified so that it effectively measures kVAh (kilo-volt-ampere-hours). Furthermore, instead of having a set of decade counter dials, as in the case of a conventional kWh meter, this instrument has a rotating pointer. When the pointer turns it is measuring kVAh and pushing a red indicator before it. At the end of 10 minutes the pointer will have moved part way round the dial (it is designed so that it can never complete one revolution in 10 minutes) and is then electrically reset to the zero position, to start another 10 minute period. The red indicator remains at the position reached by the measuring pointer, and that position, corresponds to the number of kVAh (kilo-volt-ampere-hours) taken by the load in 10 minutes. Instead of the dial being marked in kVAh at that point however it can be marked in units of average kVA. The following figures will clarify the matter.

Supposing the point at which the red indicator reached corresponds to 5 kVAh. It is known that a varying amount of kVA of apparent power has been flowing for 10 minutes, i.e. 1/6 hour.

If now, the 5 kVAh is divided by the number of hours, then the average kVA for the period is obtained.

In this case the average kVA for the period will be:

$$5 \times \frac{1}{\frac{1}{6}} = 5 \times 6 = 30 \text{ kVA}$$

Every point around the dial will be similarly marked i.e. the figure for average kVA will be 6 times greater than the kVAh value at any given point. Similar reasoning can be applied to any other reset-time interval.

At the end of the billing period, the red indicator will be at the maximum of all the average values occurring in the billing period.

The red indicator will be reset to zero at the beginning of each billing period. Electro-mechanical meters of the kind described are rapidly being replaced by electronic instruments. The basic measuring principles on which these electronic meters depend however, are the same as those described above.

# Chapter D

## MV & LV architecture selection guide

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## Choice of distribution architecture

The choice of distribution architecture has a decisive impact on installation performance throughout its lifecycle:

- right from the construction phase, choices can greatly influence the installation time, possibilities of work rate, required competencies of installation teams, etc.
- there will also be an impact on performance during the operation phase in terms of quality and continuity of power supply to sensitive loads, power losses in power supply circuits,
- and lastly, there will be an impact on the proportion of the installation that can be recycled in the end-of-life phase.

The Electrical Distribution architecture of an installation involves the spatial configuration, the choice of power sources, the definition of different distribution levels, the single-line diagram and the choice of equipment.

The choice of the best architecture is often expressed in terms of seeking a compromise between the various performance criteria that interest the customer who will use the installation at different phases in its lifecycle. The earlier we search for solutions, the more optimization possibilities exist (see Fig. D1).

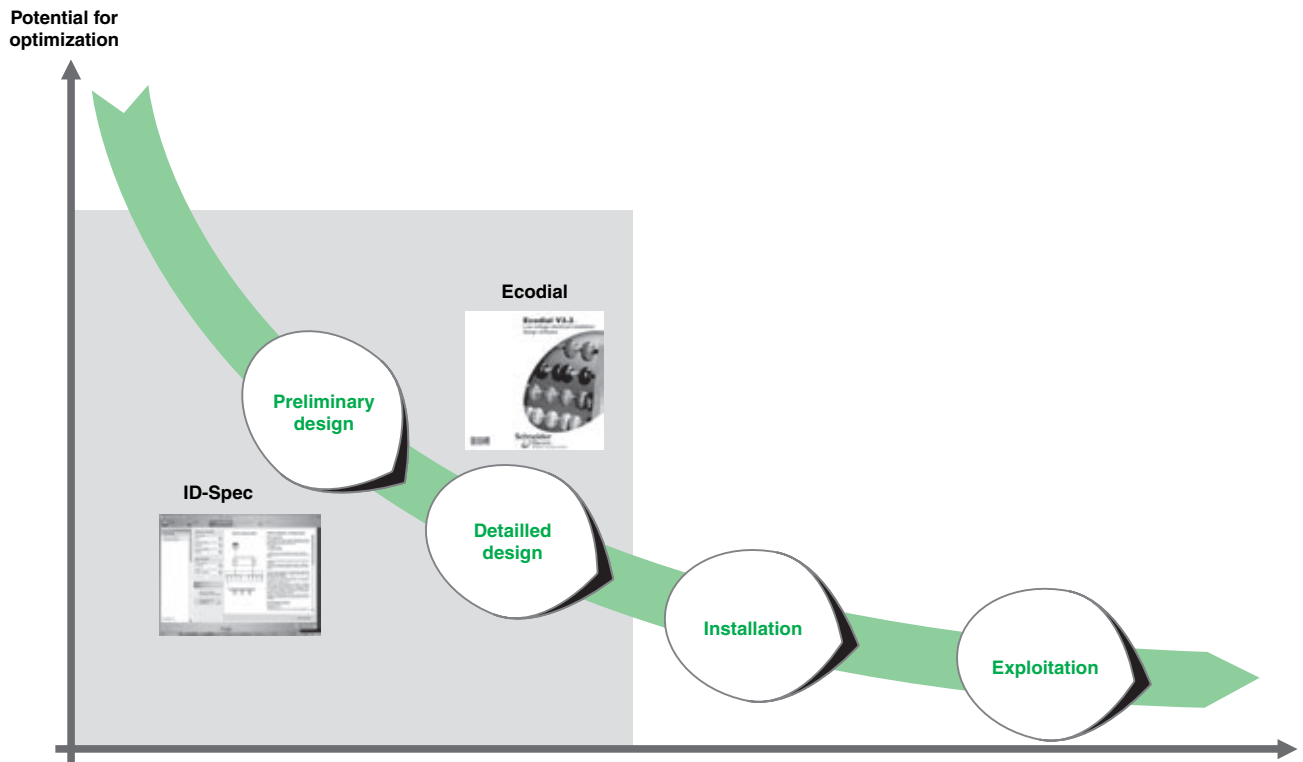


Fig. D1 : Optimization potential

A successful search for an optimal solution is also strongly linked to the ability for exchange between the various players involved in designing the various sections of a project:

- the architect who defines the organization of the building according to user requirements,
- the designers of different technical sections (lighting, heating, air conditioning, fluids, etc.),
- the user's representatives e.g. defining the process.

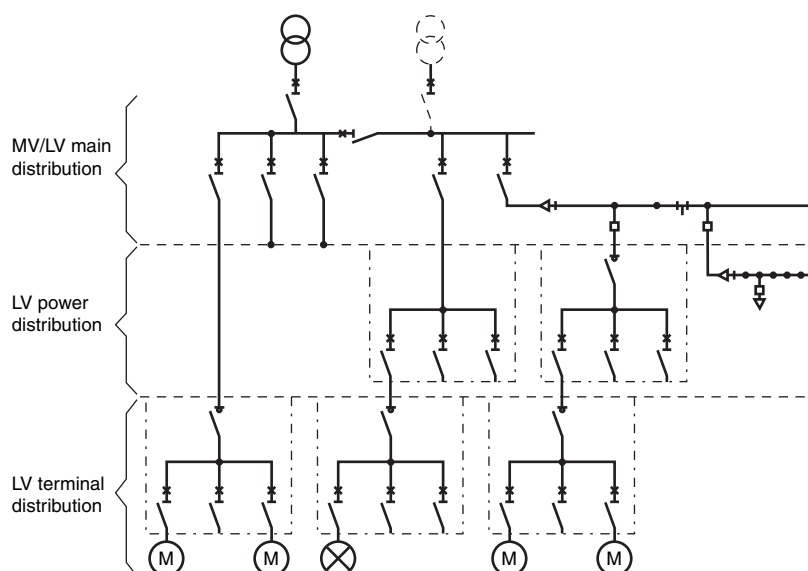
The following paragraphs present the selection criteria as well as the architecture design process to meet the project performance criteria in the context of industrial and tertiary buildings (excluding large sites).

## 2 Simplified architecture design process

### 2.1 The architecture design

The architecture design considered in this document is positioned at the Draft Design stage. It generally covers the levels of MV/LV main distribution, LV power distribution, and exceptionally the terminal distribution level. (see **Fig. D2**).

D4



**Fig. D2** : Example of single-line diagram

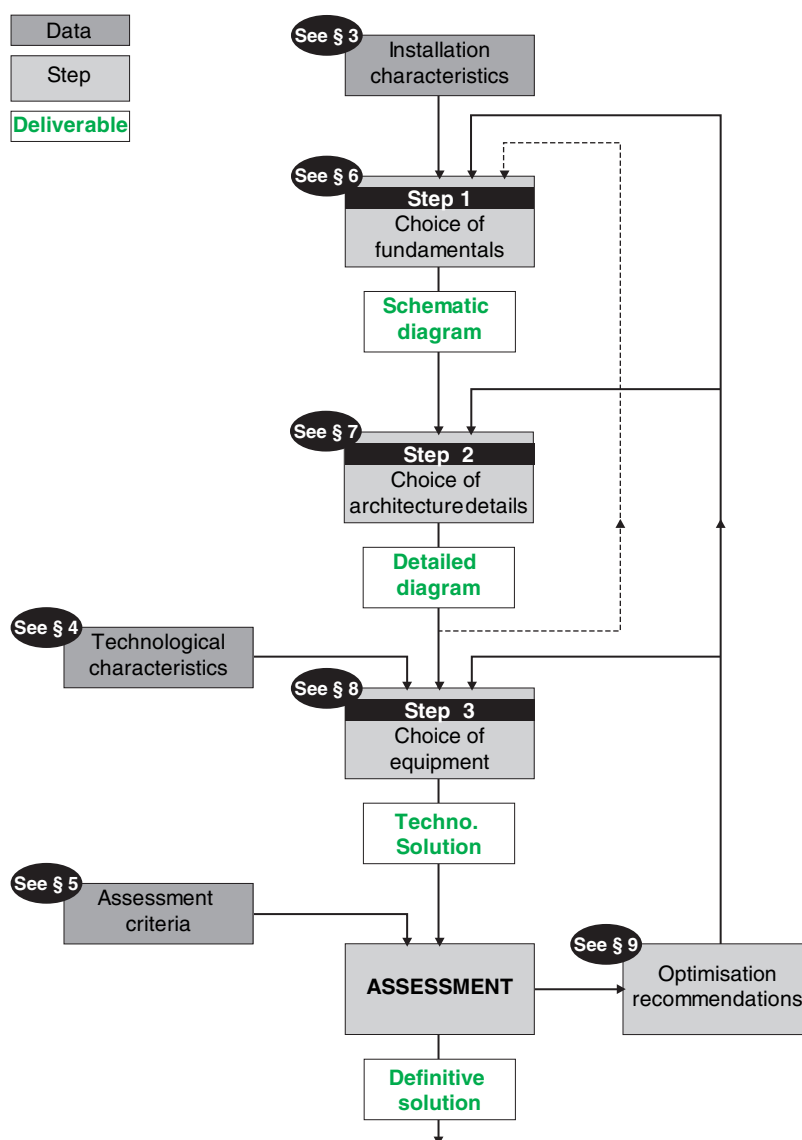
The design of an electrical distribution architecture can be described by a 3-stage process, with iterative possibilities. This process is based on taking account of the installation characteristics and criteria to be satisfied.



## 2.2 The whole process

The whole process is described briefly in the following paragraphs and illustrated on **Figure D3**.

The process described in this document is not intended as the only solution. This document is a guide intended for the use of electrical installation designers.



**Fig. D3** : Flow diagram for choosing the electrical distribution architecture

### Step 1: Choice of distribution architecture fundamentals

This involves defining the general features of the electrical installation. It is based on taking account of macroscopic characteristics concerning the installation and its usage.

These characteristics have an impact on the connection to the upstream network, MV circuits, the number of transformer substations, etc.

At the end of this step, we have several distribution schematic diagram solutions, which are used as a starting point for the single-line diagram. The definitive choice is confirmed at the end of the step 2.

## 2 Simplified architecture design process

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### Step 2: choice of architecture details

This involves defining the electrical installation in more detail. It is based on the results of the previous step, as well as on satisfying criteria relative to implementation and operation of the installation.

The process loops back into step 1 if the criteria are not satisfied. An iterative process allows several assessment criteria combinations to be analyzed.

At the end of this step, we have a detailed single-line diagram.

### Step 3: choice of equipment

The choice of equipment to be implemented is carried out in this stage, and results from the choice of architecture. The choices are made from the manufacturer catalogues, in order to satisfy certain criteria.

This stage is looped back into step 2 if the characteristics are not satisfied.

### Assessment

This assessment step allows the Engineering Office to have figures as a basis for discussions with the customer and other players.

According to the result of these discussions, it may be possible to loop back into step 1.

## 3 Electrical installation characteristics

These are the main installation characteristics enabling the defining of the fundamentals and details of the electrical distribution architecture. For each of these characteristics, we supply a definition and the different categories or possible values.

### 3.1 Activity

#### Definition:

Main economic activity carried out on the site.

#### Indicative list of sectors considered for industrial buildings:

- Manufacturing
- Food & Beverage
- Logistics

#### Indicative list of sectors considered for tertiary buildings:

- Offices buildings
- Hypermarkets
- Shopping malls

### 3.2 Site topology

#### Definition:

Architectural characteristic of the building(s), taking account of the number of buildings, number of floors, and of the surface area of each floor.

#### Different categories:

- Single storey building,
- Multi-storey building,
- Multi-building site,
- High-rise building.

### 3.3 Layout latitude

#### Definition:

Characteristic taking account of constraints in terms of the layout of the electrical equipment in the building:

- aesthetics,
- accessibility,
- presence of dedicated locations,
- use of technical corridors (per floor),
- use of technical ducts (vertical).

#### Different categories:

- Low: the position of the electrical equipment is virtually imposed
- Medium: the position of the electrical equipment is partially imposed, to the detriment of the criteria to be satisfied
- High: no constraints. The position of the electrical equipment can be defined to best satisfy the criteria.

## 3 Electrical installation characteristics

### 3.4 Service reliability

#### Definition:

The ability of a power system to meet its supply function under stated conditions for a specified period of time.

#### Different categories:

- Minimum: this level of service reliability implies risk of interruptions related to constraints that are geographical (separate network, area distant from power production centers), technical (overhead line, poorly meshed system), or economic (insufficient maintenance, under-dimensioned generation).
- Standard
- Enhanced: this level of service reliability can be obtained by special measures taken to reduce the probability of interruption (underground network, strong meshing, etc.)

### 3.5 Maintainability

#### Definition:

Features input during design to limit the impact of maintenance actions on the operation of the whole or part of the installation.

#### Different categories:

- Minimum: the installation must be stopped to carry out maintenance operations.
- Standard: maintenance operations can be carried out during installation operations, but with deteriorated performance. These operations must be preferably scheduled during periods of low activity. Example: several transformers with partial redundancy and load shedding.
- Enhanced: special measures are taken to allow maintenance operations without disturbing the installation operations. Example: double-ended configuration.

### 3.6 Installation flexibility

#### Definition:

Possibility of easily moving electricity delivery points within the installation, or to easily increase the power supplied at certain points. Flexibility is a criterion which also appears due to the uncertainty of the building during the pre-project summary stage.

#### Different categories:

- No flexibility: the position of loads is fixed throughout the lifecycle, due to the high constraints related to the building construction or the high weight of the supplied process. E.g.: smelting works.
  - Flexibility of design: the number of delivery points, the power of loads or their location are not precisely known.
  - Implementation flexibility: the loads can be installed after the installation is commissioned.
  - Operating flexibility: the position of loads will fluctuate, according to process re-organization.
- Examples:
- industrial building: extension, splitting and changing usage
  - office building: splitting

## 3.7 Power demand

### Definition:

The sum of the apparent load power (in kVA), to which is applied a usage coefficient. This represents the maximum power which can be consumed at a given time for the installation, with the possibility of limited overloads that are of short duration.

Significant power ranges correspond to the transformer power limits most commonly used:

- < 630kVA
- from 630 to 1250kVA
- from 1250 to 2500kVA
- > 2500kVA

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## 3.8 Load distribution

### Definition:

A characteristic related to the uniformity of load distribution (in kVA / m<sup>2</sup>) over an area or throughout the building.

### Different categories:

■ Uniform distribution: the loads are generally of an average or low unit power and spread throughout the surface area or over a large area of the building (uniform density).

E.g.: lighting, individual workstations

■ intermediate distribution: the loads are generally of medium power, placed in groups over the whole building surface area

E.g.: machines for assembly, conveying, workstations, modular logistics "sites"

■ localized loads: the loads are generally high power and localized in several areas of the building (non-uniform density).

E.g.: HVAC

## 3.9 Power Interruption Sensitivity

### Definition:

The aptitude of a circuit to accept a power interruption.

### Different categories:

■ "Sheddable" circuit: possible to shut down at any time for an indefinite duration

■ Long interruption acceptable: interruption time > 3 minutes \*

■ Short interruption acceptable: interruption time < 3 minutes \*

■ No interruption acceptable.

We can distinguish various levels of severity of an electrical power interruption, according to the possible consequences:

■ No notable consequence,

■ Loss of production,

■ Deterioration of the production facilities or loss of sensitive data,

■ Causing mortal danger.

This is expressed in terms of the criticality of supplying of loads or circuits.

■ Non-critical:

The load or the circuit can be "shed" at any time. E.g.: sanitary water heating circuit.

■ Low criticality:

A power interruption causes temporary discomfort for the occupants of a building, without any financial consequences. Prolonging of the interruption beyond the critical time can cause a loss of production or lower productivity. E.g.: heating, ventilation and air conditioning circuits (HVAC).

■ Medium criticality

A power interruption causes a short break in process or service. Prolonging of the interruption beyond a critical time can cause a deterioration of the production facilities or a cost of starting for starting back up.

E.g.: refrigerated units, lifts.

■ High criticality

Any power interruption causes mortal danger or unacceptable financial losses.

E.g.: operating theatre, IT department, security department.

\* indicative value, supplied by standard EN50160:

"Characteristics of the voltage supplied by public distribution networks".

## 3 Electrical installation characteristics

D10

### 3.10 Disturbance sensitivity

#### Definition

The ability of a circuit to work correctly in presence of an electrical power disturbance.

A disturbance can lead to varying degrees of malfunctioning. E.g.: stopping working, incorrect working, accelerated ageing, increase of losses, etc

Types of disturbances with an impact on circuit operations:

- brown-outs,
- overvoltages
- voltage distortion,
- voltage fluctuation,
- voltage imbalance.

#### Different categories:

- low sensitivity: disturbances in supply voltages have very little effect on operations. E.g.: heating device.
- medium sensitivity: voltage disturbances cause a notable deterioration in operations. E.g.: motors, lighting.
- high sensitivity: voltage disturbances can cause operation stoppages or even the deterioration of the supplied equipment. E.g.: IT equipment.

The sensitivity of circuits to disturbances determines the design of shared or dedicated power circuits. Indeed it is better to separate "sensitive" loads from "disturbing" loads. E.g.: separating lighting circuits from motor supply circuits. This choice also depends on operating features. E.g.: separate power supply of lighting circuits to enable measurement of power consumption.

### 3.11 Disturbance capability of circuits

#### Definition

The ability of a circuit to disturb the operation of surrounding circuits due to phenomena such as: harmonics, in-rush current, imbalance, High Frequency currents, electromagnetic radiation, etc.

#### Different categories

- Non disturbing: no specific precaution to take
- moderate or occasional disturbance: separate power supply may be necessary in the presence of medium or high sensitivity circuits. E.g.: lighting circuit generating harmonic currents.
- Very disturbing: a dedicated power circuit or ways of attenuating disturbances are essential for the correct functioning of the installation. E.g.: electrical motor with a strong start-up current, welding equipment with fluctuating current.

### 3.12 Other considerations or constraints

- Environment  
E.g.: lightning classification, sun exposure
- Specific rules  
E.g.: hospitals, high rise buildings, etc.
- Rule of the Energy Distributor  
Example: limits of connection power for LV, access to MV substation, etc
- Attachment loads  
Loads attached to 2 independent circuits for reasons of redundancy.
- Designer experience  
Consistency with previous designs or partial usage of previous designs, standardization of sub-assemblies, existence of an installed equipment base.
- Load power supply constraints  
Voltage level (230V, 400V, 690V), voltage system (single-phase, three-phase with or without neutral, etc)

The technological solutions considered concern the various types of MV and LV equipment, as well as Busbar Trunking Systems .

The choice of technological solutions is made following the choice of single-line diagram and according to characteristics given below.

### 4.1 Environment, atmosphere

A notion taking account of all of the environmental constraints (average ambient temperature, altitude, humidity, corrosion, dust, impact, etc.) and bringing together protection indexes IP and IK.

Different categories:

- Standard: no particular environmental constraints
- Enhanced: severe environment, several environmental parameters generate important constraints for the installed equipment
- Specific: atypical environment, requiring special enhancements

### 4.2 Service Index

The service index (IS) is a value that allows us to characterize an LV switchboard according to user requirements in terms of operation, maintenance, and scalability. The different index values are indicated in the following table (**Fig D4**):

	Operation	Maintenance	Upgrade
Level 1	IS = 1 • • Operation may lead to complete stoppage of the switchboard	IS = • 1 • Operation may lead to complete stoppage of the switchboard	IS = • • 1 Operation may lead to complete stoppage of the switchboard
Level 2	IS = 2 • • Operation may lead to stoppage of only the functional unit	IS = • 2 • Operation may lead to stoppage of only the functional unit, with work on connections	IS = • • 2 Operation may lead to stoppage of only the functional unit, with functional units provided for back-up
Level 3	IS = 3 • • Operation may lead to stoppage of the power of the functional unit only	IS = • 3 • Operation may lead to stoppage of only the functional unit, without work on connections	IS = • • 3 Operation may lead to stoppage of only the functional unit, with total freedom in terms of upgrade

**Fig. D4** : Different index values

- Examples of an operation event: turning off a circuit-breaker, switching operation to energize/de-energize a machine
- Example of a maintenance operation: tightening connections
- Example of an upgrade operation: connecting an additional feeder

There are a limited number of relevant service indices (see **Fig. D5**)

IS	Operation	Maintenance	Upgrade
1 1 1	Switching off the whole switchboard	Working time > 1h, with total non-availability	Extension not planned
2 1 1	Individually switching off the functional unit and re-commissioning < 1h	Working time between 1/4h and 1h, with work on connections	Possible adding of functional units without stopping the switchboard
2 2 3			Possible adding of functional units with stopping the switchboard
2 3 2			Possible adding of functional units without stopping the switchboard
2 3 3	Individually switching off the functional unit and re-commissioning < 1/4h	Working time between 1/4h and 1h, without work on connections	Possible adding of functional units with stopping the switchboard
3 3 2			Possible adding of functional units without stopping the switchboard
3 3 3			Possible adding of functional units without stopping the switchboard

**Fig. D5** : Relevant service indices (IS)



The types of electrical connections of functional units can be denoted by a three-letter code:

- The first letter denotes the type of electrical connection of the main incoming circuit,
- The second letter denotes the type of electrical connection of the main outgoing circuit,
- The third letter denotes the type of electrical connection of the auxiliary circuits.

The following letters are used:

- F for fixed connections,
- D for disconnectable connections,
- W for withdrawable connections.

Service ratings are related to other mechanical parameters, such as the Protection Index (IP), form of internal separations, the type of connection of functional units or switchgear (**Fig. D6**):

Service rating	Protection index IP	Form	Functional Unit Withdrawability
1 1 1	2 X X	1	F F F
2 1 1	2 X B	1	F F F
2 2 3	2 X B	3b	W F D
2 3 2	2 X B	3b	W F W
2 3 3	2 X B	3b	W W W
3 3 2	2 X B	3b	W W W
3 3 3	2 X B	3b	W W W

**Fig. D6** : Correspondence between service index and other mechanical parameters

Technological examples are given in **chapter E2**.

- Definition of the protection index: see IEC 60529: "Degree of protection given by enclosures (IP code)",
- Definitions of the form and withdrawability: see IEC 60439-1: "Low-voltage switchgear and controlgear assemblies; part 1: type-tested and partially type-tested assemblies".

### 4.3 Other considerations

Other considerations have an impact on the choice of technological solutions:

- Designer experience,
- Consistency with past designs or the partial use of past designs,
- Standardization of sub-assemblies,
- The existence of an installed equipment base,
- Utilities requirements,
- Technical criteria: target power factor, backed-up load power, presence of harmonic generators...

These considerations should be taken into account during the detailed electrical definition phase following the draft design stage.

Certain decisive criteria are assessed at the end of the 3 stages in defining architecture, in order to validate the architecture choice. These criteria are listed below with the different allocated levels of priority.

## 5.1 On-site work time

Time for implementing the electrical equipment on the site.

### Different levels of priority:

- Secondary: the on-site work time can be extended, if this gives a reduction in overall installation costs,
- Special: the on-site work time must be minimized, without generating any significant excess cost,
- Critical: the on-site work time must be reduced as far as possible, imperatively, even if this generates a higher total installation cost,

## 5.2 Environmental impact

Taking into consideration environmental constraints in the installation design. This takes account of: consumption of natural resources, Joule losses (related to CO<sub>2</sub> emission), "recyclability" potential, throughout the installation's lifecycle.

### Different levels of priority:

- Non significant: environmental constraints are not given any special consideration,
- Minimal: the installation is designed with minimum regulatory requirements,
- Proactive: the installation is designed with a specific concern for protecting the environment. Excess cost is allowed in this situation. E.g.: using low-loss transformers.

The environmental impact of an installation will be determined according to the method carrying out an installation lifecycle analysis, in which we distinguish between the following 3 phases:

- manufacture,
- operation,
- end of life (dismantling, recycling).

In terms of environmental impact, 3 indicators (at least) can be taken into account and influenced by the design of an electrical installation. Although each lifecycle phase contributes to the three indicators, each of these indicators is mainly related to one phase in particular:

- consumption of natural resources mainly has an impact on the manufacturing phase,
- consumption of energy has an impact on the operation phase,
- "recycleability" potential has an impact on the end of life.

The following table details the contributing factors to the 3 environmental indicators (Fig D7).

Indicators	Contributors
Natural resources consumption	Mass and type of materials used
Power consumption	Joule losses at full load and no load
«Recyclability» potential	Mass and type of material used

**Fig D7** : Contributing factors to the 3 environmental indicators

### 5.3 Preventive maintenance level

#### Definition:

Number of hours and sophistication of maintenance carried out during operations in conformity with manufacturer recommendations to ensure dependable operation of the installation and the maintaining of performance levels (avoiding failure: tripping, down time, etc).

#### Different categories:

- Standard: according to manufacturer recommendations.
- Enhanced: according to manufacturer recommendations, with a severe environment,
- Specific: specific maintenance plan, meeting high requirements for continuity of service, and requiring a high level of maintenance staff competency.

### 5.4 Availability of electrical power supply

#### Definition:

This is the probability that an electrical installation be capable of supplying quality power in conformity with the specifications of the equipment it is supplying. This is expressed by an availability level:

$$\text{Availability (\%)} = (1 - \text{MTTR} / \text{MTBF}) \times 100$$

MTTR (Mean Time To Repair): the average time to make the electrical system once again operational following a failure (this includes detection of the reason for failure, its repair and re-commissioning),

MTBF (Mean Time Between Failure): measurement of the average time for which the electrical system is operational and therefore enables correct operation of the application.

The different availability categories can only be defined for a given type of installation. E.g.: hospitals, data centers.

#### Example of classification used in data centers:

Tier 1: the power supply and air conditioning are provided by one single channel, without redundancy, which allows availability of 99.671%,

Tier 2: the power supply and air conditioning are provided by one single channel, with redundancy, which allows availability of 99.741%,

Tier 3: the power supply and air conditioning are provided by several channels, with one single redundant channel, which allows availability of 99.982%,

Tier 4: the power supply and air conditioning are provided by several channels, with redundancy, which allows availability of 99.995%.

## 6 Choice of architecture fundamentals

The single-line diagram can be broken down into different key parts, which are determined throughout a process in 2 successive stages. During the first stage we make the following choices:

- connection to the utilities network,
- configuration of MV circuits,
- number of power transformers,
- number and distribution of transformation substations,
- MV back-up generator

D15

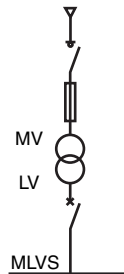
### 6.1 Connection to the upstream network

The main configurations for possible connection are as follows (see **Fig. D8** for MV service):

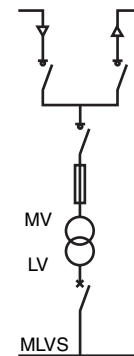
- LV service,
- MV single-line service,
- MV ring-main service,
- MV duplicate supply service,
- MV duplicate supply service with double busbar.

Metering, protection, disconnection devices, located in the delivery substations are not represented on the following diagrams. They are often specific to each utilities company and do not have an influence on the choice of installation architecture. For each connection, one single transformer is shown for simplification purposes, but in the practice, several transformers can be connected.  
(MLVS: Main Low Voltage Switchboard)

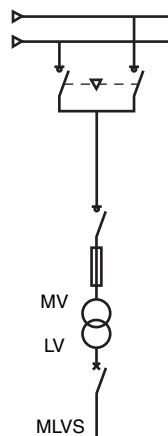
a) Single-line:



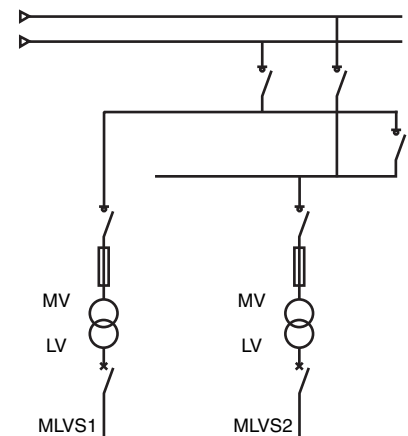
b) Ring-main:



c) Duplicate supply:



d) Double busbar with duplicate supply:



**Fig. D8** : MV connection to the utilities network

# 6 Choice of architecture fundamentals

For the different possible configurations, the most probable and usual set of characteristics is given in the following table:

D16

Characteristic to consider	Configuration				
	LV	MV			
		Simple-line	Ring-main	Duplicate supply	Duplicate supply with double busbars
Activity	Any	Any	Any	Hi-tech, sensitive office, health-care	Any
Site topology	Single building	Single building	Single building	Single building	Several buildings
Service reliability	Minimal	Minimal	Standard	Enhanced	Enhanced
Power demand	< 630kVA	≤ 1250kVA	≤ 2500kVA	> 2500kVA	> 2500kVA
Other connection constraints	Any	Isolated site	Low density urban area	High density urban area	Urban area with utility constraint

## 6.2 MV circuit configuration

The main possible connection configurations are as follows (Fig. D9):

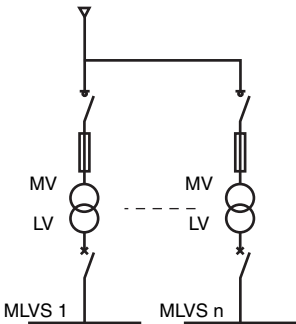
- single feeder, one or several transformers
- open ring, one MV incomer
- open ring, 2 MV incomers

The basic configuration is a radial single-feeder architecture, with one single transformer.

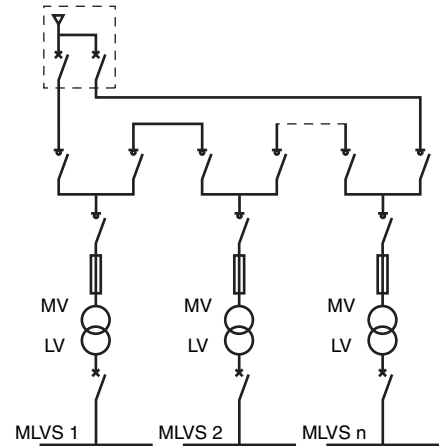
In the case of using several transformers, no ring is realised unless all of the transformers are located in a same substation.

Closed-ring configuration is not taken into account.

a) Single feeder:



b) Open ring, 1 MV substation:



c) Open ring, 2 MV substations:

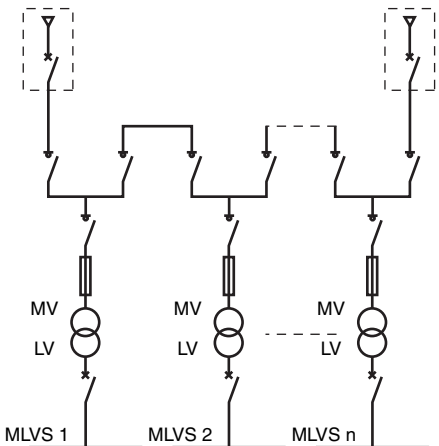


Fig. D9 : MV circuit configuration

## 6 Choice of architecture fundamentals

For the different possible configurations, the most probable and usual set of characteristics is given in the table on **Fig D10**.

Characteristic to consider	MV circuit configuration		
	Single feeder	Open ring 1 MV substation	Open ring 2 MV substations
Site topology	Any < 25000m <sup>2</sup>	Building with one level or several buildings ≤ 25000m <sup>2</sup>	Several buildings ≥ 25000m <sup>2</sup>
Maintainability	Minimal or standard	Enhanced	Enhanced
Power demand	Any	> 1250kVA	> 2500kVA
Disturbance sensitivity	Long interruption acceptable	Short interruption acceptable	Short interruption acceptable

**Fig. D10** : Typical values of the installation characteristics

Another exceptional configuration: power supply by 2 MV substations and connection of the transformers to each of these 2 substations (MV “double ended” connection).

### 6.3 Number and distribution of MV/LV transformation substations

Main characteristics to consider to determine the transformation substations:

- Surface area of building or site
- Power demand, (to be compared with standardized transformer power),
- Load distribution

The preferred basic configuration comprises one single substation. Certain factors contribute to increasing the number of substations (> 1):

- A large surface area (> 25000m<sup>2</sup>),
- The site configuration: several buildings,
- Total power > 2500kVA,
- Sensitivity to interruption: need for redundancy in the case of a fire.

Characteristic to consider	Configuration		
	1 substation with N transformers	N substations N transformers (identical substations)	N substations M transformers (different powers)
Building configuration	< 25000m <sup>2</sup>	≥ 25000m <sup>2</sup> 1 building with several floors	≥ 25000m <sup>2</sup> several buildings
Power demand	< 2500kVA	≥ 2500kVA	≥ 2500kVA
Load distribution	Localized loads	Uniform distribution	Medium density

**Fig. D11** : Typical characteristics of the different configurations

D17

## 6.4 Number of MV/LV transformers

Main characteristics to consider to determine the number of transformers:

- Surface of building or site
- Total power of the installed loads
- Sensitivity of circuits to power interruptions
- Sensitivity of circuits to disturbances
- Installation scalability

The basic preferred configuration comprises a single transformer supplying the total power of the installed loads. Certain factors contribute to increasing the number of transformers (> 1), preferably of equal power:

- A high total installed power (> 1250kVA): practical limit of unit power (standardization, ease of replacement, space requirement, etc),
- A large surface area (> 5000m<sup>2</sup>): the setting up of several transformers as close as possible to the distributed loads allows the length of LV trunking to be reduced
- A need for partial redundancy (down-graded operation possible in the case of a transformer failure) or total redundancy (normal operation ensured in the case of a transformer failure)
- Separating of sensitive and disturbing loads (e.g.: IT, motors)

## 6.5 MV back-up generator

Main characteristics to consider for the implementation of an MV back-up generator:

- Site activity
- Total power of the installed loads
- Sensitivity of circuits to power interruptions
- Availability of the public distribution network

The preferred basic configuration does not include an MV generator. Certain factors contribute to installing an MV generator:

- Site activity: process with co-generation, optimizing the energy bill,
- Low availability of the public distribution network.

Installation of a back-up generator can also be carried out at LV level.

This is the second stage in designing of the electrical installation. During this stage we carry out the following choices are carried out:

- Layout,
- Centralized or decentralized distribution,
- Presence of back-up generators,
- Presence of uninterruptible power supplies,
- Configuration of LV circuits,
- Architecture combinations.

## 7.1 Layout

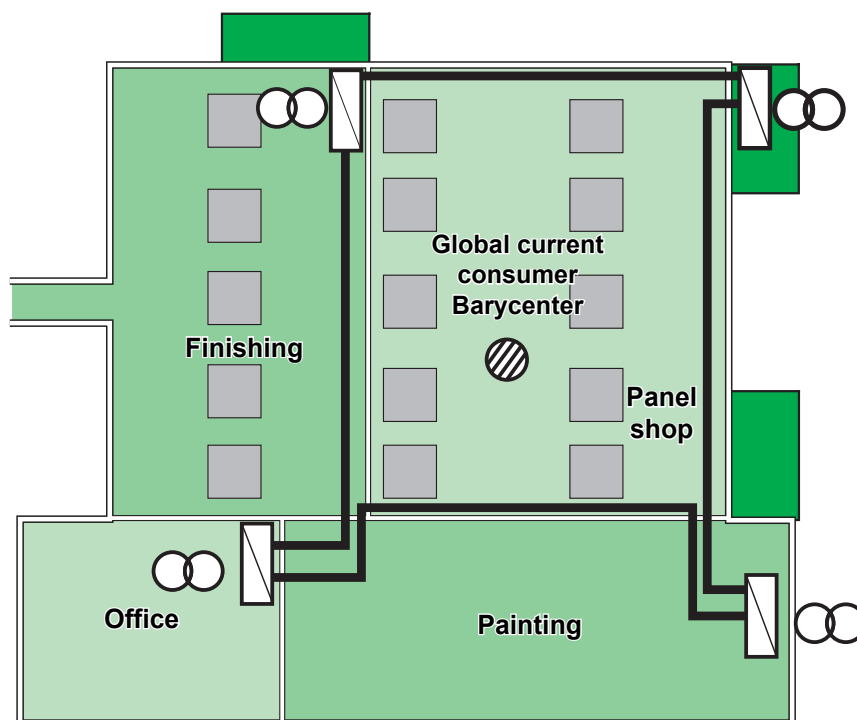
Position of the main MV and LV equipment on the site or in the building.

This layout choice is applied to the results of stage 1.

### Selection guide:

- Place power sources as close as possible to the barycenter of power consumers,
- Reduce atmospheric constraints: building dedicated premises if the layout in the workshop is too restrictive (temperature, vibrations, dust, etc.),
- Placing heavy equipment (transformers, generators, etc) close to walls or main exists for ease of maintenance,

A layout example is given in the following diagram (Fig. D12):

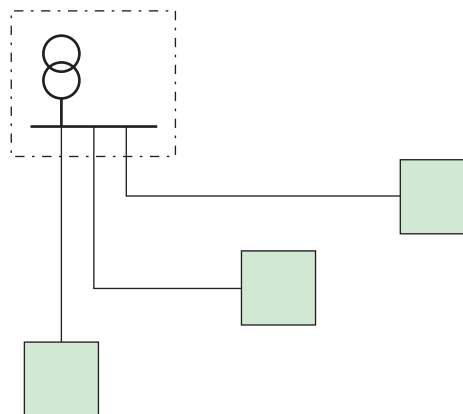


**Fig. D12** : The position of the global current consumer barycenter guides the positioning of power sources



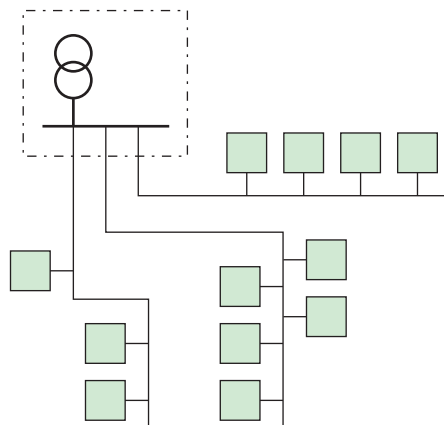
## 7.2 Centralized or distributed layout

In **centralized layout**, current consumers are connected to the power sources by a star-connection. Cables are suitable for centralized layout, with point to point links between the MLVS and current consumers or sub-distribution boards (radial distribution, star- distribution) (**Fig. D13**):



**Fig. D13:** Example of centralized layout with point to point links

In **decentralized layout**, current consumers are connected to sources via a busway. Busbar trunking systems are well suited to decentralized layout, to supply many loads that are spread out, making it easy to change, move or add connections (**Fig D14**):



**Fig. D14 :** Example of decentralized layout, with busbar trunking links

Factors in favour of centralized layout (see summary table in **Fig. D15**):

- Installation flexibility: no,
- Load distribution: localized loads (high unit power loads).

Factors in favor of decentralized layout:

- Installation flexibility: "Implementation" flexibility (moving of workstations, etc...),
- Load distribution: uniform distribution of low unit power loads

	Load distribution			
Flexibility	Localized loads	Intermediate distribution	Uniform distributed	
No flexibility	Centralized		Decentralized	
Design flexibility				
Implementation flexibility	Centralized	Decentralized		
Operation flexibility				

D21

**Fig. D15 :** Recommendations for centralized or decentralized layout

Power supply by cables gives greater independence of circuits (lighting, power sockets, HVAC, motors, auxiliaries, security, etc), reducing the consequences of a fault from the point of view of power availability.

The use of busbar trunking systems allows load power circuits to be combined and saves on conductors by taking advantage of a clustering coefficient. The choice between cable and busbar trunking, according to the clustering coefficient, allows us to find an economic optimum between investment costs, implementation costs and operating costs.

These two distribution modes are often combined.

### Presence of back-up generators (Fig. D16)

Here we only consider LV back-up generators.

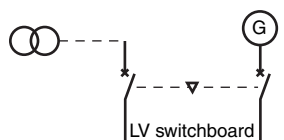
The electrical power supply supplied by a back-up generator is produced by an alternator, driven by a thermal engine.

No power can be produced until the generator has reached its rated speed. This type of device is therefore not suitable for an uninterrupted power supply.

According to the generator's capacity to supply power to all or only part of the installation, there is either total or partial redundancy.

A back-up generator functions generally disconnected from the network. A source switching system is therefore necessary.

The generator can function permanently or intermittently. Its back-up time depends on the quantity of available fuel.



**Fig. D16 :** Connection of a back-up generator

The main characteristics to consider for implementing LV back-up generator:

- Sensitivity of loads to power interruption,
- Availability of the public distribution network,
- Other constraints (e.g.: generators compulsory in hospitals or high-vise buildings)

The presence of generators can be decided to reduce the energy bill or due to the opportunity for co-generation. These two aspects are not taken into account in this guide.

The presence of a back-up generator is essential if the loads cannot be shed for an indefinite duration (long interruption only acceptable) or if the utility network availability is low.

Determining the number of back-up generator units is in line with the same criteria as determining the number of transformers, as well as taking account of economic and availability considerations (redundancy, start-up reliability, maintenance facility).

### 7.3 Presence of an Uninterruptible Power Supply (UPS)

The electrical power from a UPS is supplied from a storage unit: batteries or inertia wheel. This system allows us to avoid any power failure. The back-up time of the system is limited: from several minutes to several hours.

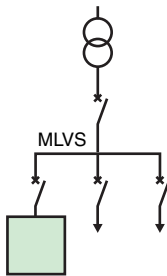
The simultaneous presence of a back-up generator and a UPS unit is used for permanently supply loads for which no failure is acceptable (**Fig. D17**). The back-up time of the battery or the inertia wheel must be compatible with the maximum time for the generator to start up and be brought on-line.

A UPS unit is also used for supply power to loads that are sensitive to disturbances (generating a "clean" voltage that is independent of the network).

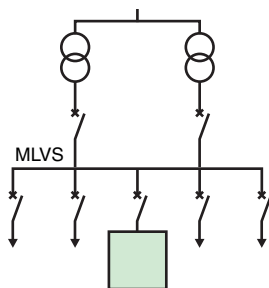
Main characteristics to be considered for implementing a UPS:

- Sensitivity of loads to power interruptions,
- Sensitivity of loads to disturbances.

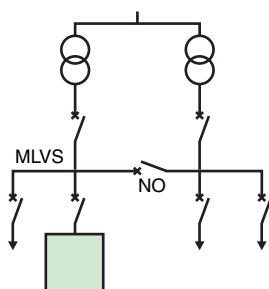
The presence of a UPS unit is essential if and only if no failure is acceptable.



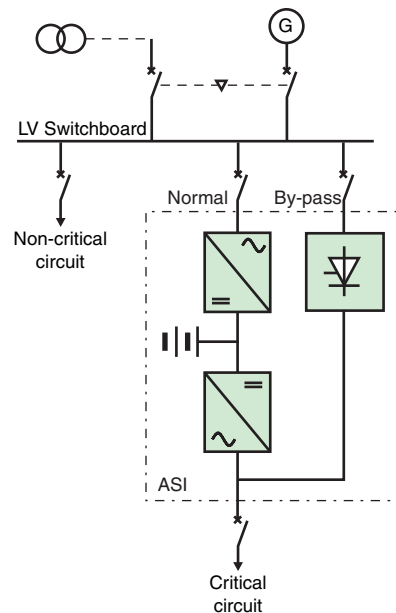
**Fig. D18 :** Radial single feeder configuration



**Fig. D19 :** Two-pole configuration



**Fig. D20 :** Two-pole configuration with two 1/2 MLVS and NO link



**Fig. D17 :** Example of connection for a UPS

### 7.4 Configuration of LV circuits

Main possible configurations (see **figures D18 to D25**):

■ **Radial single feeder configuration:** This is the reference configuration and the most simple. A load is connected to only one single source. This configuration provides a minimum level of availability, since there is no redundancy in case of power source failure.

■ **Two-pole configuration:** The power supply is provided by 2 transformers, connected to the same MV line. When the transformers are close, they are generally connected in parallel to the same MLVS.

■ **Variant: two-pole with two 1/2 MLVS:** In order to increase the availability in case of failure of the busbars or authorize maintenance on one of the transformers, it is possible to split the MLVS into 2 parts, with a normally open link (NO). This configuration generally requires an Automatic Transfer Switch, (ATS).

■ **Shedable switchboard (simple disconnectable attachment):** A series of shedable circuits can be connected to a dedicated switchboard. The connection to the MLVS is interrupted when needed (overload, generator operation, etc)

■ **Interconnected switchboards:** If transformers are physically distant from one another, they may be connected by a busbar trunking. A critical load can be supplied by one or other of the transformers. The availability of power is therefore improved, since the load can always be supplied in the case of failure of one of the sources. The redundancy can be:

- Total: each transformer being capable of supplying all of the installation,
- Partial: each transformer only being able to supply part of the installation. In this case, part of the loads must be disconnected (load-shedding) in the case of one of the transformers failing.

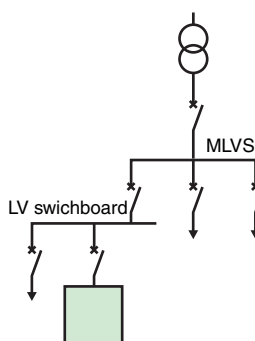


Fig. D21 : Shedable switchboard

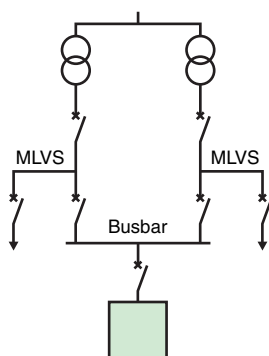


Fig. D22 : Interconnected switchboards

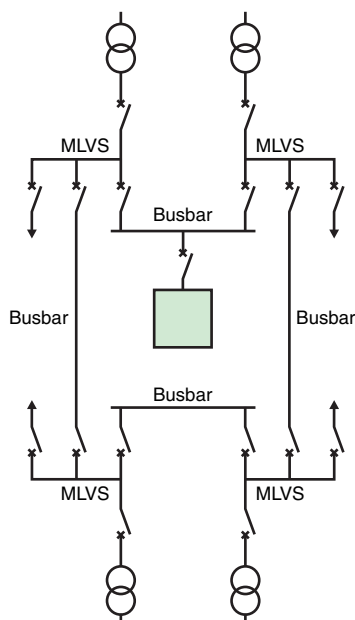


Fig. D23 : Ring configuration

■ **Ring configuration:** This configuration can be considered as an extension of the configuration with interconnection between switchboards. Typically, 4 transformers connected to the same MV line, supply a ring using busbar trunking. A given load is then supplied power by several clustered transformers. This configuration is well suited to extended installations, with a high load density (in kVA/m<sup>2</sup>). If all of the loads can be supplied by 3 transformers, there is total redundancy in the case of failure of one of the transformers. In fact, each busbar can be fed power by one or other of its ends. Otherwise, downgraded operation must be considered (with partial load shedding). This configuration requires special design of the protection plan in order to ensure discrimination in all of the fault circumstances.

■ **Double-ended power supply:** This configuration is implemented in cases where maximum availability is required. The principle involves having 2 independent power sources, e.g.:

- 2 transformers supplied by different MV lines,
- 1 transformer and 1 generator,
- 1 transformer and 1 UPS.

An automatic transfer switch (ATS) is used to avoid the sources being parallel connected. This configuration allows preventive and curative maintenance to be carried out on all of the electrical distribution system upstream without interrupting the power supply.

■ **Configuration combinations:** An installation can be made up of several sub-assemblies with different configurations, according to requirements for the availability of the different types of load. E.g.: generator unit and UPS, choice by sectors (some sectors supplied by cables and others by busbar trunking).

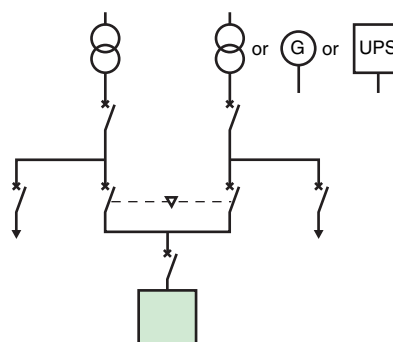


Fig. D24 : Double-ended configuration with automatic transfer switch

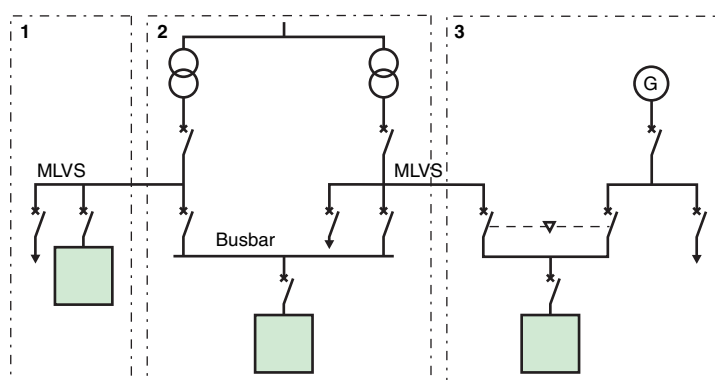


Fig. D25 : Example of a configuration combination  
1: Single feeder, 2: Switchboard interconnection, 3: Double-ended

For the different possible configurations, the most probable and usual set of characteristics is given in the following table:

D24

Characteristic to be considered	Configuration					
	Radial	Two-pole	Sheddable load	Interconnected switchboards	Ring	Double-ended
Site topology	Any	Any	Any	1 level 5 to 25000m <sup>2</sup>	1 level 5 to 25000m <sup>2</sup>	Any
Location latitude	Any	Any	Any	Medium or high	Medium or high	Any
Maintainability	Minimal	Standard	Minimal	Standard	Standard	Enhanced
Power demand	< 2500kVA	Any	Any	≥ 1250kVA	> 2500kVA	Any
Load distribution	Localized loads	Localized loads	Localized load	Intermediate or uniforme distribution	Uniform distribution	Localized loads
Interruptions sensitivity	Long interruption acceptable	Long interruption acceptable	Sheddable	Long interruption acceptable	Long interruption acceptable	Short or no interruption
Disturbances sensitivity	Low sensitivity	High sensitivity	Low sensitivity	High sensitivity	High sensitivity	High sensitivity
Other constraints	/	/	/	/	/	Double-ended loads

The choice of equipment is step 3 in the design of an electrical installation. The aim of this step is to select equipment from the manufacturers' catalogues. The choice of technological solutions results from the choice of architecture.

**List of equipment to consider:**

- MV/LV substation,
- MV switchboards,
- Transformers,
- LV switchboards,
- Busbar trunking,
- UPS units,
- Power factor correction and filtering equipment.

**Criteria to consider:**

- Atmosphere, environment,
- Service index,
- Offer availability per country,
- Utilities requirements,
- Previous architecture choices.

The choice of equipment is basically linked to the offer availability in the country. This criterion takes into account the availability of certain ranges of equipment or local technical support.

The detailed selection of equipment is out of the scope of this document.

## 9 Recommendations for architecture optimization

These recommendations are intended to guide the designer towards architecture upgrades which allow him to improve assessment criteria.

### 9.1 On-site work

To be compatible with the “special” or “critical” work-site time, it is recommended to limit uncertainties by applying the following recommendations:

- Use of proven solutions and equipment that has been validated and tested by manufacturers (“functional” switchboard or “manufacturer” switchboard according to the application criticality),
- Prefer the implementation of equipment for which there is a reliable distribution network and for which it is possible to have local support (supplier well established),
- Prefer the use of factory-built equipment (MV/LV substation, busbar trunking), allowing the volume of operations on site to be limited,
- Limit the variety of equipment implemented (e.g. the power of transformers),
- Avoid mixing equipment from different manufacturers.

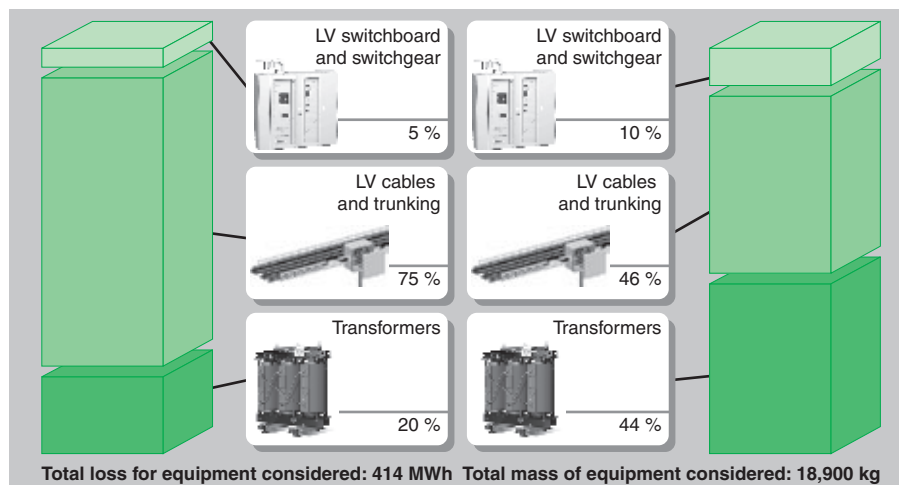
### 9.2 Environmental impact

The optimization of the environmental assessment of an installation will involve reducing:

- Power losses at full load and no load during installation operation,
- Overall, the mass of materials used to produce the installation.

Taken separately and when looking at only one piece of equipment, these 2 objectives may seem contradictory. However, when applied to whole installation, it is possible to design the architecture to contribute to both objectives. The optimal installation will therefore not be the sum of the optimal equipment taken separately, but the result of an optimization of the overall installation.

**Figure D26** gives an example of the contribution per equipment category to the weight and energy dissipation for a 3500 kVA installation spread over 10000m<sup>2</sup>.



**Fig. D26** : Example of the spread of losses and the weight of material for each equipment category

Generally speaking, LV cables and trunking as well as the MV/LV transformers are the main contributors to operating losses and the weight of equipment used.

Environmental optimization of the installation by the architecture will therefore involve:

- reducing the length of LV circuits in the installation,
- clustering LV circuits wherever possible to take advantage of the factor of simultaneity  $k_s$  (see chapter A: General rules of electrical installation design, Chapter – Power loading of an installation, 4.3 “Estimation of actual maximum kVA demand”)

# 9 Recommendations for architecture optimization

Objectives	Resources
Reducing the length of LV circuits	Placing MV/LV substations as close as possible to the barycenter of all of the LV loads to be supplied
Clustering LV circuits	<p>When the simultaneity factor of a group of loads to be supplied is less than 0.7, the clustering of circuits allows us to limit the volume of conductors supplying power to these loads.</p> <p>In real terms this involves:</p> <ul style="list-style-type: none"><li>■ setting up sub-distribution switchboards as close as possible to the barycenter of the groups of loads if they are localized,</li><li>■ setting up busbar trunking systems as close as possible to the barycenter of the groups of loads if they are distributed.</li></ul> <p>The search for an optimal solution may lead to consider several clustering scenarios.</p> <p>In all cases, reducing the distance between the barycenter of a group of loads and the equipment that supplies them power allows to reduce environmental impact.</p>

D27

Fig. D27 : Environmental optimization : Objectives and Ressources.

As an example **figure D28** shows the impact of clustering circuits on reducing the distance between the barycenter of the loads of an installation and that of the sources considered (MLVS whose position is imposed). This example concerns a mineral water bottling plant for which:

- the position of electrical equipment (MLVS) is imposed in the premises outside of the process area for reasons of accessibility and atmosphere constraints,
- the installed power is around 4 MVA.

In solution No.1, the circuits are distributed for each workshop.

In solution No. 2, the circuits are distributed by process functions (production lines).

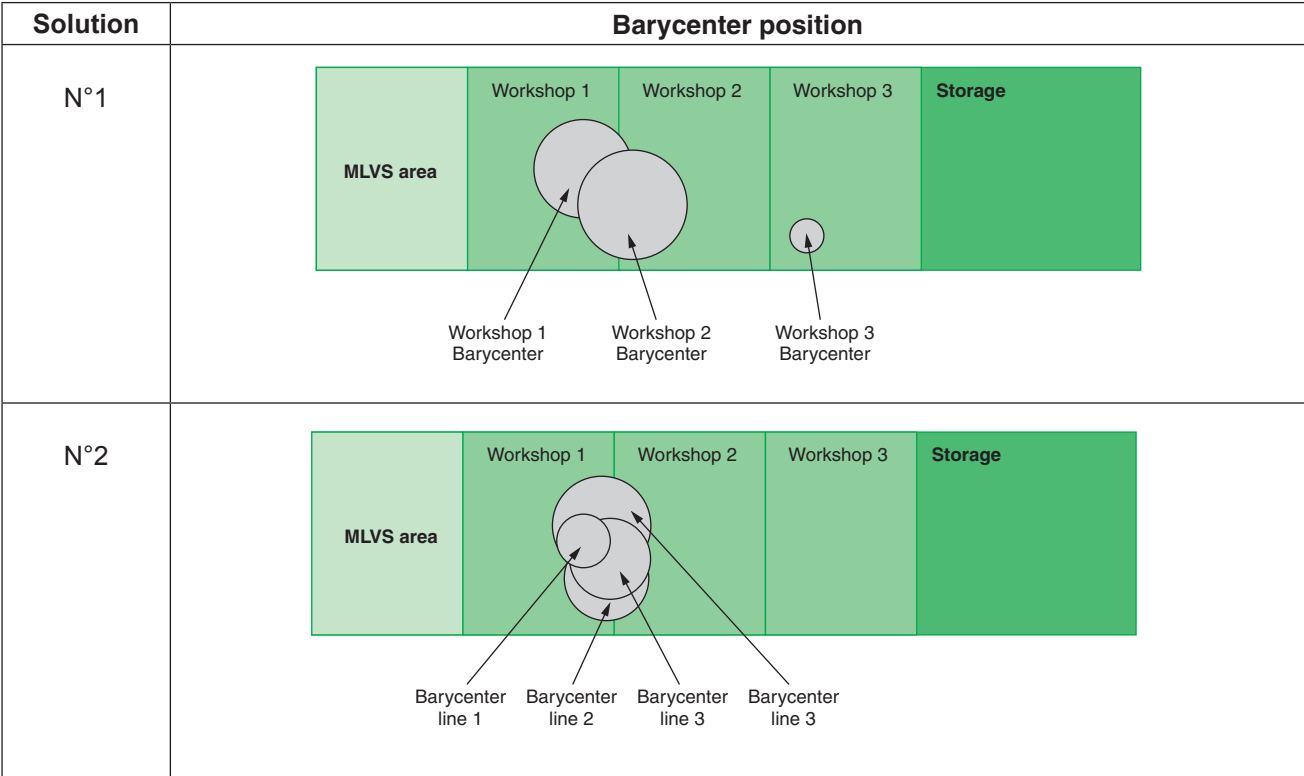


Fig. D28 : Example of barycenter positioning



## 9 Recommendations for architecture optimization

D28

Without changing the layout of electrical equipment, the second solution allows us to achieve gains of around 15% on the weight of LV cables to be installed (gain on lengths) and a better uniformity of transformer power.

To supplement the optimizations carried out in terms of architecture, the following points also contribute to the optimization:

- the setting up of LV power factor correction to limit losses in the transformers and LV circuits if this compensation is distributed,
- the use of low loss transformers,
- the use of aluminum LV busbar trunking when possible, since natural resources of this metal are greater.

### 9.3 Preventive maintenance volume

Recommendations for reducing the volume of preventive maintenance:

- Use the same recommendations as for reducing the work site time,
- Focus maintenance work on critical circuits,
- Standardize the choice of equipment,
- Use equipment designed for severe atmospheres (requires less maintenance).

### 9.4 Electrical power availability

Recommendations for improving the electrical power availability:

- Reduce the number of feeders per switchboard, in order to limit the effects of a possible failure of a switchboard,
- Distributing circuits according to availability requirements,
- Using equipment that is in line with requirements (see Service Index, 4.2),
- Follow the selection guides proposed for steps 1 & 2 (see **Fig. D3 page D5**).

Recommendations to increase the level of availability:

- Change from a radial single feeder configuration to a two-pole configuration,
- Change from a two-pole configuration to a double-ended configuration,
- Change from a double-ended configuration to a uninterruptible configuration with a UPS unit and a Static Transfer Switch
- Increase the level of maintenance (reducing the MTTR, increasing the MTBF)

**Architecture:** choice of a single-line diagram and technological solutions, from connection to the utility network through to load power supply circuits.

**Main MV/LV distribution:** Level upstream of the architecture, from connection to the network utility through to LV distribution equipment on the site (MLVS – or equivalent).

**MLVS – Main Low Voltage Switchboard:** Main switchboard downstream of the MV/LV transformer, starting point of power distribution circuits in the installation

**LV power distribution:** intermediate level in the architecture, downstream of the main level through to the sub-distribution switchboards (spatial and functional distribution of electrical power in the circuits).

**LV terminal distribution:** Downstream level of the architecture, downstream of the sub-distribution switchboards through to the loads. This level of distribution is not dealt with in this guide.

**Single-line diagram:** general electrical schematic diagram to represent the main electrical equipment and their interconnection.

**MV substation, transformation substation:** Enclosures grouping together MV equipment and/or MV/LV transformers. These enclosures can be shared or separate, according to the site layout, or the equipment technology. In certain countries, the MV substation is assimilated with the delivery substation.

**Technological solution:** Resulting from the choice of technology for an installation sub-assembly, from among the different products and equipment proposed by the manufacturer.

**Characteristics:** Technical or environmental data relative to the installation, enabling the best-suited architecture to be selected.

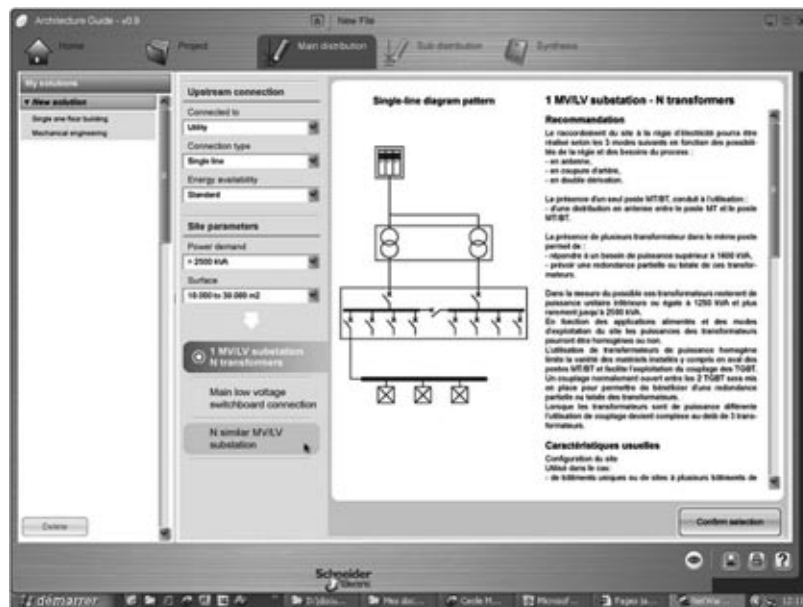
**Criteria:** Parameters for assessing the installation, enabling selection of the architecture that is the best-suited to the needs of the customer.

# 11 ID-Spec software

**ID-Spec** is a new software which aims at helping the designer to be more productive in draft design phase and argue easily his design decisions.

It supports the designer in selecting the relevant single line diagram patterns for main distribution and sub distribution and in adapting these patterns to his project. It also supports the designer in equipment technology and rating selection. Its generates automatically the corresponding design specification documentation including single line diagram and its argument, list and specification of the corresponding equipment.

D30



# 12 Example: electrical installation in a printworks

## 12.1 Brief description

Printing of personalized mailshots intended for mail order sales.

## 12.2 Installation characteristics

Characteristic	Category
Activity	Mechanical
Site topology	single storey building, 10000m <sup>2</sup> (8000m <sup>2</sup> dedicated to the process, 2000m <sup>2</sup> for ancillary areas)
Layout latitude	High
Service reliability	Standard
Maintainability	Standard
Installation flexibility	<ul style="list-style-type: none"> <li>■ No flexibility planned:</li> <li>□ HVAC</li> <li>□ Process utilities</li> <li>□ Office power supply</li> <li>■ Possible flexibility:</li> <li>□ finishing, putting in envelopes</li> <li>□ special machines, installed at a later date</li> <li>□ rotary machines (uncertainty at the draft design stage)</li> </ul>
Power demand	3500kVA
Load distribution	Intermediate distribution
Power interruptions sensitivity	<ul style="list-style-type: none"> <li>■ Sheddable circuits:</li> <li>□ offices (apart from PC power sockets)</li> <li>□ air conditioning, office heating</li> <li>□ social premises</li> <li>□ maintenance premises</li> <li>■ long interruptions acceptable:</li> <li>□ printing machines</li> <li>□ workshop HVAC (hygrometric control)</li> <li>□ Finishing, envelope filling</li> <li>□ Process utilities (compressor, recycling of cooled water)</li> <li>■ No interruptions acceptable:</li> <li>□ servers, office PCs</li> </ul>
Disturbance sensitivity	<ul style="list-style-type: none"> <li>■ Average sensitivity:</li> <li>□ motors, lighting</li> <li>■ High sensitivity:</li> <li>□ IT</li> </ul> <p>No special precaution to be taken due to the connection to the EdF network (low level of disturbance)</p>
Disturbance capability	Non disturbing
Other constraints	<ul style="list-style-type: none"> <li>■ Building with lightning classification: lightning surge arresters installed</li> <li>■ Power supply by overhead single feeder line</li> </ul>

## 12.3 Technological characteristics

Criteria	Category
Atmosphere, environment	<ul style="list-style-type: none"> <li>■ IP: standard (no dust, no water protection)</li> <li>■ IK: standard (use of technical pits, dedicated premises)</li> <li>■ °C: standard (temperature regulation)</li> </ul>
Service index	211
Offer availability by country	No problem (project carried out in France)
Other criteria	Nothing particular

D31

D32

## 12.4 Architecture assessment criteria

Criteria	Category
On-site work time	Secondary
Environmental impact	Minimal: compliance with European standard regulations
Preventive maintenance costs	Standard
Power supply availability	Level I

### Step 1: Architecture fundamentals

Choice	Main criteria	Solution
Connection to upstream network	Isolated site	single branch circuit
MV Circuits	Layout + criticality	single feeder
Number of transformers	Power > 2500kVA	2 x 2000kVA
Number and distribution of substations	Surface area and power distribution	2 possible solutions: 1 substation or 2 substations ■ if 1 substations: NO link between MLVS ■ if 2 substations: interconnected switchboards
MV Generator	Site activity	No

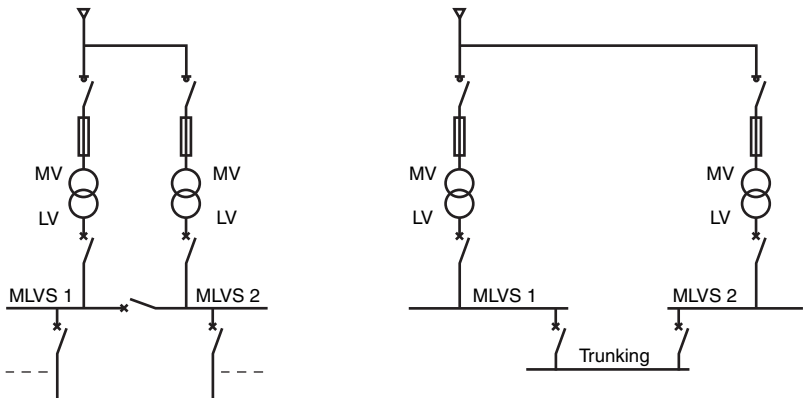


Fig. D29 : Two possible single-line diagrams

# 12 Example: electrical installation in a printworks

## Step 2: Architecture details

“1 substation” solution

Choice	Main criteria	Solution
Layout	Atmospheric constraint	Dedicated premises
Centralized or decentralized layout	Uniform loads, distributed power, scalability possibilities  Non-uniform loads, direct link from MLVS	<div>■ Decentralized with busbar trunking: □ finishing sector, envelope filling</div> <div>■ Centralized with cables: □ special machines, rotary machines, HVAC, process utilities, offices (2 switchboards), office air conditioning, social premises, maintenance</div>
Presence of back-up generator	Criticality ≤ low Network availability: standard	No back-up generator
Presence of UPS	Criticality	UPS unit for servers and office PCs
LV circuit configuration	2 transformers, possible partial redundancy	<div>■ Two-pole, variant 2 ½ MLVS + NO link (reduction of the Isc by MLVS, no redundancy)</div> <div>■ process (≤ weak)</div> <div>■ sheddable circuit for non-critical loads</div>

D33

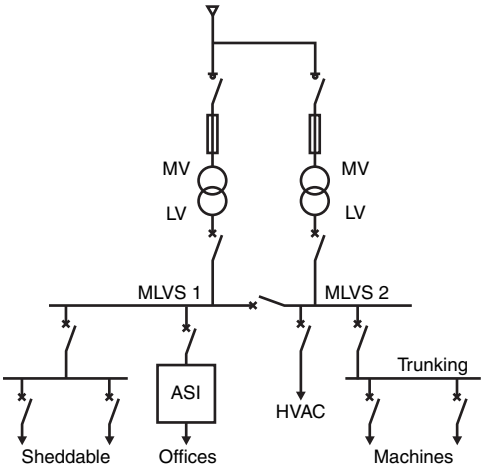


Fig. D30 : Detailed single-line diagram (1 substation)

# 12 Example: electrical installation in a printworks

D34

## 12.5 Choice of technological solutions:

Choice	Main criteria	Solution
MV/LV substation	Atmosphere, environment	indoor (dedicated premises)
MV switchboard	Offer availability by country	SM6 (installation produced in France)
Transformers	Atmosphere, environment	cast resin transfo (avoids constraints related to oil)
LV switchboard	Atmosphere, IS	MLVS: Prisma + P Sub-distribution: Prisma +
Busbar trunking	Installed power to be supplied	Canalis KS
UPS units	Installed power to be supplied, back-up time	Galaxy PW
Power factor correction	Installed power, presence of harmonics	LV, standard, automatic (Average Q, ease of installation)

### “2 substation” solution

Ditto apart from:  
LV circuit: 2 remote MLVS connected via busbar trunking

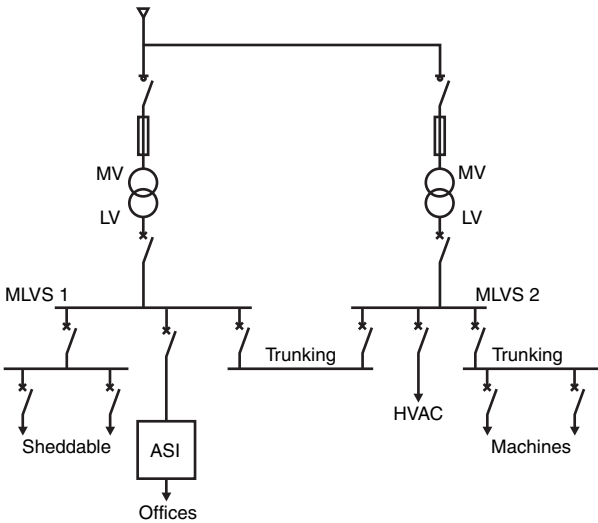


Fig. D31 : Detailed single-line diagram (2 substations)

# Chapter E

## LV Distribution

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E1



*In a building, the connection of all metal parts of the building and all exposed conductive parts of electrical equipment to an earth electrode prevents the appearance of dangerously high voltages between any two simultaneously accessible metal parts*

## 1.1 Earthing connections

### Definitions

National and international standards (IEC 60364) clearly define the various elements of earthing connections. The following terms are commonly used in industry and in the literature. Bracketed numbers refer to **Figure E1** :

- **Earth electrode (1):** A conductor or group of conductors in intimate contact with, and providing an electrical connection with Earth (cf details in section 1.6 of Chapter E.)
- **Earth:** The conductive mass of the Earth, whose electric potential at any point is conventionally taken as zero
- **Electrically independent earth electrodes:** Earth electrodes located at such a distance from one another that the maximum current likely to flow through one of them does not significantly affect the potential of the other(s)
- **Earth electrode resistance:** The contact resistance of an earth electrode with the Earth
- **Earthing conductor (2):** A protective conductor connecting the main earthing terminal (6) of an installation to an earth electrode (1) or to other means of earthing (e.g. TN systems);
- **Exposed-conductive-part:** A conductive part of equipment which can be touched and which is not a live part, but which may become live under fault conditions
- **Protective conductor (3):** A conductor used for some measures of protection against electric shock and intended for connecting together any of the following parts:
  - Exposed-conductive-parts
  - Extraneous-conductive-parts
  - The main earthing terminal
  - Earth electrode(s)
  - The earthed point of the source or an artificial neutral
- **Extraneous-conductive-part:** A conductive part liable to introduce a potential, generally earth potential, and not forming part of the electrical installation (4).  
For example:
  - Non-insulated floors or walls, metal framework of buildings
  - Metal conduits and pipework (not part of the electrical installation) for water, gas, heating, compressed-air, etc. and metal materials associated with them
- **Bonding conductor (5):** A protective conductor providing equipotential bonding
- **Main earthing terminal (6):** The terminal or bar provided for the connection of protective conductors, including equipotential bonding conductors, and conductors for functional earthing, if any, to the means of earthing.

### Connections

#### The main equipotential bonding system

The bonding is carried out by protective conductors and the aim is to ensure that, in the event of an incoming extraneous conductor (such as a gas pipe, etc.) being raised to some potential due to a fault external to the building, no difference of potential can occur between extraneous-conductive-parts within the installation.

The bonding must be effected as close as possible to the point(s) of entry into the building, and be connected to the main earthing terminal (6).

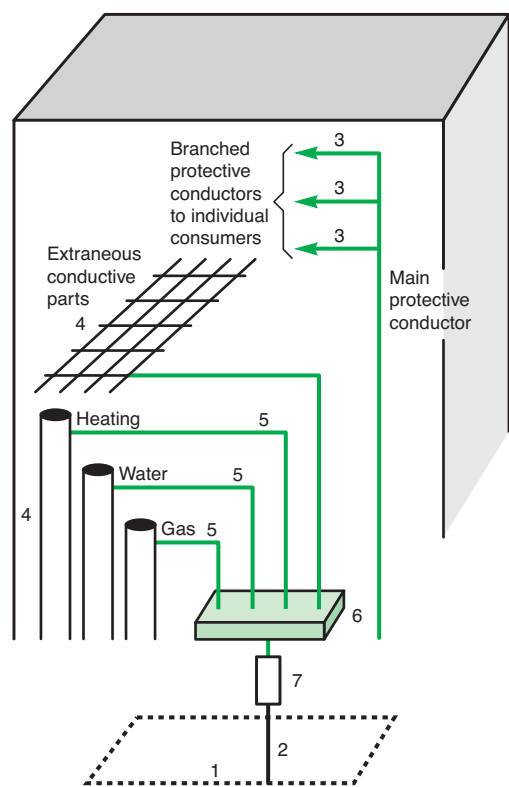
However, connections to earth of metallic sheaths of communications cables require the authorisation of the owners of the cables.

#### Supplementary equipotential connections

These connections are intended to connect all exposed-conductive-parts and all extraneous-conductive-parts simultaneously accessible, when correct conditions for protection have not been met, i.e. the original bonding conductors present an unacceptably high resistance.

#### Connection of exposed-conductive-parts to the earth electrode(s)

The connection is made by protective conductors with the object of providing a low-resistance path for fault currents flowing to earth.



**Fig. E1** : An example of a block of flats in which the main earthing terminal (6) provides the main equipotential connection; the removable link (7) allows an earth-electrode-resistance check

**Components** (see Fig. E2)

Effective connection of all accessible metal fixtures and all exposed-conductive-parts of electrical appliances and equipment, is essential for effective protection against electric shocks.

<b>Component parts to consider:</b>	
<b>as exposed-conductive-parts</b>	<b>as extraneous-conductive-parts</b>
Cableways ■ Conduits ■ Impregnated-paper-insulated lead-covered cable, armoured or unarmoured ■ Mineral insulated metal-sheathed cable (pyrotenax, etc.)	Elements used in building construction ■ Metal or reinforced concrete (RC): □ Steel-framed structure □ Reinforcement rods □ Prefabricated RC panels ■ Surface finishes: □ Floors and walls in reinforced concrete without further surface treatment □ Tiled surface ■ Metallic covering: □ Metallic wall covering
Switchgear ■ cradle of withdrawable switchgear	
Appliances ■ Exposed metal parts of class 1 insulated appliances	
Non-electrical elements ■ metallic fittings associated with cableways (cable trays, cable ladders, etc.) ■ Metal objects: □ Close to aerial conductors or to busbars □ In contact with electrical equipment.	Building services elements other than electrical ■ Metal pipes, conduits, trunking, etc. for gas, water and heating systems, etc. ■ Related metal components (furnaces, tanks, reservoirs, radiators) ■ Metallic fittings in wash rooms, bathrooms, toilets, etc. ■ Metallised papers
<b>Component parts not to be considered:</b>	
<b>as exposed-conductive-parts</b>	<b>as extraneous-conductive-parts</b>
Diverse service channels, ducts, etc. ■ Conduits made of insulating material ■ Mouldings in wood or other insulating material ■ Conductors and cables without metallic sheaths	■ Wooden-block floors ■ Rubber-covered or linoleum-covered floors ■ Dry plaster-block partition ■ Brick walls ■ Carpets and wall-to-wall carpeting
Switchgear ■ Enclosures made of insulating material	
Appliances ■ All appliances having class II insulation regardless of the type of exterior envelope	

**Fig. E2** : List of exposed-conductive-parts and extraneous-conductive-parts

*The different earthing schemes (often referred to as the type of power system or system earthing arrangements) described characterise the method of earthing the installation downstream of the secondary winding of a MV/LV transformer and the means used for earthing the exposed conductive-parts of the LV installation supplied from it*

## 1.2 Definition of standardised earthing schemes

The choice of these methods governs the measures necessary for protection against indirect-contact hazards.

The earthing system qualifies three originally independent choices made by the designer of an electrical distribution system or installation:

- The type of connection of the electrical system (that is generally of the neutral conductor) and of the exposed parts to earth electrode(s)
  - A separate protective conductor or protective conductor and neutral conductor being a single conductor
  - The use of earth fault protection of overcurrent protective switchgear which clear only relatively high fault currents or the use of additional relays able to detect and clear small insulation fault currents to earth
- In practice, these choices have been grouped and standardised as explained below. Each of these choices provides standardised earthing systems with three advantages and drawbacks:
- Connection of the exposed conductive parts of the equipment and of the neutral conductor to the PE conductor results in equipotentiality and lower overvoltages but increases earth fault currents
  - A separate protective conductor is costly even if it has a small cross-sectional area but it is much more unlikely to be polluted by voltage drops and harmonics, etc. than a neutral conductor is. Leakage currents are also avoided in extraneous conductive parts
  - Installation of residual current protective relays or insulation monitoring devices are much more sensitive and permits in many circumstances to clear faults before heavy damage occurs (motors, fires, electrocution). The protection offered is in addition independent with respect to changes in an existing installation

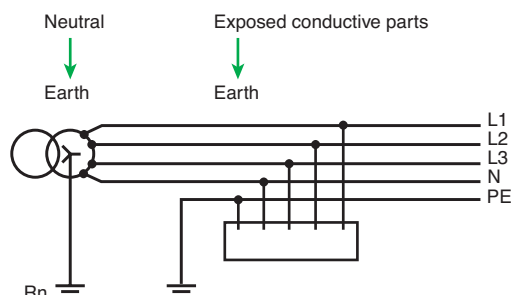


Fig. E3 : TT System

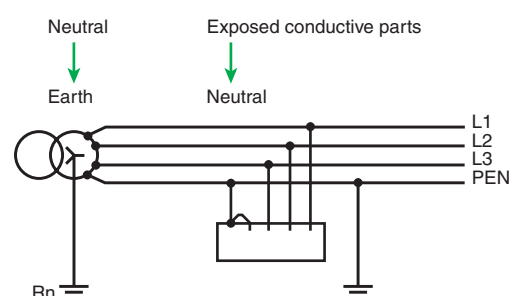


Fig. E4 : TN-C system

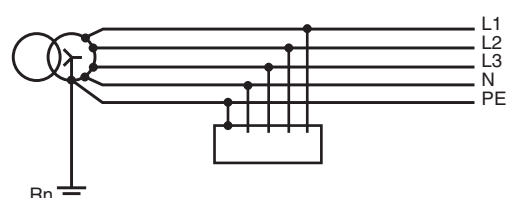


Fig. E5 : TN-S system

### TT system (earthed neutral) (see Fig. E3)

One point at the supply source is connected directly to earth. All exposed- and extraneous-conductive-parts are connected to a separate earth electrode at the installation. This electrode may or may not be electrically independent of the source electrode. The two zones of influence may overlap without affecting the operation of protective devices.

### TN systems (exposed conductive parts connected to the neutral)

The source is earthed as for the TT system (above). In the installation, all exposed- and extraneous-conductive-parts are connected to the neutral conductor. The several versions of TN systems are shown below.

#### TN-C system (see Fig. E4)

The neutral conductor is also used as a protective conductor and is referred to as a PEN (Protective Earth and Neutral) conductor. This system is not permitted for conductors of less than 10 mm<sup>2</sup> or for portable equipment.

The TN-C system requires an effective equipotential environment within the installation with dispersed earth electrodes spaced as regularly as possible since the PEN conductor is both the neutral conductor and at the same time carries phase unbalance currents as well as 3<sup>rd</sup> order harmonic currents (and their multiples).

The PEN conductor must therefore be connected to a number of earth electrodes in the installation.

Caution: In the TN-C system, the "protective conductor" function has priority over the "neutral function". In particular, a PEN conductor must always be connected to the earthing terminal of a load and a jumper is used to connect this terminal to the neutral terminal.

#### TN-S system (see Fig. E5)

The TN-S system (5 wires) is obligatory for circuits with cross-sectional areas less than 10 mm<sup>2</sup> for portable equipment.

The protective conductor and the neutral conductor are separate. On underground cable systems where lead-sheathed cables exist, the protective conductor is generally the lead sheath. The use of separate PE and N conductors (5 wires) is obligatory for circuits with cross-sectional areas less than 10 mm<sup>2</sup> for portable equipment.

#### TN-C-S system (see Fig. E6 below and Fig. E7 next page)

The TN-C and TN-S systems can be used in the same installation. In the TN-C-S system, the TN-C (4 wires) system must never be used downstream of the TN-S (5 wires) system, since any accidental interruption in the neutral on the upstream part would lead to an interruption in the protective conductor in the downstream part and therefore a danger.

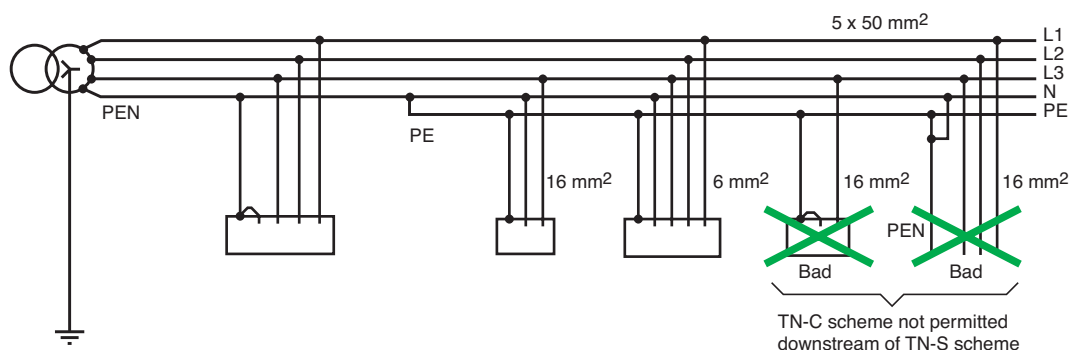


Fig. E6 : TN-C-S system

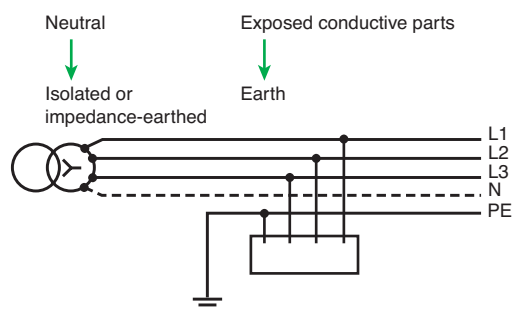


Fig. E8 : IT system (isolated neutral)

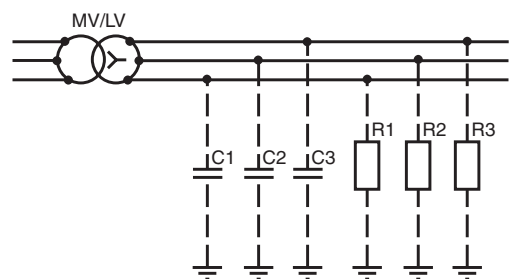


Fig. E9 : IT system (isolated neutral)

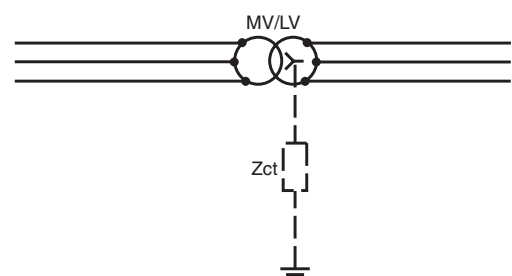


Fig. E10 : Impedance equivalent to leakage impedances in an IT system

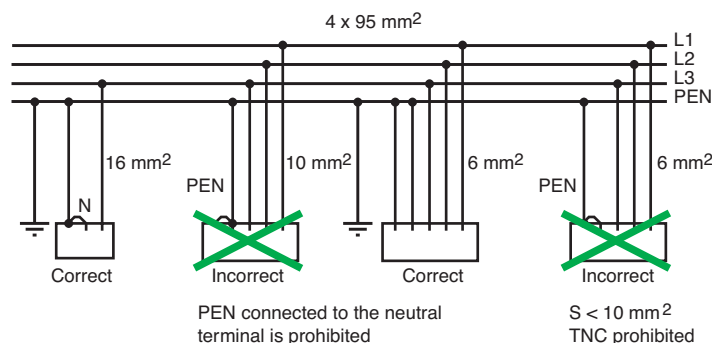


Fig. E7 : Connection of the PEN conductor in the TN-C system

## IT system (isolated or impedance-earthed neutral)

### IT system (isolated neutral)

No intentional connection is made between the neutral point of the supply source and earth (see Fig. E8).

Exposed- and extraneous-conductive-parts of the installation are connected to an earth electrode.

In practice all circuits have a leakage impedance to earth, since no insulation is perfect. In parallel with this (distributed) resistive leakage path, there is the distributed capacitive current path, the two paths together constituting the normal leakage impedance to earth (see Fig. E9).

### Example (see Fig. E10)

In a LV 3-phase 3-wire system, 1 km of cable will have a leakage impedance due to C1, C2, C3 and R1, R2 and R3 equivalent to a neutral earth impedance  $Z_{ct}$  of 3,000 to 4,000  $\Omega$ , without counting the filtering capacitances of electronic devices.

### IT system (impedance-earthed neutral)

An impedance  $Z_s$  (in the order of 1,000 to 2,000  $\Omega$ ) is connected permanently between the neutral point of the transformer LV winding and earth (see Fig. E11). All exposed- and extraneous-conductive-parts are connected to an earth electrode. The reasons for this form of power-source earthing are to fix the potential of a small network with respect to earth ( $Z_s$  is small compared to the leakage impedance) and to reduce the level of overvoltages, such as transmitted surges from the MV windings, static charges, etc. with respect to earth. It has, however, the effect of slightly increasing the first-fault current level.

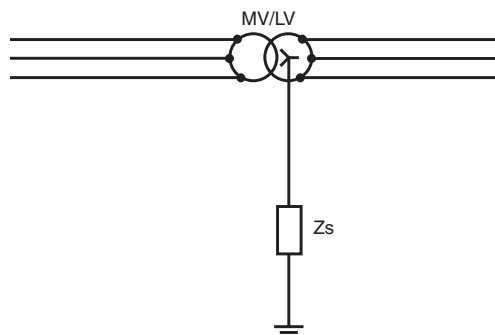


Fig. E11 : IT system (impedance-earthed neutral)

## 1.3 Characteristics of TT, TN and IT systems

*The TT system:*

- *Technique for the protection of persons: the exposed conductive parts are earthed and residual current devices (RCDs) are used*
- *Operating technique: interruption for the first insulation fault*

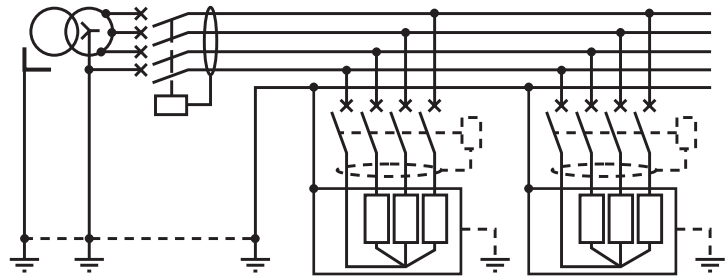
**TT system** (see Fig. E12)

Fig. E12 : TT system

**Note:** If the exposed conductive parts are earthed at a number of points, an RCD must be installed for each set of circuits connected to a given earth electrode.

**Main characteristics**

- Simplest solution to design and install. Used in installations supplied directly by the public LV distribution network.
- Does not require continuous monitoring during operation (a periodic check on the RCDs may be necessary).
- Protection is ensured by special devices, the residual current devices (RCD), which also prevent the risk of fire when they are set to  $\leq 500$  mA.
- Each insulation fault results in an interruption in the supply of power, however the outage is limited to the faulty circuit by installing the RCDs in series (selective RCDs) or in parallel (circuit selection).
- Loads or parts of the installation which, during normal operation, cause high leakage currents, require special measures to avoid nuisance tripping, i.e. supply the loads with a separation transformer or use specific RCDs (see section 5.1 in chapter F).

**TN system** (see Fig. E13 and Fig. E14)*The TN system:*

- *Technique for the protection of persons:*
  - *Interconnection and earthing of exposed conductive parts and the neutral are mandatory*
  - *Interruption for the first fault using overcurrent protection (circuit-breakers or fuses)*
- *Operating technique: interruption for the first insulation fault*

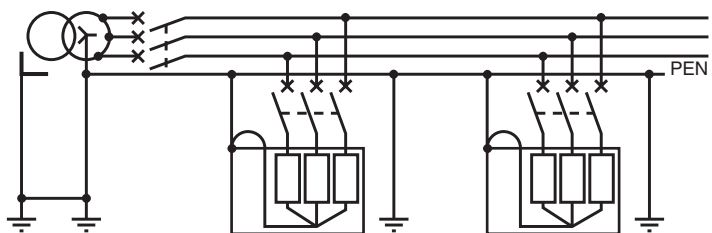


Fig. E13 : TN-C system

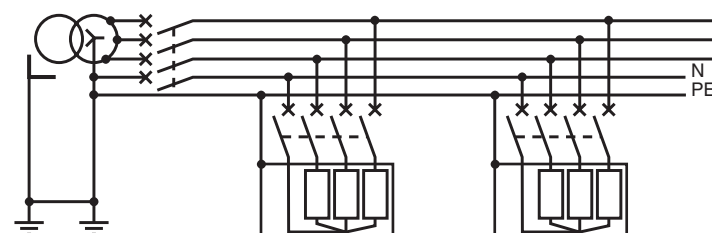


Fig. E14 : TN-S system

**IT system:**■ **Protection technique:**

- Interconnection and earthing of exposed conductive parts
- Indication of the first fault by an insulation monitoring device (IMD)
- Interruption for the second fault using overcurrent protection (circuit-breakers or fuses)

■ **Operating technique:**

- Monitoring of the first insulation fault
- Mandatory location and clearing of the fault
- Interruption for two simultaneous insulation faults

**Main characteristics**

- Generally speaking, the TN system:
  - requires the installation of earth electrodes at regular intervals throughout the installation
  - Requires that the initial check on effective tripping for the first insulation fault be carried out by calculations during the design stage, followed by mandatory measurements to confirm tripping during commissioning
  - Requires that any modification or extension be designed and carried out by a qualified electrician
  - May result, in the case of insulation faults, in greater damage to the windings of rotating machines
  - May, on premises with a risk of fire, represent a greater danger due to the higher fault currents
- In addition, the TN-C system:
  - At first glance, would appear to be less expensive (elimination of a device pole and of a conductor)
  - Requires the use of fixed and rigid conductors
  - Is forbidden in certain cases:
    - Premises with a risk of fire
    - For computer equipment (presence of harmonic currents in the neutral)
- In addition, the TN-S system:
  - May be used even with flexible conductors and small conduits
  - Due to the separation of the neutral and the protection conductor, provides a clean PE (computer systems and premises with special risks)

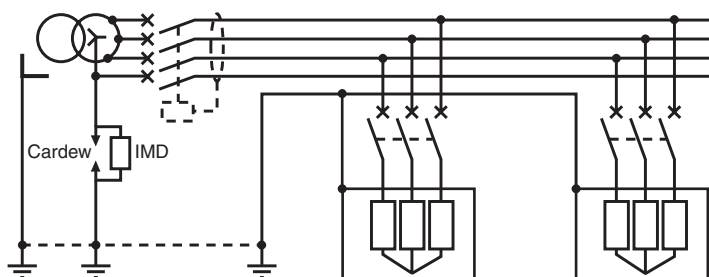
**IT system** (see Fig. E15)

Fig. E15 : IT system

**Main characteristics**

- Solution offering the best continuity of service during operation
- Indication of the first insulation fault, followed by mandatory location and clearing, ensures systematic prevention of supply outages
- Generally used in installations supplied by a private MV/LV or LV/LV transformer
- Requires maintenance personnel for monitoring and operation
- Requires a high level of insulation in the network (implies breaking up the network if it is very large and the use of circuit-separation transformers to supply loads with high leakage currents)
- The check on effective tripping for two simultaneous faults must be carried out by calculations during the design stage, followed by mandatory measurements during commissioning on each group of interconnected exposed conductive parts
- Protection of the neutral conductor must be ensured as indicated in section 7.2 of Chapter G

*Selection does not depend on safety criteria. The three systems are equivalent in terms of protection of persons if all installation and operating rules are correctly followed. The selection criteria for the best system(s) depend on the regulatory requirements, the required continuity of service, operating conditions and the types of network and loads.*

## 1.4 Selection criteria for the TT, TN and IT systems

In terms of the protection of persons, the three system earthing arrangements (SEA) are equivalent if all installation and operating rules are correctly followed. Consequently, selection does not depend on safety criteria.

It is by combining all requirements in terms of regulations, continuity of service, operating conditions and the types of network and loads that it is possible to determine the best system(s) (see **Fig. E16**).

Selection is determined by the following factors:

- Above all, the applicable regulations which in some cases impose certain types of SEA
- Secondly, the decision of the owner if supply is via a private MV/LV transformer (MV subscription) or the owner has a private energy source (or a separate-winding transformer)

If the owner effectively has a choice, the decision on the SEA is taken following discussions with the network designer (design office, contractor)

The discussions must cover:

- First of all, the operating requirements (the required level of continuity of service) and the operating conditions (maintenance ensured by electrical personnel or not, in-house personnel or outsourced, etc.)
- Secondly, the particular characteristics of the network and the loads (see **Fig. E17** next page)

	TT	TN-S	TN-C	IT1	IT2	Comments
<b>Electrical characteristics</b>						
Fault current	-	--	--	+	--	Only the IT system offers virtually negligible first-fault currents
Fault voltage	-	-	-	+	-	In the IT system, the touch voltage is very low for the first fault, but is considerable for the second
Touch voltage	+/-	-	-	+	-	In the TT system, the touch voltage is very low if system is equipotential, otherwise it is high
<b>Protection</b>						
Protection of persons against indirect contact	+	+	+	+	+	All SEAs (system earthing arrangement) are equivalent, if the rules are followed
Protection of persons with emergency generating sets	+	-	-	+	-	Systems where protection is ensured by RCDs are not sensitive to a change in the internal impedance of the source
Protection against fire (with an RCD)	+	+	Not allowed	+	+	All SEAs in which RCDs can be used are equivalent. The TN-C system is forbidden on premises where there is a risk of fire
<b>Overvoltages</b>						
Continuous overvoltage	+	+	+	-	+	A phase-to-earth overvoltage is continuous in the IT system if there is a first insulation fault
Transient overvoltage	+	-	-	+	-	Systems with high fault currents may cause transient overvoltages
Overtvoltage if transformer breakdown (primary/secondary)	-	+	+	+	+	In the TT system, there is a voltage imbalance between the different earth electrodes. The other systems are interconnected to a single earth electrode
<b>Electromagnetic compatibility</b>						
Immunity to nearby lightning strikes	-	+	+	+	+	In the TT system, there may be voltage imbalances between the earth electrodes. In the IT system, there is a significant current loop between the two separate earth electrodes
Immunity to lightning strikes on MV lines	-	-	-	-	-	All SEAs are equivalent when a MV line takes a direct lightning strike
Continuous emission of an electromagnetic field	+	+	-	+	+	Connection of the PEN to the metal structures of the building is conducive to the continuous generation of electromagnetic fields
Transient non-equipotentiality of the PE	+	-	-	+	-	The PE is no longer equipotential if there is a high fault current
<b>Continuity of service</b>						
Interruption for first fault	-	-	-	+	+	Only the IT system avoids tripping for the first insulation fault
Voltage dip during insulation fault	+	-	-	+	-	The TN-S, TNC and IT (2 <sup>nd</sup> fault) systems generate high fault currents which may cause phase voltage dips
<b>Installation</b>						
Special devices	-	+	+	-	-	The TT system requires the use of RCDs. The IT system requires the use of IMDs
Number of earth electrodes	-	+	+	-/+	-/+	The TT system requires two distinct earth electrodes. The IT system offers a choice between one or two earth electrodes
Number of cables	-	-	+	-	-	Only the TN-C system offers, in certain cases, a reduction in the number of cables
<b>Maintenance</b>						
Cost of repairs	-	--	--	-	--	The cost of repairs depends on the damage caused by the amplitude of the fault currents
Installation damage	+	-	-	++	-	Systems causing high fault currents require a check on the installation after clearing the fault

**Fig. E16** : Comparison of system earthing arrangements



Type of network		Advised	Possible	Not advised
Very large network with high-quality earth electrodes for exposed conductive parts ( $10\ \Omega$ max.)			TT, TN, IT <sup>(1)</sup> or mixed	
Very large network with low-quality earth electrodes for exposed conductive parts ( $> 30\ \Omega$ )		TN	TN-S	IT <sup>(1)</sup> TN-C
Disturbed area (storms) (e.g. television or radio transmitter)		TN	TT	IT <sup>(2)</sup>
Network with high leakage currents ( $> 500\text{ mA}$ )		TN <sup>(4)</sup>	IT <sup>(4)</sup> TT <sup>(3) (4)</sup>	
Network with outdoor overhead lines		TT <sup>(5)</sup>	TN <sup>(5) (6)</sup>	IT <sup>(6)</sup>
Emergency standby generator set		IT	TT	TN <sup>(7)</sup>
Type of loads				
Loads sensitive to high fault currents (motors, etc.)		IT	TT	TN <sup>(8)</sup>
Loads with a low insulation level (electric furnaces, welding machines, heating elements, immersion heaters, equipment in large kitchens)		TN <sup>(9)</sup>	TT <sup>(9)</sup>	IT
Numerous phase-neutral single-phase loads (mobile, semi-fixed, portable)		TT <sup>(10)</sup> TN-S		IT <sup>(10)</sup> TN-C <sup>(10)</sup>
Loads with sizeable risks (hoists, conveyers, etc.)		TN <sup>(11)</sup>	TT <sup>(11)</sup>	IT <sup>(11)</sup>
Numerous auxiliaries (machine tools)		TN-S	TN-C IT <sup>(12 bis)</sup>	TT <sup>(12)</sup>
Miscellaneous				
Supply via star-star connected power transformer <sup>(13)</sup>		TT	IT without neutral	IT <sup>(13)</sup> with neutral
Premises with risk of fire		IT <sup>(15)</sup>	TN-S <sup>(15)</sup> TT <sup>(15)</sup>	TN-C <sup>(14)</sup>
Increase in power level of LV utility subscription, requiring a private substation		TT <sup>(16)</sup>		
Installation with frequent modifications		TT <sup>(17)</sup>		TN <sup>(18)</sup> IT <sup>(18)</sup>
Installation where the continuity of earth circuits is uncertain (work sites, old installations)		TT <sup>(19)</sup>	TN-S	TN-C IT <sup>(19)</sup>
Electronic equipment (computers, PLCs)		TN-S	TT	TN-C
Machine control-monitoring network, PLC sensors and actuators		IT <sup>(20)</sup>	TN-S, TT	

(1) When the SEA is not imposed by regulations, it is selected according to the level of operating characteristics (continuity of service that is mandatory for safety reasons or desired to enhance productivity, etc.)

Whatever the SEA, the probability of an insulation failure increases with the length of the network. It may be a good idea to break up the network, which facilitates fault location and makes it possible to implement the system advised above for each type of application.

(2) The risk of flashover on the surge limiter turns the isolated neutral into an earthed neutral. These risks are high for regions with frequent thunder storms or installations supplied by overhead lines. If the IT system is selected to ensure a higher level of continuity of service, the system designer must precisely calculate the tripping conditions for a second fault.

(3) Risk of RCD nuisance tripping.

(4) Whatever the SEA, the ideal solution is to isolate the disturbing section if it can be easily identified.

(5) Risks of phase-to-earth faults affecting equipotentiality.

(6) Insulation is uncertain due to humidity and conducting dust.

(7) The TN system is not advised due to the risk of damage to the generator in the case of an internal fault. What is more, when generator sets supply safety equipment, the system must not trip for the first fault.

(8) The phase-to-earth current may be several times higher than  $I_n$ , with the risk of damaging or accelerating the ageing of motor windings, or of destroying magnetic circuits.

(9) To combine continuity of service and safety, it is necessary and highly advised, whatever the SEA, to separate these loads from the rest of the installation (transformers with local neutral connection).

(10) When load equipment quality is not a design priority, there is a risk that the insulation resistance will fall rapidly. The TT system with RCDs is the best means to avoid problems.

(11) The mobility of this type of load causes frequent faults (sliding contact for bonding of exposed conductive parts) that must be countered. Whatever the SEA, it is advised to supply these circuits using transformers with a local neutral connection.

(12) Requires the use of transformers with a local TN system to avoid operating risks and nuisance tripping at the first fault (TT) or a double fault (IT).

(12 bis) With a double break in the control circuit.

(13) Excessive limitation of the phase-to-neutral current due to the high value of the zero-phase impedance (at least 4 to 5 times the direct impedance). This system must be replaced by a star-delta arrangement.

(14) The high fault currents make the TN system dangerous. The TN-C system is forbidden.

(15) Whatever the system, the RCD must be set to  $\Delta n \leq 500\text{ mA}$ .

(16) An installation supplied with LV energy must use the TT system. Maintaining this SEA means the least amount of modifications on the existing network (no cables to be run, no protection devices to be modified).

(17) Possible without highly competent maintenance personnel.

(18) This type of installation requires particular attention in maintaining safety. The absence of preventive measures in the TN system means highly qualified personnel are required to ensure safety over time.

(19) The risks of breaks in conductors (supply, protection) may cause the loss of equipotentiality for exposed conductive parts. A TT system or a TN-S system with 30 mA RCDs is advised and is often mandatory. The IT system may be used in very specific cases.

(20) This solution avoids nuisance tripping for unexpected earth leakage.

Fig. E17 : Influence of networks and loads on the selection of system earthing arrangements



## 1.5 Choice of earthing method - implementation

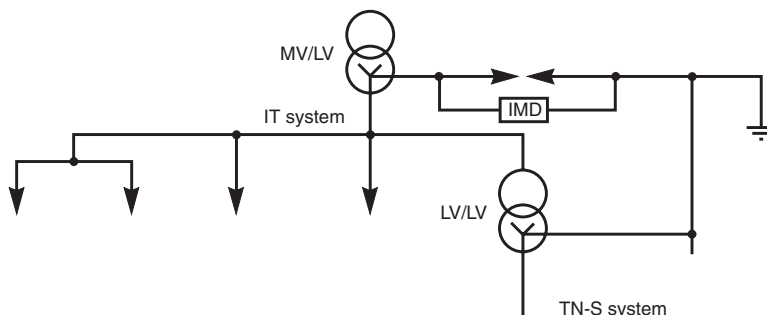
After consulting applicable regulations, Figures E16 and E17 can be used as an aid in deciding on divisions and possible galvanic isolation of appropriate sections of a proposed installation.

### Division of source

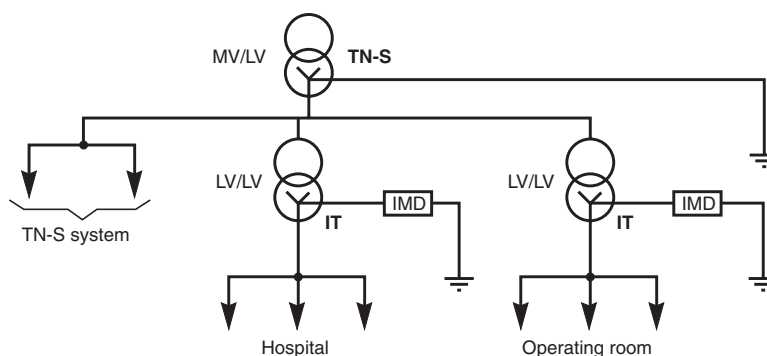
This technique concerns the use of several transformers instead of employing one high-rated unit. In this way, a load that is a source of network disturbances (large motors, furnaces, etc.) can be supplied by its own transformer. The quality and continuity of supply to the whole installation are thereby improved. The cost of switchgear is reduced (short-circuit current level is lower). The cost-effectiveness of separate transformers must be determined on a case by case basis.

### Network islands

The creation of galvanically-separated “islands” by means of LV/LV transformers makes it possible to optimise the choice of earthing methods to meet specific requirements (see **Fig. E18** and **Fig. E19**).



**Fig. E18** : TN-S island within an IT system



**Fig. E19** : IT islands within a TN-S system

### Conclusion

The optimisation of the performance of the whole installation governs the choice of earthing system.

Including:

- Initial investments, and
- Future operational expenditures, hard to assess, that can arise from insufficient reliability, quality of equipment, safety, continuity of service, etc.

An ideal structure would comprise normal power supply sources, local reserve power supply sources (see section 1.4 of Chapter E) and the appropriate earthing arrangements.

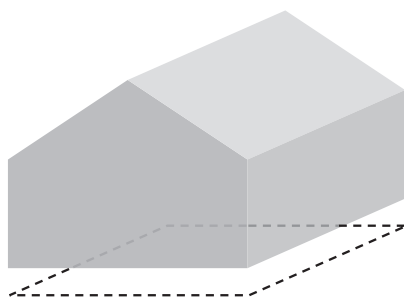
A very effective method of obtaining a low-resistance earth connection is to bury a conductor in the form of a closed loop in the soil at the bottom of the excavation for building foundations.

The resistance  $R$  of such an electrode (in homogeneous soil) is given (approximately) in ohms by:  $R = \frac{2\rho}{L}$  where

$L$  = length of the buried conductor in metres

$\rho$  = soil resistivity in ohm-metres

For  $n$  rods:  $R = \frac{1\rho}{nL}$



**Fig. E20** : Conductor buried below the level of the foundations, i.e. not in the concrete

## 1.6 Installation and measurements of earth electrodes

The quality of an earth electrode (resistance as low as possible) depends essentially on two factors:

- Installation method
- Type of soil

### Installation methods

Three common types of installation will be discussed:

#### Buried ring (see Fig. E20)

This solution is strongly recommended, particularly in the case of a new building. The electrode should be buried around the perimeter of the excavation made for the foundations. It is important that the bare conductor be in intimate contact with the soil (and not placed in the gravel or aggregate hard-core, often forming a base for concrete). At least four (widely-spaced) vertically arranged conductors from the electrode should be provided for the installation connections and, where possible, any reinforcing rods in concrete work should be connected to the electrode.

The conductor forming the earth electrode, particularly when it is laid in an excavation for foundations, must be in the earth, at least 50 cm below the hard-core or aggregate base for the concrete foundation. Neither the electrode nor the vertical rising conductors to the ground floor, should ever be in contact with the foundation concrete.

For existing buildings, the electrode conductor should be buried around the outside wall of the premises to a depth of at least 1 metre. As a general rule, all vertical connections from an electrode to above-ground level should be insulated for the nominal LV voltage (600-1,000 V).

The conductors may be:

- Copper: Bare cable ( $\geq 25 \text{ mm}^2$ ) or multiple-strip ( $\geq 25 \text{ mm}^2$  and  $\geq 2 \text{ mm}$  thick)
- Aluminium with lead jacket: Cable ( $\geq 35 \text{ mm}^2$ )
- Galvanised-steel cable: Bare cable ( $\geq 95 \text{ mm}^2$ ) or multiple-strip ( $\geq 100 \text{ mm}^2$  and  $\geq 3 \text{ mm}$  thick)

The approximate resistance  $R$  of the electrode in ohms:

$$R = \frac{2\rho}{L}$$

where

$L$  = length of conductor in metres

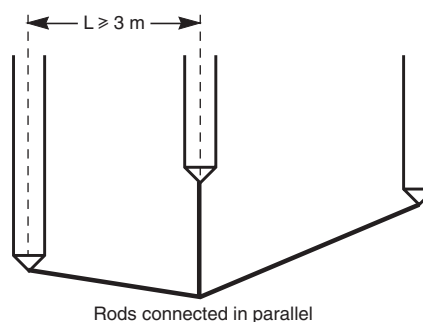
$\rho$  = resistivity of the soil in ohm-metres (see "Influence of the type of soil" next page)

#### Earthing rods (see Fig. E21)

Vertically driven earthing rods are often used for existing buildings, and for improving (i.e. reducing the resistance of) existing earth electrodes.

The rods may be:

- Copper or (more commonly) copper-clad steel. The latter are generally 1 or 2 metres long and provided with screwed ends and sockets in order to reach considerable depths, if necessary (for instance, the water-table level in areas of high soil resistivity)
- Galvanised (see note (1) next page) steel pipe  $\geq 25 \text{ mm}$  diameter or rod  $\geq 15 \text{ mm}$  diameter,  $\geq 2$  metres long in each case.



**Fig. E21** : Earthing rods

E11

E12

For a vertical plate electrode:  $R = \frac{0.8 \rho}{L}$

Measurements on earth electrodes in similar soils are useful to determine the resistivity value to be applied for the design of an earth-electrode system

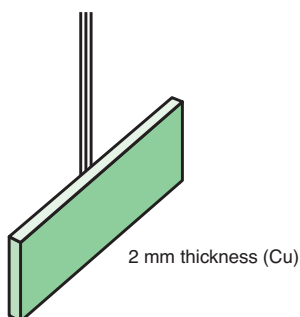


Fig. E22 : Vertical plate

It is often necessary to use more than one rod, in which case the spacing between them should exceed the depth to which they are driven, by a factor of 2 to 3.

The total resistance (in homogeneous soil) is then equal to the resistance of one rod, divided by the number of rods in question. The approximate resistance R obtained is:

$$R = \frac{1 \rho}{n L} \quad \text{if the distance separating the rods} > 4L$$

where

L = the length of the rod in metres

$\rho$  = resistivity of the soil in ohm-metres (see "Influence of the type of soil" below)

n = the number of rods

**Vertical plates** (see Fig. E22)

Rectangular plates, each side of which must be  $\geq 0.5$  metres, are commonly used as earth electrodes, being buried in a vertical plane such that the centre of the plate is at least 1 metre below the surface of the soil.

The plates may be:

- Copper of 2 mm thickness
- Galvanised <sup>(1)</sup> steel of 3 mm thickness

The resistance R in ohms is given (approximately), by:

$$R = \frac{0.8 \rho}{L}$$

L = the perimeter of the plate in metres

$\rho$  = resistivity of the soil in ohm-metres (see "Influence of the type of soil" below)

### Influence of the type of soil

Type of soil	Mean value of resistivity in $\Omega m$
Swampy soil, bogs	1 - 30
Silt alluvium	20 - 100
Humus, leaf mould	10 - 150
Peat, turf	5 - 100
Soft clay	50
Marl and compacted clay	100 - 200
Jurassic marl	30 - 40
Clayey sand	50 - 500
Siliceous sand	200 - 300
Stoney ground	1,500 - 3,000
Grass-covered-stoney sub-soil	300 - 500
Chalky soil	100 - 300
Limestone	1,000 - 5,000
Fissured limestone	500 - 1,000
Schist, shale	50 - 300
Mica schist	800
Granite and sandstone	1,500 - 10,000
Modified granite and sandstone	100 - 600

Fig. E23 : Resistivity ( $\Omega m$ ) for different types of soil

Type of soil	Average value of resistivity in $\Omega m$
Fertile soil, compacted damp fill	50
Arid soil, gravel, uncompacted non-uniform fill	500
Stoney soil, bare, dry sand, fissured rocks	3,000

Fig. E24 : Average resistivity ( $\Omega m$ ) values for approximate earth-elect

(1) Where galvanised conducting materials are used for earth electrodes, sacrificial cathodic protection anodes may be necessary to avoid rapid corrosion of the electrodes where the soil is aggressive. Specially prepared magnesium anodes (in a porous sack filled with a suitable "soil") are available for direct connection to the electrodes. In such circumstances, a specialist should be consulted

### Measurement and constancy of the resistance between an earth electrode and the earth

#### The resistance of the electrode/earth interface rarely remains constant

Among the principal factors affecting this resistance are the following:

##### ■ Humidity of the soil

The seasonal changes in the moisture content of the soil can be significant at depths of up to 2 meters.

At a depth of 1 metre the resistivity and therefore the resistance can vary by a ratio of 1 to 3 between a wet winter and a dry summer in temperate regions

##### ■ Frost

Frozen earth can increase the resistivity of the soil by several orders of magnitude.

This is one reason for recommending the installation of deep electrodes, in particular in cold climates

##### ■ Ageing

The materials used for electrodes will generally deteriorate to some extent for various reasons, for example:

##### □ Chemical reactions (in acidic or alkaline soils)

Galvanic: due to stray DC currents in the earth, for example from electric railways, etc. or due to dissimilar metals forming primary cells. Different soils acting on sections of the same conductor can also form cathodic and anodic areas with consequent loss of surface metal from the latter areas. Unfortunately, the most favourable conditions for low earth-electrode resistance (i.e. low soil resistivity) are also those in which galvanic currents can most easily flow.

##### ■ Oxidation

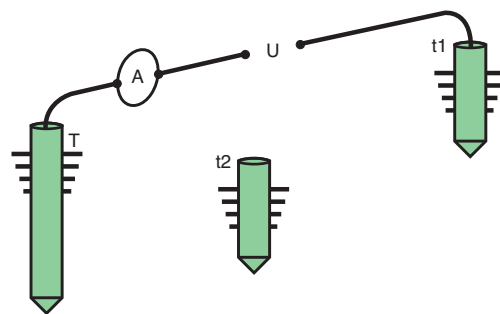
Brazed and welded joints and connections are the points most sensitive to oxidation. Thorough cleaning of a newly made joint or connection and wrapping with a suitable greased-tape binding is a commonly used preventive measure.

#### Measurement of the earth-electrode resistance

There must always be one or more removable links to isolate an earth electrode so that it can be tested.

There must always be removable links which allow the earth electrode to be isolated from the installation, so that periodic tests of the earthing resistance can be carried out. To make such tests, two auxiliary electrodes are required, each consisting of a vertically driven rod.

##### ■ Ammeter method (see Fig. E25)



**Fig. E25** : Measurement of the resistance to earth of the earth electrode of an installation by means of an ammeter

$$A = R_T + R_{t1} = \frac{U_{Tt1}}{i_1}$$

$$B = R_{t1} + R_{t2} = \frac{U_{t1t2}}{i_2}$$

$$C = R_{t2} + R_T = \frac{U_{t2T}}{i_3}$$

When the source voltage  $U$  is constant (adjusted to be the same value for each test) then:

$$R_T = \frac{U}{2} \left( \frac{1}{i_1} + \frac{1}{i_3} - \frac{1}{i_2} \right)$$

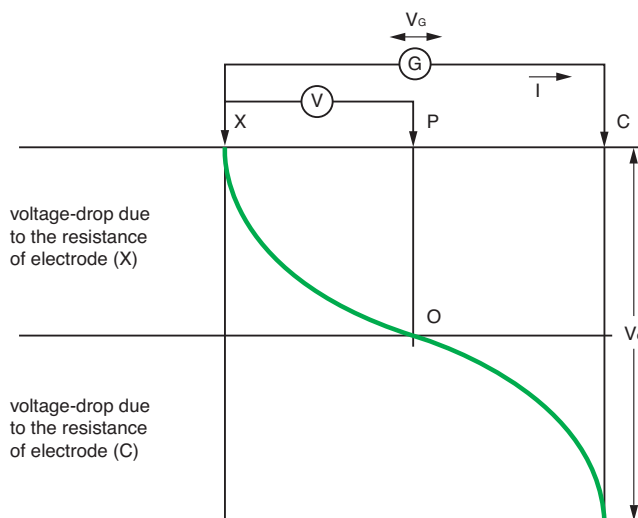
In order to avoid errors due to stray earth currents (galvanic -DC- or leakage currents from power and communication networks and so on) the test current should be AC, but at a different frequency to that of the power system or any of its harmonics. Instruments using hand-driven generators to make these measurements usually produce an AC voltage at a frequency of between 85 Hz and 135 Hz.

The distances between the electrodes are not critical and may be in different directions from the electrode being tested, according to site conditions. A number of tests at different spacings and directions are generally made to cross-check the test results.

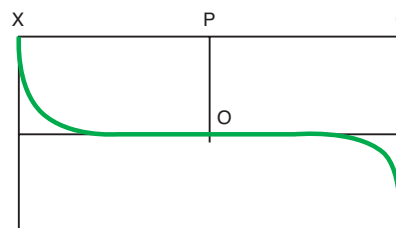
■ Use of a direct-reading earthing-resistance ohmmeter

These instruments use a hand-driven or electronic-type AC generator, together with two auxiliary electrodes, the spacing of which must be such that the zone of influence of the electrode being tested should not overlap that of the test electrode (C). The test electrode (C) furthest from the electrode (X) under test, passes a current through the earth and the electrode under test, while the second test electrode (P) picks up a voltage. This voltage, measured between (X) and (P), is due to the test current and is a measure of the contact resistance (of the electrode under test) with earth. It is clear that the distance (X) to (P) must be carefully chosen to give accurate results. If the distance (X) to (C) is increased, however, the zones of resistance of electrodes (X) and (C) become more remote, one from the other, and the curve of potential (voltage) becomes more nearly horizontal about the point (O).

In practical tests, therefore, the distance (X) to (C) is increased until readings taken with electrode (P) at three different points, i.e. at (P) and at approximately 5 metres on either side of (P), give similar values. The distance (X) to (P) is generally about 0.68 of the distance (X) to (C).



a) the principle of measurement is based on assumed homogeneous soil conditions. Where the zones of influence of electrodes C and X overlap, the location of test electrode P is difficult to determine for satisfactory results.



b) showing the effect on the potential gradient when (X) and (C) are widely spaced. The location of test electrode P is not critical and can be easily determined.

**Fig. E26 :** Measurement of the resistance to the mass of earth of electrode (X) using an earth-electrode-testing ohmmeter.

*Distribution switchboards, including the main LV switchboard (MLVS), are critical to the dependability of an electrical installation. They must comply with well-defined standards governing the design and construction of LV switchgear assemblies*

*The load requirements dictate the type of distribution switchboard to be installed*

## 2.1 Distribution switchboards

A distribution switchboard is the point at which an incoming-power supply divides into separate circuits, each of which is controlled and protected by the fuses or switchgear of the switchboard. A distribution switchboard is divided into a number of functional units, each comprising all the electrical and mechanical elements that contribute to the fulfilment of a given function. It represents a key link in the dependability chain.

Consequently, the type of distribution switchboard must be perfectly adapted to its application. Its design and construction must comply with applicable standards and working practises.

The distribution switchboard enclosure provides dual protection:

- Protection of switchgear, indicating instruments, relays, fusegear, etc. against mechanical impacts, vibrations and other external influences likely to interfere with operational integrity (EMI, dust, moisture, vermin, etc.)
- The protection of human life against the possibility of direct and indirect electric shock (see degree of protection IP and the IK index in section 3.3 of Chapter E).

### Types of distribution switchboards

Distribution switchboards may differ according to the kind of application and the design principle adopted (notably in the arrangement of the busbars).

#### Distribution switchboards according to specific applications

The principal types of distribution switchboards are:

- The main LV switchboard - MLVS - (see Fig. E27a)
- Motor control centres - MCC - (see Fig. E27b)
- Sub-distribution switchboards (see Fig. E28)
- Final distribution switchboards (see Fig. E29)

Distribution switchboards for specific applications (e.g. heating, lifts, industrial processes) can be located:

- Adjacent to the main LV switchboard, or
- Near the application concerned

Sub-distribution and final distribution switchboards are generally distributed throughout the site.



**Fig. E27 :** [a] A main LV switchboard - MLVS - (Prisma Plus P) with incoming circuits in the form of busways - [b] A LV motor control centre - MCC - (Okken)



**Fig. E28 :** A sub-distribution switchboard (Prisma Plus G)



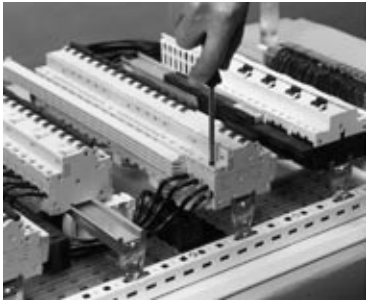
**Fig. E29 :** Final distribution switchboards [a] Prisma Plus G Pack; [b] Kaedra; [c] mini-Pragma



A distinction is made between:

- Traditional distribution switchboards in which switchgear and fusegear, etc. are fixed to a chassis at the rear of an enclosure
- Functional distribution switchboards for specific applications, based on modular and standardised design.

E16



**Fig. E30** : Assembly of a final distribution switchboard with fixed functional units (Prisma Plus G)



**Fig. E31** : Distribution switchboard with disconnectable functional units



**Fig. E32** : Distribution switchboard with withdrawable functional units in drawers

## Two technologies of distribution switchboards

### Traditional distribution switchboards

Switchgear and fusegear, etc. are normally located on a chassis at the rear of the enclosure. Indications and control devices (meters, lamps, pushbuttons, etc.) are mounted on the front face of the switchboard.

The placement of the components within the enclosure requires very careful study, taking into account the dimensions of each item, the connections to be made to it, and the clearances necessary to ensure safe and trouble-free operation. .

### Functional distribution switchboards

Generally dedicated to specific applications, these distribution switchboards are made up of functional modules that include switchgear devices together with standardised accessories for mounting and connections, ensuring a high level of reliability and a great capacity for last-minute and future changes.

#### ■ Many advantages

The use of functional distribution switchboards has spread to all levels of LV electrical distribution, from the main LV switchboard (MLVS) to final distribution switchboards, due to their many advantages:

- System modularity that makes it possible to integrate numerous functions in a single distribution switchboard, including protection, control, technical management and monitoring of electrical installations. Modular design also enhances distribution switchboard maintenance, operation and upgrades
- Distribution switchboard design is fast because it simply involves adding functional modules
- Prefabricated components can be mounted faster
- Finally, these distribution switchboards are subjected to type tests that ensure a high degree of dependability.

The new Prisma Plus G and P ranges of functional distribution switchboards from Schneider Electric cover needs up to 3200 A and offer:

- Flexibility and ease in building distribution switchboards
- Certification of a distribution switchboard complying with standard IEC 60439 and the assurance of servicing under safe conditions
- Time savings at all stages, from design to installation, operation and modifications or upgrades
- Easy adaptation, for example to meet the specific work habits and standards in different countries

Figures E27a, E28 and E29 show examples of functional distribution switchboards ranging for all power ratings and figure E27b shows a high-power industrial functional distribution switchboard.

#### ■ Main types of functional units

Three basic technologies are used in functional distribution switchboards.

##### □ Fixed functional units (see **Fig. E30**)

These units cannot be isolated from the supply so that any intervention for maintenance, modifications and so on, requires the shutdown of the entire distribution switchboard. Plug-in or withdrawable devices can however be used to minimise shutdown times and improve the availability of the rest of the installation.

##### □ Disconnectable functional units (see **Fig. E31**)

Each functional unit is mounted on a removable mounting plate and provided with a means of isolation on the upstream side (busbars) and disconnecting facilities on the downstream (outgoing circuit) side. The complete unit can therefore be removed for servicing, without requiring a general shutdown.

##### □ Drawer-type withdrawable functional units (see **Fig. E32**)

The switchgear and associated accessories for a complete function are mounted on a drawer-type horizontally withdrawable chassis. The function is generally complex and often concerns motor control.

Isolation is possible on both the upstream and downstream sides by the complete withdrawal of the drawer, allowing fast replacement of a faulty unit without de-energising the rest of the distribution switchboard.

*Compliance with applicable standards is essential in order to ensure an adequate degree of dependability*

*Three elements of standard IEC 60439-1 contribute significantly to dependability:*

- Clear definition of functional units
- Forms of separation between adjacent functional units in accordance with user requirements
- Clearly defined routine tests and type tests

## Standards

### Different standards

Certain types of distribution switchboards (in particular, functional distribution switchboards) must comply with specific standards according to the application or environment involved.

The reference international standard is IEC 60439-1 type-tested and partially type-tested assemblies

### Standard IEC 60439-1

#### ■ Categories of assemblies

Standard IEC 60439-1 distinguishes between two categories of assemblies:

- Type-tested LV switchgear and controlgear assemblies (TTA), which do not diverge significantly from an established type or system for which conformity is ensured by the type tests provided in the standard
- Partially type-tested LV switchgear and controlgear assemblies (PTTA), which may contain non-type-tested arrangements provided that the latter are derived from type-tested arrangements

When implemented in compliance with professional work standards and manufacturer instructions by qualified personnel, they offer the same level of safety and quality.

#### ■ Functional units

The same standard defines functional units:

- Part of an assembly comprising all the electrical and mechanical elements that contribute to the fulfilment of the same function
- The distribution switchboard includes an incoming functional unit and one or more functional units for outgoing circuits, depending on the operating requirements of the installation

What is more, distribution switchboard technologies use functional units that may be fixed, disconnectable or withdrawable (see section 3.1 of Chapter E).

#### ■ Forms (see Fig. E33)

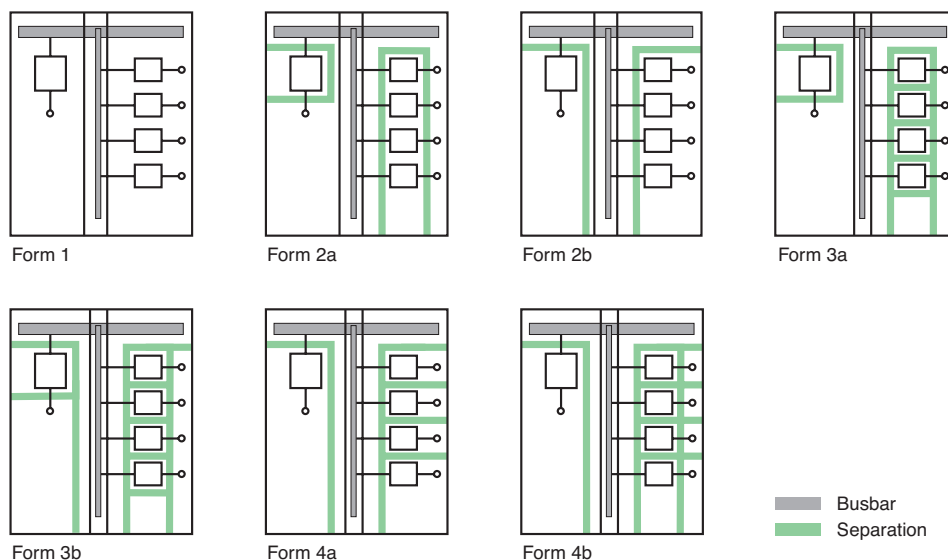
Separation of functional units within the assembly is provided by forms that are specified for different types of operation.

The various forms are numbered from 1 to 4 with variations labelled "a" or "b". Each step up (from 1 to 4) is cumulative, i.e. a form with a higher number includes the characteristics of forms with lower numbers. The standard distinguishes:

- Form 1: No separation
- Form 2: Separation of busbars from the functional units
- Form 3: Separation of busbars from the functional units and separation of all functional units, one from another, except at their output terminals
- Form 4: As for Form 3, but including separation of the outgoing terminals of all functional units, one from another

The decision on which form to implement results from an agreement between the manufacturer and the user.

The Prima Plus functional range offers solutions for forms 1, 2b, 3b, 4a, 4b.



**Fig. E33** : Representation of different forms of LV functional distribution switchboards



*Total accessibility of electrical information and intelligent distribution switchboards are now a reality*

E18

#### ■ Type tests and routine tests

They ensure compliance of each distribution switchboard with the standard. The availability of test documents certified by independent organisations is a guarantee for users.

### Remote monitoring and control of the electrical installation

Remote monitoring and control are no longer limited to large installations. These functions are increasingly used and provide considerable cost savings. The main potential advantages are:

- Reductions in energy bills
- Reductions in structural costs to maintain the installation in running order
- Better use of the investment, notably concerning optimisation of the installation life cycle
- Greater satisfaction for energy users (in a building or in process industries) due to improved power availability and/or quality

The above possibilities are all the more an option given the current deregulation of the electrical-energy sector.

Modbus is increasingly used as the open standard for communication within the distribution switchboard and between the distribution switchboard and customer power monitoring and control applications. Modbus exists in two forms, twisted pair (RS 485) and Ethernet-TCP/IP (IEEE 802.3).

The [www.modbus.org](http://www.modbus.org) site presents all bus specifications and constantly updates the list of products and companies using the open industrial standard.

The use of web technologies has largely contributed to wider use by drastically reducing the cost of accessing these functions through the use of an interface that is now universal (web pages) and a degree of openness and upgradeability that simply did not exist just a few years ago.

*Two types of distribution are possible:*

- By insulated wires and cables
- By busbar trunking (busways)

## 2.2 Cables and busway trunking

### Distribution by insulated conductors and cables

#### Definitions

- Conductor



A conductor comprises a single metallic core with or without an insulating envelope.

- Cable



A cable is made up of a number of conductors, electrically separated, but joined mechanically, generally enclosed in a protective flexible sheath.

- Cableway



The term cableway refers to conductors and/or cables together with the means of support and protection, etc. for example : cable trays, ladders, ducts, trenches, and so on... are all "cableways".

#### Conductor marking

Conductor identification must always respect the following three rules:

- Rule 1

The double colour green and yellow is strictly reserved for the PE and PEN protection conductors.

- Rule 2

□ When a circuit comprises a neutral conductor, it must be light blue or marked "1" for cables with more than five conductors

□ When a circuit does not have a neutral conductor, the light blue conductor may be used as a phase conductor if it is part of a cable with more than one conductor

- Rule 3

Phase conductors may be any colour except:

- Green and yellow
- Green
- Yellow
- Light blue (see rule 2)

Conductors in a cable are identified either by their colour or by numbers (see Fig. E34).

Number of conductors in circuit	Circuit	Fixed cableways									
		Insulated conductors					Rigid and flexible multi-conductor cables				
		Ph	Ph	Pn	N	PE	Ph	Ph	Ph	N	PE
1	Protection or earth					G/Y					
2	Single-phase between phases	■	■				BL	LB			
	Single-phase between phase and neutral	■			LB		BL			LB	
	Single-phase between phase and neutral + protection conductor	■			G/Y		BL			G/Y	
3	Three-phase without neutral	■	■	■			BL	B	LB		
	2 phases + neutral	■	■		LB		BL	B		LB	
	2 phases + protection conductor	■	■			G/Y	BL	LB			G/Y
	Single-phase between phase and neutral + protection conductor	■			LB	G/Y	BL			LB	G/Y
4	Three-phase with neutral	■	■	■	LB		BL	B	BL	LB	
	Three-phase with neutral + protection conductor	■	■	■		G/Y	BL	B	LB		G/Y
	2 phases + neutral + protection conductor	■	■		LB	G/Y	BL	B		LB	G/Y
	Three-phase with PEN conductor	■	■	■	G/Y		BL	B	LB	G/Y	
5	Three-phase + neutral + protection conductor	■	■	■	LB	G/Y	BL	B	BL	LB	G/Y
> 5		Protection conductor: G/Y - Other conductors: BL: with numbering The number "1" is reserved for the neutral conductor if it exists									

G/Y: Green and yellow

BL: Black



: As indicated in rule 3

LB: Light blue

B: Brown

Fig. E34 : Conductor identification according to the type of circuit

**Note:** If the circuit includes a protection conductor and if the available cable does not have a green and yellow conductor, the protection conductor may be:

- A separate green and yellow conductor
- The blue conductor if the circuit does not have a neutral conductor
- A black conductor if the circuit has a neutral conductor

In the last two cases, the conductor used must be marked by green and yellow bands or markings at the ends and on all visible lengths of the conductor.

Equipment power cords are marked similar to multi-conductor cables (see Fig. E35).

**Distribution and installation methods** (see Fig. E36)

Distribution takes place via cableways that carry single insulated conductors or cables and include a fixing system and mechanical protection.

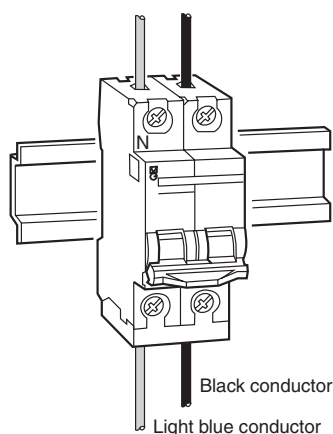


Fig. E35 : Conductor identification on a circuit-breaker with a phase and a neutral

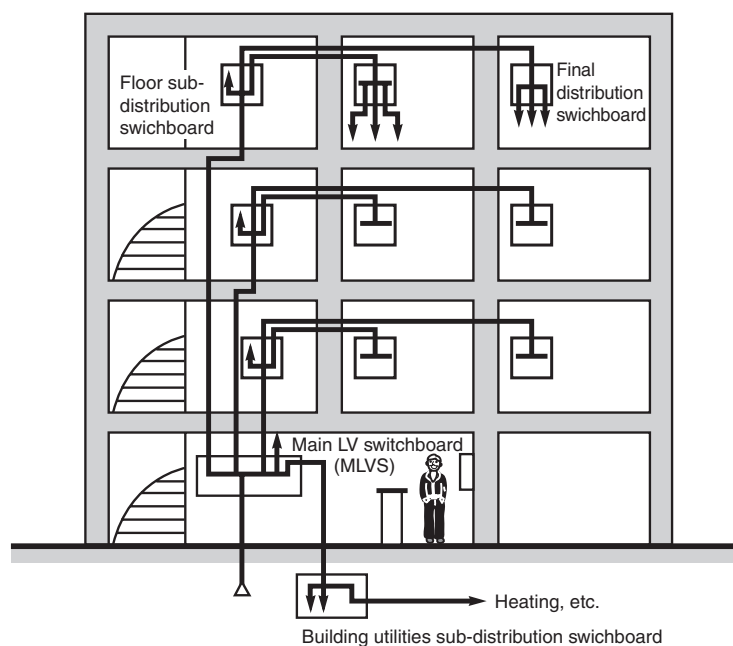


Fig. E36 : Radial distribution using cables in a hotel

*Busways, also referred to as busbar trunking systems, stand out for their ease of installation, flexibility and number of possible connection points*

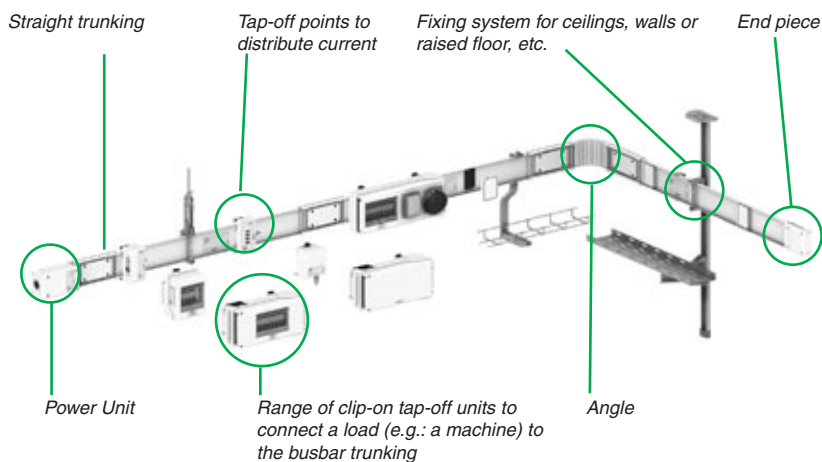
E20

### Busbar trunking (busways)

Busbar trunking is intended to distribute power (from 20 A to 5000 A) and lighting (in this application, the busbar trunking may play a dual role of supplying electrical power and physically holding the lights).

### Busbar trunking system components

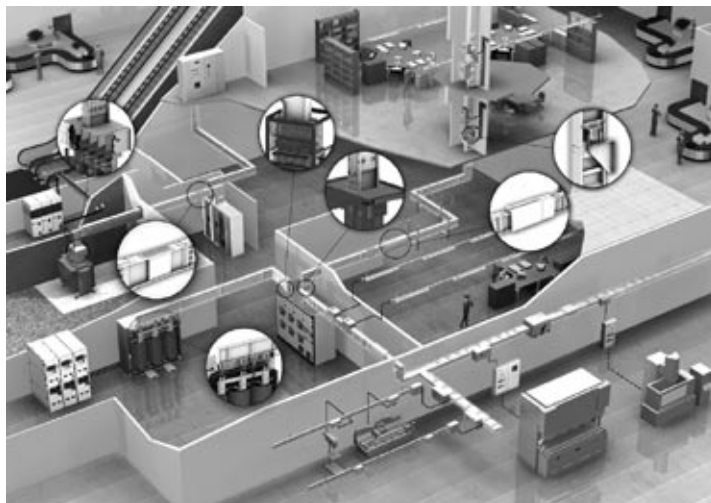
A **busbar trunking** system comprises a set of conductors protected by an enclosure (see Fig. E37). Used for the transmission and distribution of electrical power, busbar trunking systems have all the necessary features for fitting: connectors, straights, angles, fixings, etc. The tap-off points placed at regular intervals make power available at every point in the installation.



**Fig. E37** : Busbar trunking system design for distribution of currents from 25 to 4000 A.

### The various types of busbar trunking:

Busbar trunking systems are present at every level in electrical distribution: from the link between the transformer and the low voltage switch switchboard (MLVS) to the distribution of power sockets and lighting to offices, or power distribution to workshops.



**Fig. E38** : Radial distribution using busways

We talk about a distributed network architecture.

There are essentially three categories of busways.

■ **Transformer to MLVS busbar trunking**

Installation of the busway may be considered as permanent and will most likely never be modified. There are no tap-off points.

Frequently used for short runs, it is almost always used for ratings above 1,600 / 2,000 A, i.e. when the use of parallel cables makes installation impossible. Busways are also used between the MLVS and downstream distribution switchboards.

The characteristics of main-distribution busways authorize operational currents from 1,000 to 5,000 A and short-circuit withstands up to 150 kA.

■ **Sub-distribution busbar trunking with low or high tap-off densities**

Downstream of main-distribution busbar trunking, two types of applications must be supplied:

□ Mid-sized premises (industrial workshops with injection presses and metalwork machines or large supermarkets with heavy loads). The short-circuit and current levels can be fairly high (respectively 20 to 70 kA and 100 to 1,000 A)

□ Small sites (workshops with machine-tools, textile factories with small machines, supermarkets with small loads). The short-circuit and current levels are lower (respectively 10 to 40 kA and 40 to 400 A)

Sub-distribution using busbar trunking meets user needs in terms of:

□ Modifications and upgrades given the high number of tap-off points

□ Dependability and continuity of service because tap-off units can be connected under energized conditions in complete safety

The sub-distribution concept is also valid for vertical distribution in the form of 100 to 5,000 A risers in tall buildings.

■ **Lighting distribution busbar trunking**

Lighting circuits can be distributed using two types of busbar trunking according to whether the lighting fixtures are suspended from the busbar trunking or not.

□ busbar trunking designed for the suspension of lighting fixtures

These busways supply and support light fixtures (industrial reflectors, discharge lamps, etc.). They are used in industrial buildings, supermarkets, department stores and warehouses. The busbar trunkings are very rigid and are designed for one or two 25 A or 40 A circuits. They have tap-off outlets every 0.5 to 1 m.

□ busbar trunking not designed for the suspension of lighting fixtures

Similar to prefabricated cable systems, these busways are used to supply all types of lighting fixtures secured to the building structure. They are used in commercial buildings (offices, shops, restaurants, hotels, etc.), especially in false ceilings. The busbar trunking is flexible and designed for one 20 A circuit. It has tap-off outlets every 1.2 m to 3 m.

Busbar trunking systems are suited to the requirements of a large number of buildings.

■ **Industrial buildings:** garages, workshops, farm buildings, logistic centers, etc.

■ **Commercial areas:** stores, shopping malls, supermarkets, hotels, etc.

■ **Tertiary buildings:** offices, schools, hospitals, sports rooms, cruise liners, etc.

## Standards

Busbar trunking systems must meet all rules stated in IEC 439-2.

This defines the manufacturing arrangements to be complied with in the design of busbar trunking systems (e.g.: temperature rise characteristics, short-circuit withstand, mechanical strength, etc.) as well as test methods to check them.

Standard IEC 439-2 defines 13 compulsory type-tests on configurations or system components.

By assembling the system components on the site according to the assembly instructions, the contractor benefits from conformity with the standard.

## The advantages of busbar trunking systems

### Flexibility

■ Easy to change configuration (on-site modification to change production line configuration or extend production areas).

■ Reusing components (components are kept intact): when an installation is subject to major modifications, the busbar trunking is easy to dismantle and reuse.

■ Power availability throughout the installation (possibility of having a tap-off point every meter).

■ Wide choice of tap-off units.

**Simplicity**

- Design can be carried out independently from the distribution and layout of current consumers.
- Performances are independent of implementation: the use of cables requires a lot of derating coefficients.
- Clear distribution layout
- Reduction of fitting time: the trunking system allows fitting times to be reduced by up to 50% compared with a traditional cable installation.
- Manufacturer's guarantee.
- Controlled execution times: the trunking system concept guarantees that there are no unexpected surprises when fitting. The fitting time is clearly known in advance and a quick solution can be provided to any problems on site with this adaptable and scalable equipment.
- Easy to implement: modular components that are easy to handle, simple and quick to connect.

**Dependability**

- Reliability guaranteed by being factory-built
- Fool-proof units
- Sequential assembly of straight components and tap-off units making it impossible to make any mistakes

**Continuity of service**

- The large number of tap-off points makes it easy to supply power to any new current consumer. Connecting and disconnecting is quick and can be carried out in complete safety even when energized. These two operations (adding or modifying) take place without having to stop operations.
- Quick and easy fault location since current consumers are near to the line
- Maintenance is non-existent or greatly reduced

**Major contribution to sustainable development**

- Busbar trunking systems allow circuits to be combined. Compared with a traditional cable distribution system, consumption of copper raw materials and insulators is divided by 3 due to the busbar trunking distributed network concept (see Fig. E39).

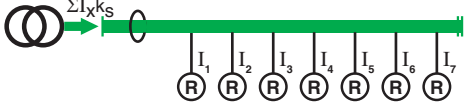



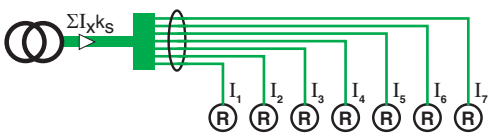



Distribution type	Conductors	Insulators	Consumption
<b>Branched</b>			
 <p>ks: clustering coefficient= 0.6</p>	 <p>Alu: 128 mm<sup>2</sup> Copper equivalent: 86 mm<sup>2</sup></p>	 <p>4 kg</p>	 <p>1 000 Joules</p>
<b>Centralized</b>			
 <p>ks: clustering coefficient= 0.6</p>	 <p>Copper: 250 mm<sup>2</sup></p>	 <p>12 kg</p>	 <p>1 600 Joules</p>

Fig. E39 : Example: 30 m of Canalis KS 250A equipped with 10 25 A, four-pole feeders

- Reusable device and all of its components are fully recyclable.
- Does not contain PVC and does not generate toxic gases or waste.
- Reduction of risks due to exposure to electromagnetic fields.

**New functional features for Canalis**

Busbar trunking systems are getting even better. Among the new features we can mention:

- Increased performance with a IP55 protection index and new ratings of 160 A through to 1000 A (Ks).
- New lighting offers with pre-cabled lights and new light ducts.
- New fixing accessories. Quick fixing system, cable ducts, shared support with "VDI" (voice, data, images) circuits.

**Busbar trunking systems are perfectly integrated with the environment:**

- white color to enhance the working environment, naturally integrated in a range of electrical distribution products.
- conformity with European regulations on reducing hazardous materials (RoHS).

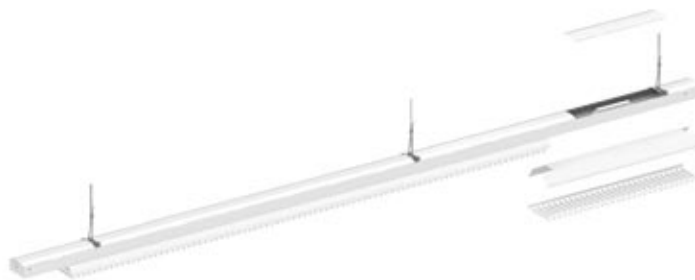
### Examples of Canalis busbar trunking systems



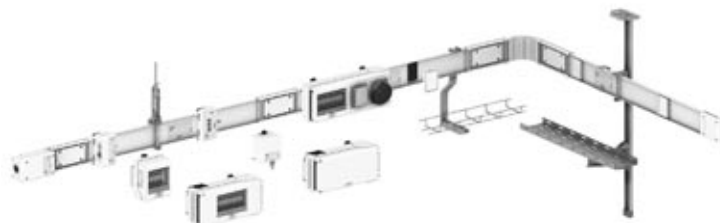
**Fig. E40** : Flexible busbar trunking not capable of supporting light fittings : Canalis KDP (20 A)



**Fig. E41** : Rigid busbar trunking able to support light fittings : Canalis KBA or KBB (25 and 40 A)



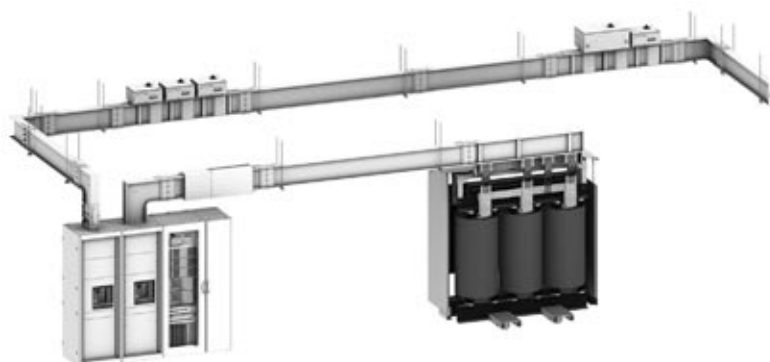
**Fig. E42** : Lighting duct : Canalis KBX (25 A)



**Fig. E43** : A busway for medium power distribution : Canalis KN (40 up to 160 A)



**Fig. E44** : A busway for medium power distribution : Canalis KS (100 up to 1000 A)



**Fig. E45** : A busway for high power distribution : Canalis KT (800 up to 1000 A)

## 3 External influences (IEC 60364-5-51)

External influences shall be taken into account when choosing:

- The appropriate measures to ensure the safety of persons (in particular in special locations or electrical installations)
- The characteristics of electrical equipment, such as degree of protection (IP), mechanical withstand (IK), etc.

If several external influences appear at the same time, they can have independent or mutual effects and the degree of protection must be chosen accordingly

### 3.1 Definition and reference standards

Every electrical installation occupies an environment that presents a variable degree of risk:

- For people
- For the equipment constituting the installation

Consequently, environmental conditions influence the definition and choice of appropriate installation equipment and the choice of protective measures for the safety of persons.

The environmental conditions are referred to collectively as “external influences”. Many national standards concerned with external influences include a classification scheme which is based on, or which closely resembles, that of international standard IEC 60364-5-51.

E25

### 3.2 Classification

Each condition of external influence is designated by a code comprising a group of two capital letters and a number as follows:

#### First letter (A, B or C)

The first letter relates to the general category of external influence :

- A = environment
- B = utilisation
- C = construction of buildings

#### Second letter

The second letter relates to the nature of the external influence.

#### Number

The number relates to the class within each external influence.

#### Additional letter (optional)

Used only if the effective protection of persons is greater than that indicated by the first IP digit.

When only the protection of persons is to be specified, the two digits of the IP code are replaced by the X's.

Example: IP XXB.

#### Example

For example the code AC2 signifies:

A = environment

AC = environment-altitude

AC2 = environment-altitude > 2,000 m

### 3.3 List of external influences

Figure E46 below is from IEC 60364-5-51, which should be referred to if further details are required.

Code	External influences			Characteristics required for equipment
A - Environment				
AA	Ambient temperature (°C)			
	Low	High		Specially designed equipment or appropriate arrangements
AA1	- 60 °C	+ 5 °C		
AA2	- 40 °C	+ 5 °C		
AA3	- 25 °C	+ 5 °C		
AA4	- 5° C	+ 40 °C		Normal (special precautions in certain cases)
AA5	+ 5 °C	+ 40 °C		Normal
AA6	+ 5 °C	+ 60 °C		Specially designed equipment or appropriate arrangements
AA7	- 25 °C	+ 55 °C		
AA8	- 50 °C	+ 40 °C		

Fig. E46 : List of external influences (taken from Appendix A of IEC 60364-5-51) (continued on next page)



# 3 External influences (IEC 60364-5-51)

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Code	External influences						Characteristics required for equipment
A - Environment							
AB	Atmospheric humidity						
	Air temperature °C		Relative humidity %		Absolute humidity g/m³		
	Low	High	Low	High	Low	High	
AB1	- 60 °C	+ 5 °C	3	100	0.003	7	Appropriate arrangements shall be made
AB2	- 40 °C	+ 5 °C	10	100	0.1	7	
AB3	- 25 °C	+ 5 °C	10	100	0.5	7	
AB4	- 5° C	+ 40 °C	5	95	1	29	Normal
AB5	+ 5 °C	+ 40 °C	5	85	1	25	Normal
AB6	+ 5 °C	+ 60 °C	10	100	1	35	Appropriate arrangements shall be made
AB7	- 25 °C	+ 55 °C	10	100	0.5	29	
AB8	- 50 °C	+ 40 °C	15	100	0.04	36	
AC	Altitude						
AC1	≤ 2000 m						Normal
AC2	> 2000 m						May necessitate precaution (derating factors)
AD	Presence of water						
AD1	Negligible		Outdoor or non-weather protected locations				IPX0
AD2	Free-falling drops						IPX1 or IPX2
AD3	Sprays						IPX3
AD4	Splashes						IPX4
AD5	Jets		Locations where hose water is used regularly				IPX5
AD6	Waves		Seashore locations (piers, beaches, quays...)				IPX6
AD7	Immersion		Water 150 mm above the highest point and equipment not more than 1m below the surface				IPX7
AD8	Submersion		Equipment is permanently and totally covered				IPX8
AE	Presence of foreign solid bodies						
			Smallest dimension		Example		
AE1	Negligible						IP0X
AE2	Small objects		2.5 mm		Tools		IP3X
AE3	Very small objects		1 mm		Wire		IP4X
AE4	Light dust						IP5X if dust penetration is not harmful to functioning
AE5	Moderate dust						IP6X if dust should not penetrate
AE6	Heavy dust						IP6X
AF	Presence of corrosive or polluting substances						
AF1	Negligible						Normal
AF2	Atmospheric						According to the nature of the substance
AF3	Intermittent, accidental						Protection against corrosion
AF4	Continuous						Equipment specially designed
AG	Mechanical stress impact						
AG1	Low severity						Normal
AG2	Medium severity						Standard where applicable or reinforced material
AG3	High severity						Reinforced protection
AH	Vibrations						
AH1	Low severity		Household or similar				Normal
AH2	Medium severity		Usual industrial conditions				Specially designed equipment or special arrangements
AH3	High severity		Severe industrial conditions				
AJ	Other mechanical stresses						
AK	Presence of flora and/or mould growth						
AH1	No hazard						Normal
AH2	Hazard						
AL	Presence of fauna						
AH1	No hazard						Normal
AH2	Hazard						
AM	Electromagnetic, electrostatic or ionising influences / Low frequency electromagnetic phenomena / Harmonics						
AM1	Harmonics, interharmonics						Refer to applicable IEC standards
AM2	Signalling voltage						
AM3	Voltage amplitude variations						
AM4	Voltage unbalance						
AM5	Power frequency variations						
AM6	Induced low-frequency voltages						
AM7	Direct current in a.c. networks						
AM8	Radiated magnetic fields						
AM9	Electric field						
AM21	Induced oscillatory voltages or currents						

Fig. E46 : List of external influences (taken from Appendix A of IEC 60364-5-51) (continued on next page)

### 3 External influences (IEC 60364-5-51)

Code	External influences	Characteristics required for equipment
A - Environment		
AM22	Conducted unidirectional transients of the nanosecond time scale	Refer to applicable IEC standards
AM23	Conducted unidirectional transients of the microsecond to the millisecond time scale	
AM24	Conducted oscillatory transients	
AM25	Radiated high frequency phenomena	
AM31	Electrostatic discharges	
AM41	Ionisation	
AN	Solar radiation	
AN1	Low	Normal
AN2	Medium	
AN3	High	
AP	Seismic effect	
AP1	Negligible	Normal
AP2	Low severity	
AP3	Medium severity	
AP4	High severity	
AQ	Lightning	
AQ1	Negligible	Normal
AQ2	Indirect exposure	
AQ3	Direct exposure	
AR	Movement of air	
AQ1	Low	Normal
AQ2	Medium	
AQ3	High	
AS	Wind	
AQ1	Low	Normal
AQ2	Medium	
AQ3	High	
B - Utilization		
BA	Capability of persons	
BA1	Ordinary	Normal
BA2	Children	
BA3	Handicapped	
BA4	Instructed	
BA5	Skilled	
BB	Electrical resistance of human body	
BC	Contact of persons with earth potential	
BC1	None	Class of equipment according to IEC61140
BC2	Low	
BC3	Frequent	
BC4	Continuous	
BD	Condition of evacuation in case of emergency	
BD1	Low density / easy exit	Normal
BD2	Low density / difficult exit	
BD3	High density / easy exit	
BD4	High density / difficult exit	
BE	Nature of processed or stored materials	
BE1	No significant risks	Normal
BE2	Fire risks	
BE3	Explosion risks	
BE4	Contamination risks	
C - Construction of building		
CA	Construction materials	
CA1	Non combustible	Normal
CA2	Combustible	
CB	Building design	
CB1	Negligible risks	Normal
CB2	Propagation of fire	
CB3	Movement	
CB4	flexible or unstable	

Fig. E46 : List of external influences (taken from Appendix A of IEC 60364-5-51) (concluded)

# 3 External influences (IEC 60364-5-51)

E28

## 3.4 Protection provided for enclosed equipment: codes IP and IK

### IP code definition (see Fig. E47)

The degree of protection provided by an enclosure is indicated in the IP code, recommended in IEC 60529.

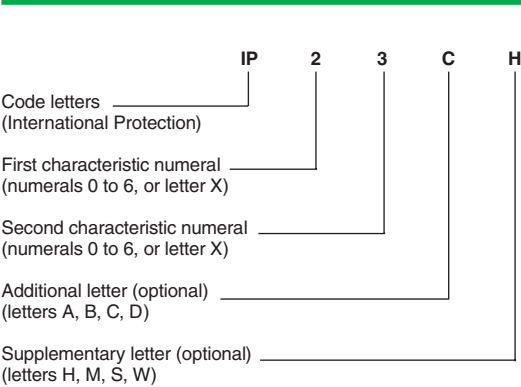
Protection is afforded against the following external influences:

- Penetration by solid bodies
- Protection of persons against access to live parts
- Protection against the ingress of dust
- Protection against the ingress of liquids

**Note:** the IP code applies to electrical equipment for voltages up to and including 72.5 kV.

### Elements of the IP Code and their meanings

A brief description of the IP Code elements is given in the following chart (see Fig. E48).



Where a characteristic numeral is not required to be specified, it shall be replaced by the letter "X" ("XX" if both numerals are omitted). Additional letters and/or supplementary letters may be omitted without replacement.

Fig. E47 : IP Code arrangement

Element	Numerals or letters	Meaning for the protection of equipment	Meaning for the protection of persons
Code letters	IP		
First characteristic numeral	0 1 2 3 4 5 6	Against ingress of solid foreign objects (non-protected) ≥ 50 mm diameter ≥ 12.5 mm diameter ≥ 2.5 mm diameter ≥ 1.0 mm diameter Dust-protected Dust-tight	Against access to hazardous parts with (non-protected) Back of hand Finger Tool Wire Wire Wire
Second characteristic numeral	0 1 2 3 4 5 6 7 8	Against ingress of water with harmful effects (non-protected) Vertically dripping Dripping (15° tilted) Spraying Splashing Jetting Powerful jetting Temporary immersion Continuous immersion	
Additional letter (optional)	A B C D		Against access to hazardous parts with back of hand Finger Tool Wire
Supplementary letter (optional)	H M S W	Supplementary information specific to: High-voltage apparatus Motion during water test Stationary during water test Weather conditions	

Fig. E48 : Elements of the IP Code

### 3 External influences (IEC 60364-5-51)

#### IK Code definition

Standard IEC 62262 defines an IK code that characterises the aptitude of equipment to resist mechanical impacts on all sides (see **Fig. E49**).

IK code	Impact energy (in Joules)	AG code
00	0	
01	≤ 0.14	
02	≤ 0.20	AG1
03	≤ 0.35	
04	≤ 0.50	
05	≤ 0.70	
06	≤ 1	
07	≤ 2	AG2
08	≤ 5	AG3
09	≤ 10	
10	≤ 20	AG4

**Fig. E49** : Elements of the IK Code

#### IP and IK code specifications for distribution switchboards

The degrees of protection IP and IK of an enclosure must be specified as a function of the different external influences defined by standard IEC 60364-5-51, in particular:

- Presence of solid bodies (code AE)
- Presence of water (code AD)
- Mechanical stresses (no code)
- Capability of persons (code BA)
- ...

Prisma Plus switchboards are designed for indoor installation. Unless the rules, standards and regulations of a specific country stipulate otherwise, Schneider Electric recommends the following IP and IK values (see **Fig. E50** and **Fig. E51** )

#### IP recommendations

IP codes according to conditions		
Normal without risk of vertically falling water	Technical rooms	30
Normal with risk of vertically falling water	Hallways	31
Very severe with risk of splashing water from all directions	Workshops	54/55

**Fig. E50** : IP recommendations

#### IK recommendations

IK codes according to conditions		
No risk of major impact	Technical rooms	07
Significant risk of major impact that could damage devices	Hallways	08 (enclosure with door)
Maximum risk of impact that could damage the enclosure	Workshops	10

**Fig. E51** : IK recommendations

# Chapter F

## Protection against electric shocks

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F1

When a current exceeding 30 mA passes through a part of a human body, the person concerned is in serious danger if the current is not interrupted in a very short time.

The protection of persons against electric shock in LV installations must be provided in conformity with appropriate national standards statutory regulations, codes of practice, official guides and circulars etc.

Relevant IEC standards include: IEC 60364, IEC 60479 series, IEC 61008, IEC 61009 and IEC 60947-2.

## 1.1 Electric shock

An electric shock is the pathophysiological effect of an electric current through the human body.

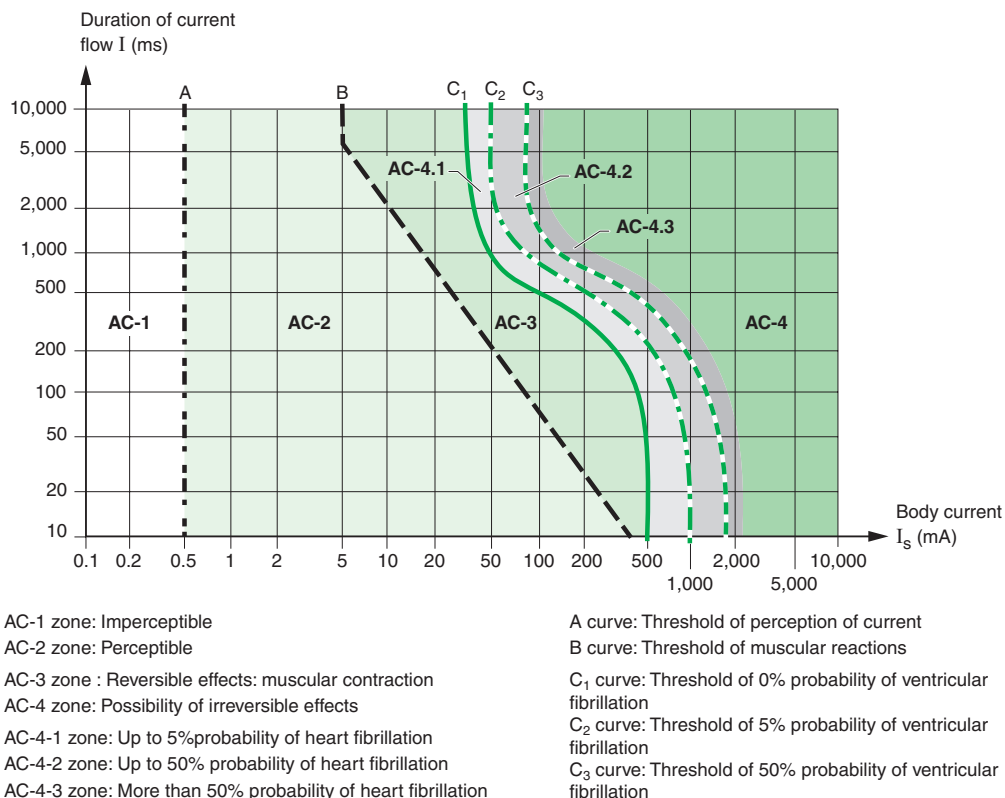
Its passage affects essentially the muscular, circulatory and respiratory functions and sometimes results in serious burns. The degree of danger for the victim is a function of the magnitude of the current, the parts of the body through which the current passes, and the duration of current flow.

IEC publication 60479-1 updated in 2005 defines four zones of current-magnitude/time-duration, in each of which the pathophysiological effects are described (see **Fig F1**). Any person coming into contact with live metal risks an electric shock.

Curve C1 shows that when a current greater than 30 mA passes through a human being from one hand to feet, the person concerned is likely to be killed, unless the current is interrupted in a relatively short time.

The point 500 ms/100 mA close to the curve C1 corresponds to a probability of heart fibrillation of the order of 0.14%.

The protection of persons against electric shock in LV installations must be provided in conformity with appropriate national standards and statutory regulations, codes of practice, official guides and circulars, etc. Relevant IEC standards include: IEC 60364 series, IEC 60479 series, IEC 60755, IEC 61008 series, IEC 61009 series and IEC 60947-2.



**Fig. F1** : Zones time/current of effects of AC current on human body when passing from left hand to feet

## 1.2 Protection against electric shock

The fundamental rule of protection against electric shock is provided by the document IEC 61140 which covers both electrical installations and electrical equipment.

Hazardous-live-parts shall not be accessible and accessible conductive parts shall not be hazardous.

This requirement needs to apply under:

- Normal conditions, and
- Under a single fault condition

Various measures are adopted to protect against this hazard, and include:

- Automatic disconnection of the power supply to the connected electrical equipment
- Special arrangements such as:
  - The use of class II insulation materials, or an equivalent level of insulation
  - Non-conducting location, out of arm's reach or interposition of barriers
  - Equipotential bonding
  - Electrical separation by means of isolating transformers

F3

## 1.3 Direct and indirect contact

*Two measures of protection against direct contact hazards are often required, since, in practice, the first measure may not be infallible*

*Standards and regulations distinguish two kinds of dangerous contact,*

- Direct contact
  - Indirect contact
- and corresponding protective measures*

### Direct contact

A direct contact refers to a person coming into contact with a conductor which is live in normal circumstances (see **Fig. F2**).

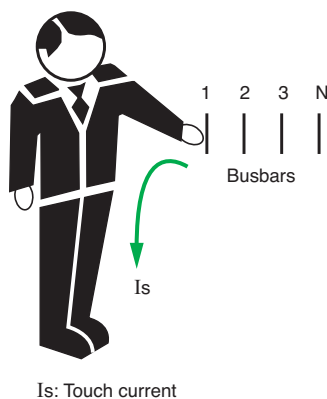
IEC 61140 standard has renamed "protection against direct contact" with the term "basic protection". The former name is at least kept for information.

### Indirect contact

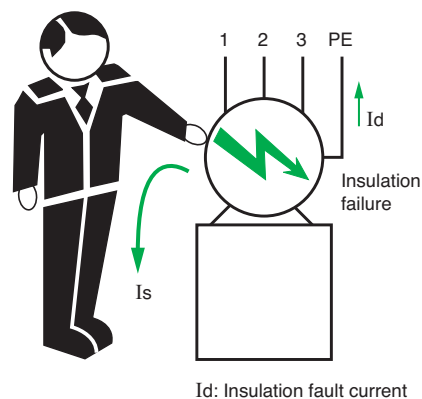
An indirect contact refers to a person coming into contact with an exposed-conductive-part which is not normally alive, but has become alive accidentally (due to insulation failure or some other cause).

The fault current raise the exposed-conductive-part to a voltage liable to be hazardous which could be at the origin of a touch current through a person coming into contact with this exposed-conductive-part (see **Fig. F3**).

IEC 61140 standard has renamed "protection against indirect contact" with the term "fault protection". The former name is at least kept for information.



**Fig. F2** : Direct contact



**Fig F3** : Indirect contact

Two complementary measures are commonly used as protection against the dangers of direct contact:

- The physical prevention of contact with live parts by barriers, insulation, inaccessibility, etc.
- Additional protection in the event that a direct contact occurs, despite or due to failure of the above measures. This protection is based on residual-current operating device with a high sensitivity ( $I_{\Delta n} \leq 30 \text{ mA}$ ) and a low operating time. These devices are highly effective in the majority of case of direct contact.

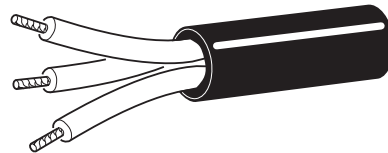
IEC and national standards frequently distinguish two protections:

- Complete (insulation, enclosures)
- Partial or particular

## 2.1 Measures of protection against direct contact

### Protection by the insulation of live parts

This protection consists of an insulation which complies with the relevant standards (see **Fig. F4**). Paints, lacquers and varnishes do not provide an adequate protection.



**Fig. F4** : Inherent protection against direct contact by insulation of a 3-phase cable with outer sheath

### Protection by means of barriers or enclosures

This measure is in widespread use, since many components and materials are installed in cabinets, assemblies, control panels and distribution boards (see **Fig. F5**).

To be considered as providing effective protection against direct contact hazards, these equipment must possess a degree of protection equal to at least IP 2X or IP XXB (see chapter E sub-clause 3.4).

Moreover, an opening in an enclosure (door, front panel, drawer, etc.) must only be removable, open or withdrawn:

- By means of a key or tool provided for this purpose, or
- After complete isolation of the live parts in the enclosure, or
- With the automatic interposition of another screen removable only with a key or a tool. The metal enclosure and all metal removable screen must be bonded to the protective earthing conductor of the installation.

### Partial measures of protection

- Protection by means of obstacles, or by placing out of arm's reach

This protection is reserved only to locations to which skilled or instructed persons only have access. The erection of this protective measure is detailed in IEC 60364-4-41.

### Particular measures of protection

- Protection by use of extra-low voltage SELV (Safety Extra-Low Voltage) or by limitation of the energy of discharge.

These measures are used only in low-power circuits, and in particular circumstances, as described in section 3.5.



**Fig. F5** : Example of isolation by envelope



*An additional measure of protection against the hazards of direct contact is provided by the use of residual current operating device, which operate at 30 mA or less, and are referred to as RCDs of high sensitivity*



**Fig. F6** : High sensitivity RCD

## 2.2 Additional measure of protection against direct contact

All the preceding protective measures are preventive, but experience has shown that for various reasons they cannot be regarded as being infallible. Among these reasons may be cited:

- Lack of proper maintenance
- Imprudence, carelessness
- Normal (or abnormal) wear and tear of insulation; for instance flexure and abrasion of connecting leads
- Accidental contact
- Immersion in water, etc. A situation in which insulation is no longer effective

In order to protect users in such circumstances, highly sensitive fast tripping devices, based on the detection of residual currents to earth (which may or may not be through a human being or animal) are used to disconnect the power supply automatically, and with sufficient rapidity to prevent injury to, or death by electrocution, of a normally healthy human being (see **Fig. F6**).

These devices operate on the principle of differential current measurement, in which any difference between the current entering a circuit and that leaving it (on a system supplied from an earthed source) be flowing to earth, either through faulty insulation or through contact of an earthed part, such as a person, with a live conductor.

Standardised residual-current devices, referred to as RCDs, sufficiently sensitive for protection against direct contact are rated at 30 mA of differential current.

According to IEC 60364-4-41, additional protection by means of high sensitivity RCDs ( $I_{\Delta n} \leq 30 \text{ mA}$ ) must be provided for circuits supplying socket-outlets with a rated current  $\leq 20 \text{ A}$  in all locations, and for circuits supplying mobile equipment with a rated current  $\leq 32 \text{ A}$  for use outdoors.

This additional protection is required in certain countries for circuits supplying socket-outlets rated up to 32 A, and even higher if the location is wet and/or temporary (such as work sites for instance).

It is also recommended to limit the number of socket-outlets protected by a RCD (e.g. 10 socket-outlets for one RCD).

Chapter P section 3 itemises various common locations in which RCDs of high sensitivity are obligatory (in some countries), but in any case, are highly recommended as an effective protection against both direct and indirect contact hazards.

# 3 Protection against indirect contact

Exposed-conductive-parts used in the manufacturing process of an electrical equipment is separated from the live parts of the equipment by the “basic insulation”. Failure of the basic insulation will result in the exposed-conductive-parts being alive. Touching a normally dead part of an electrical equipment which has become live due to the failure of its insulation, is referred to as an indirect contact.

## 3.1 Measures of protection: two levels

Protection against indirect contact hazards can be achieved by automatic disconnection of the supply if the exposed-conductive-parts of equipment are properly earthed

- Two levels of protective measures exist:
- 1<sup>st</sup> level: The earthing of all exposed-conductive-parts of electrical equipment in the installation and the constitution of an equipotential bonding network (see chapter G section 6).
  - 2<sup>nd</sup> level: Automatic disconnection of the supply of the section of the installation concerned, in such a way that the touch-voltage/time safety requirements are respected for any level of touch voltage  $U_c^{(1)}$  (see Fig. F7).

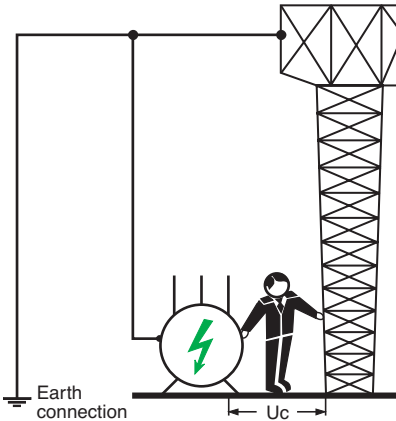


Fig. F7 : Illustration of the dangerous touch voltage  $U_c$

The greater the value of  $U_c$ , the greater the rapidity of supply disconnection required to provide protection (see Fig. F8). The highest value of  $U_c$  that can be tolerated indefinitely without danger to human beings is 50 V a.c.

### Reminder of the theoretical disconnecting-time limits

Uo (V)		50 < Uo ≤ 120	120 < Uo ≤ 230	230 < Uo ≤ 400	Uo > 400
System	TN or IT	0.8	0.4	0.2	0.1
	TT	0.3	0.2	0.07	0.04

Fig. F8 : Maximum safe duration of the assumed values of AC touch voltage (in seconds)

(1) Touch voltage  $U_c$  is the voltage existing (as the result of insulation failure) between an exposed-conductive-part and any conductive element within reach which is at a different (generally earth) potential.

Automatic disconnection for TT system is achieved by RCD having a sensitivity of

$I_{\Delta n} \leq \frac{50}{R_A}$  where  $R_A$  is the resistance of the installation earth electrode

## 3.2 Automatic disconnection for TT system

### Principle

In this system all exposed-conductive-parts and extraneous-conductive-parts of the installation must be connected to a common earth electrode. The neutral point of the supply system is normally earthed at a point outside the influence area of the installation earth electrode, but need not be so. The impedance of the earth-fault loop therefore consists mainly in the two earth electrodes (i.e. the source and installation electrodes) in series, so that the magnitude of the earth fault current is generally too small to operate overcurrent relay or fuses, and the use of a residual current operated device is essential.

This principle of protection is also valid if one common earth electrode only is used, notably in the case of a consumer-type substation within the installation area, where space limitation may impose the adoption of a TN system earthing, but where all other conditions required by the TN system cannot be fulfilled.

Protection by automatic disconnection of the supply used in TT system is by RCD of sensitivity:  $I_{\Delta n} \leq \frac{50}{R_A}$

where

$R_A$  is the resistance of the earth electrode for the installation

$I_{\Delta n}$  is the rated residual operating current of the RCD

For temporary supplies (to work sites, ...) and agricultural and horticultural premises, the value of 50 V is replaced by 25 V.

### Example (see Fig. F9)

- The resistance of the earth electrode of substation neutral  $R_n$  is 10  $\Omega$ .
- The resistance of the earth electrode of the installation  $R_A$  is 20  $\Omega$ .
- The earth-fault loop current  $I_d = 7.7$  A.
- The fault voltage  $U_f = I_d \times R_A = 154$  V and therefore dangerous, but  $I_{\Delta n} = 50/20 = 2.5$  A so that a standard 300 mA RCD will operate in about 30 ms without intentional time delay and will clear the fault where a fault voltage exceeding appears on an exposed-conductive-part.

$U_o^{(1)}$ (V)	T (s)
$50 < U_o \leq 120$	0.3
$120 < U_o \leq 230$	0.2
$230 < U_o \leq 400$	0.07
$U_o > 400$	0.04

(1)  $U_o$  is the nominal phase to earth voltage

Fig. F10 : Maximum disconnecting time for AC final circuits not exceeding 32 A

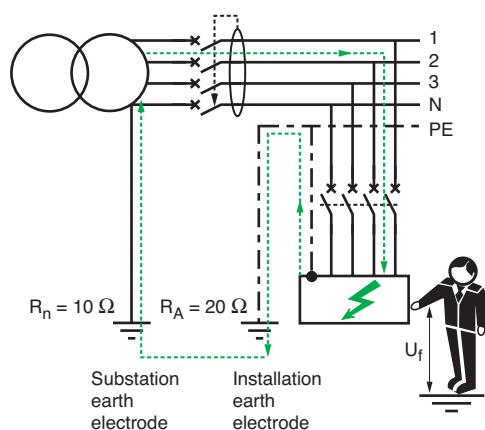


Fig. F9 : Automatic disconnection of supply for TT system

### Specified maximum disconnection time

The tripping times of RCDs are generally lower than those required in the majority of national standards; this feature facilitates their use and allows the adoption of an effective discriminative protection.

The IEC 60364-4-41 specifies the maximum operating time of protective devices used in TT system for the protection against indirect contact:

- For all final circuits with a rated current not exceeding 32 A, the maximum disconnecting time will not exceed the values indicated in **Figure F10**
  - For all other circuits, the maximum disconnecting time is fixed to 1s. This limit enables discrimination between RCDs when installed on distribution circuits.
- RCD is a general term for all devices operating on the residual-current principle. RCCB (Residual Current Circuit-Breaker) as defined in IEC 61008 series is a specific class of RCD.

Type G (general) and type S (Selective) of IEC 61008 have a tripping time/current characteristics as shown in **Figure F11** next page. These characteristics allow a certain degree of selective tripping between the several combination of ratings and types, as shown later in sub-clause 4.3. Industrial type RCD according to IEC 60947-2 provide more possibilities of discrimination due to their flexibility of time-delaying.

The automatic disconnection for TN system is achieved by overcurrent protective devices or RCD's

$x_{1\Delta n}$		1	2	5	> 5
Domestic	Instantaneous	0.3	0.15	0.04	0.04
	Type S	0.5	0.2	0.15	0.15
Industrial	Instantaneous	0.3	0.15	0.04	0.04
	Time-delay (0.06)	0.5	0.2	0.15	0.15
	Time-delay (other)	According to manufacturer			

**Fig. F11** : Maximum operating time of RCD's (in seconds)

### 3.3 Automatic disconnection for TN systems

## Principle

In this system all exposed and extraneous-conductive-parts of the installation are connected directly to the earthed point of the power supply by protective conductors.

As noted in Chapter E Sub-clause 1.2, the way in which this direct connection is carried out depends on whether the TN-C, TN-S, or TN-C-S method of implementing the TN principle is used. In figure F12 the method TN-C is shown, in which the neutral conductor acts as both the Protective-Earth and Neutral (PEN) conductor. In all TN systems, any insulation fault to earth results in a phase to neutral short-circuit. High fault current levels allow to use overcurrent protection but can give rise to touch voltages exceeding 50% of the phase to neutral voltage at the fault position during the short disconnection time.

In practice for utility distribution network, earth electrodes are normally installed at regular intervals along the protective conductor (PE or PEN) of the network, while the consumer is often required to install an earth electrode at the service entrance.

On large installations additional earth electrodes dispersed around the premises are often provided, in order to reduce the touch voltage as much as possible. In high-rise apartment blocks, all extraneous conductive parts are connected to the protective conductor at each level. In order to ensure adequate protection, the earth-fault current

$$I_d = \frac{U_o}{Z_s} \text{ or } 0.8 \frac{U_o}{Z_c}; \text{ must be higher or equal to } I_a, \text{ where:}$$

- $U_0$  = nominal phase to neutral voltage
- $I_d$  = the fault current
- $I_a$  = current equal to the value required to operate the protective device in the time specified
- $Z_s$  = earth-fault current loop impedance, equal to the sum of the impedances of the source, the live phase conductors to the fault position, the protective conductors from the fault position back to the source
- $Z_c$  = the faulty-circuit loop impedance (see “conventional method” Sub-clause 6.2)

**Note:** The path through earth electrodes back to the source will have (generally) much higher impedance values than those listed above, and need not be considered.

**Example** (see Fig. F12)

The fault voltage  $U_f = \frac{230}{2} = 115 \text{ V}$  and is hazardous;

The fault loop impedance  $Z_s = Z_{AB} + Z_{BC} + Z_{DE} + Z_{EN} + Z_{NA}$ .

If  $Z_{BC}$  and  $Z_{DE}$  are predominant, then:

$$Z_s = 2\rho \frac{L}{S} = 64.3 \text{ m}\Omega \text{ , so that}$$

$$I_d = \frac{230}{64.3 \times 10^{-3}} = 3,576 \text{ A } (\approx 22 \text{ In based on a NSX160 circuit-breaker}).$$

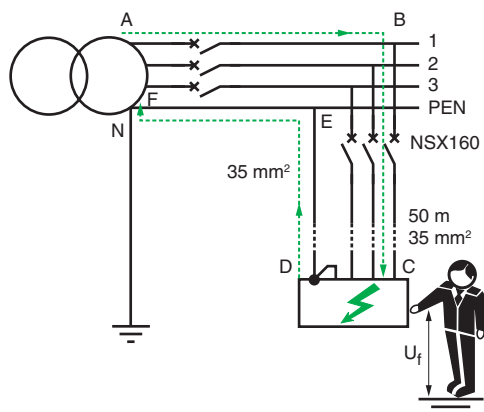
The “instantaneous” magnetic trip unit adjustment of the circuit-breaker is many times less than this short-circuit value, so that positive operation in the shortest possible time is assured.

**Note:** Some authorities base such calculations on the assumption that a voltage drop of 20% occurs in the part of the impedance loop BANE.

This method, which is recommended, is explained in chapter F sub-clause 6.2

“conventional method” and in this example will give an estimated fault current of

$$\frac{230 \times 0.8 \times 10^3}{64.3} = 2,816 \text{ A } (\approx 18 \text{ In}).$$



**Fig. F12 :** Automatic disconnection in TN system

### 3 Protection against indirect contact

#### Specified maximum disconnection time

The IEC 60364-4-41 specifies the maximum operating time of protective devices used in TN system for the protection against indirect contact:

- For all final circuits with a rated current not exceeding 32 A, the maximum disconnecting time will not exceed the values indicated in **Figure F13**
- For all other circuits, the maximum disconnecting time is fixed to 5s. This limit enables discrimination between protective devices installed on distribution circuits

**Note:** The use of RCDs may be necessary on TN-earthed systems. Use of RCDs on TN-C-S systems means that the protective conductor and the neutral conductor must (evidently) be separated upstream of the RCD. This separation is commonly made at the service entrance.

$U_o^{(1)}$ (V)	T (s)
$50 < U_o \leq 120$	0.8
$120 < U_o \leq 230$	0.4
$230 < U_o \leq 400$	0.2
$U_o > 400$	0.1

(1)  $U_o$  is the nominal phase to earth voltage

**Fig. F13** : Maximum disconnecting time for AC final circuits not exceeding 32 A

If the protection is to be provided by a circuit-breaker, it is sufficient to verify that the fault current will always exceed the current-setting level of the instantaneous or short-time delay tripping unit ( $I_m$ )

$I_a$  can be determined from the fuse performance curve. In any case, protection cannot be achieved if the loop impedance  $Z_s$  or  $Z_c$  exceeds a certain value

#### Protection by means of circuit-breaker (see Fig. F14)

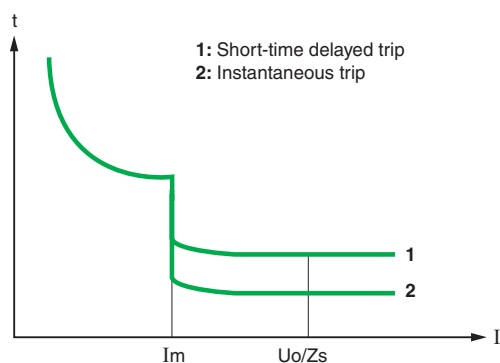
The instantaneous trip unit of a circuit-breaker will eliminate a short-circuit to earth in less than 0.1 second.

In consequence, automatic disconnection within the maximum allowable time will always be assured, since all types of trip unit, magnetic or electronic, instantaneous or slightly retarded, are suitable:  $I_a = I_m$ . The maximum tolerance authorised by the relevant standard, however, must always be taken into consideration. It is sufficient therefore that the fault current  $\frac{U_o}{Z_s}$  or  $0.8 \frac{U_o}{Z_c}$  determined by calculation (or estimated on site) be greater than the instantaneous trip-setting current, or than the very short-time tripping threshold level, to be sure of tripping within the permitted time limit.

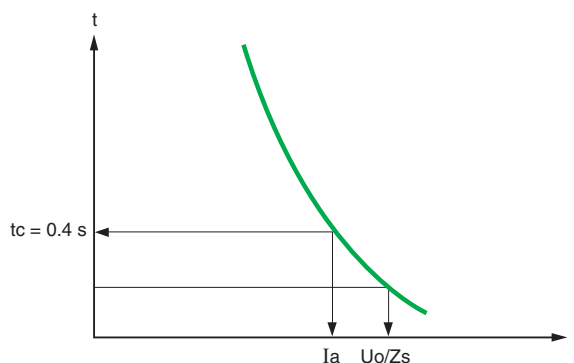
#### Protection by means of fuses (see Fig. F15)

The value of current which assures the correct operation of a fuse can be ascertained from a current/time performance graph for the fuse concerned.

The fault current  $\frac{U_o}{Z_s}$  or  $0.8 \frac{U_o}{Z_c}$  as determined above, must largely exceed that necessary to ensure positive operation of the fuse. The condition to observe therefore is that  $I_a < \frac{U_o}{Z_s}$  or  $0.8 \frac{U_o}{Z_c}$  as indicated in Figure F15.



**Fig. F14** : Disconnection by circuit-breaker for a TN system



**Fig. F15** : Disconnection by fuses for a TN system

## 3 Protection against indirect contact

F10

**Example:** The nominal phase to neutral voltage of the network is 230 V and the maximum disconnection time given by the graph in Figure F15 is 0.4 s. The corresponding value of  $I_a$  can be read from the graph. Using the voltage (230 V) and the current  $I_a$ , the complete loop impedance or the circuit loop impedance can be calculated from  $Z_s = \frac{230}{I_a}$  or  $Z_c = 0.8 \frac{230}{I_a}$ . This impedance value must never be exceeded and should preferably be substantially less to ensure satisfactory fuse operation.

### Protection by means of Residual Current Devices for TN-S circuits

Residual Current Devices must be used where:

- The loop impedance cannot be determined precisely (lengths difficult to estimate, presence of metallic material close to the wiring)
- The fault current is so low that the disconnecting time cannot be met by using overcurrent protective devices

The rated tripping current of RCDs being in the order of a few amps, it is well below the fault current level. RCDs are consequently well adapted to this situation.

In practice, they are often installed in the LV sub distribution and in many countries, the automatic disconnection of final circuits shall be achieved by Residual Current Devices.

### 3.4 Automatic disconnection on a second fault in an IT system

In this type of system:

- The installation is isolated from earth, or the neutral point of its power-supply source is connected to earth through a high impedance
- All exposed and extraneous-conductive-parts are earthed via an installation earth electrode.

#### First fault situation

On the occurrence of a true fault to earth, referred to as a "first fault", the fault current is very low, such that the rule  $I_d \times R_A \leq 50 \text{ V}$  (see F3.2) is fulfilled and no dangerous fault voltages can occur.

In practice the current  $I_d$  is low, a condition that is neither dangerous to personnel, nor harmful to the installation.

However, in this system:

- A permanent monitoring of the insulation to earth must be provided, coupled with an alarm signal (audio and/or flashing lights, etc.) operating in the event of a first earth fault (see Fig. F16)
- The rapid location and repair of a first fault is imperative if the full benefits of the IT system are to be realised. Continuity of service is the great advantage afforded by the system.

For a network formed from 1 km of new conductors, the leakage (capacitive) impedance to earth  $Z_f$  is of the order of 3,500  $\Omega$  per phase. In normal operation, the capacitive current<sup>(1)</sup> to earth is therefore:

$$\frac{U_o}{Z_f} = \frac{230}{3,500} = 66 \text{ mA per phase.}$$

During a phase to earth fault, as indicated in **Figure F17** opposite page, the current passing through the electrode resistance  $R_{nA}$  is the vector sum of the capacitive currents in the two healthy phases. The voltages of the healthy phases have (because of the fault) increased to  $\sqrt{3}$  the normal phase voltage, so that the capacitive currents increase by the same amount. These currents are displaced, one from the other by  $60^\circ$ , so that when added vectorially, this amounts to  $3 \times 66 \text{ mA} = 198 \text{ mA}$ , in the present example.

The fault voltage  $U_f$  is therefore equal to  $198 \times 5 \times 10^{-3} = 0.99 \text{ V}$ , which is obviously harmless.

The current through the short-circuit to earth is given by the vector sum of the neutral-resistor current  $I_{d1}$  (=153 mA) and the capacitive current  $I_{d2}$  (198 mA).

Since the exposed-conductive-parts of the installation are connected directly to earth, the neutral impedance  $Z_{ct}$  plays practically no part in the production of touch voltages to earth.

*In IT system the first fault to earth should not cause any disconnection*



**Fig. F16 :** Phases to earth insulation monitoring device obligatory in IT system

(1) Resistive leakage current to earth through the insulation is assumed to be negligibly small in the example.

### 3 Protection against indirect contact

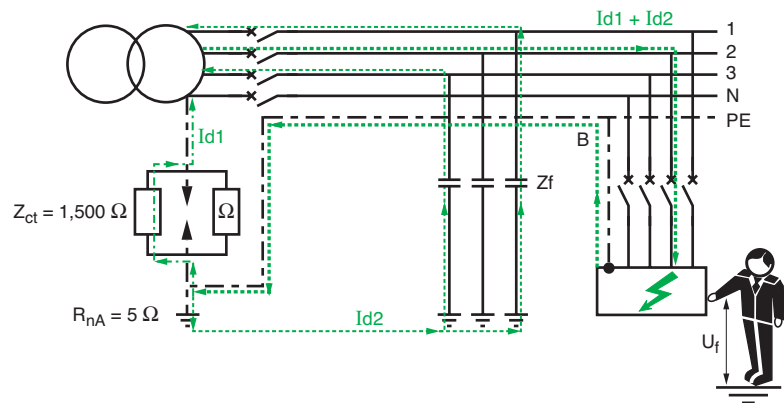


Fig. F17 : Fault current path for a first fault in IT system

#### Second fault situation

On the appearance of a second fault, on a different phase, or on a neutral conductor, a rapid disconnection becomes imperative. Fault clearance is carried out differently in each of the following cases:

##### 1<sup>st</sup> case

It concerns an installation in which all exposed conductive parts are bonded to a common PE conductor, as shown in Figure F18.

In this case no earth electrodes are included in the fault current path, so that a high level of fault current is assured, and conventional overcurrent protective devices are used, i.e. circuit-breakers and fuses.

The first fault could occur at the end of a circuit in a remote part of the installation, while the second fault could feasibly be located at the opposite end of the installation.

For this reason, it is conventional to double the loop impedance of a circuit, when calculating the anticipated fault setting level for its overcurrent protective device(s).

Where the system includes a neutral conductor in addition to the 3 phase conductors, the lowest short-circuit fault currents will occur if one of the (two) faults is from the neutral conductor to earth (all four conductors are insulated from earth in an IT scheme). In four-wire IT installations, therefore, the phase-to-neutral voltage must

be used to calculate short-circuit protective levels i.e.  $0.8 \frac{U_0}{2 Z_c} \geq I_a^{(1)}$  where

$U_0$  = phase to neutral voltage

$Z_c$  = impedance of the circuit fault-current loop (see F3.3)

$I_a$  = current level for trip setting

If no neutral conductor is distributed, then the voltage to use for the fault-current calculation is the phase-to-phase value, i.e.  $0.8 \frac{\sqrt{3} U_0}{2 Z_c} \geq I_a^{(1)}$

##### ■ Maximum tripping times

Disconnecting times for IT system depends on how the different installation and substation earth electrodes are interconnected.

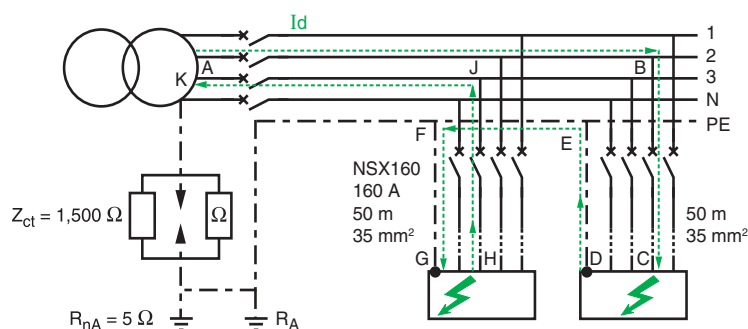
For final circuits supplying electrical equipment with a rated current not exceeding 32 A and having their exposed-conductive-parts bonded with the substation earth electrode, the maximum tripping time is given in table F8. For the other circuits within the same group of interconnected exposed-conductive-parts, the maximum disconnecting time is 5 s. This is due to the fact that any double fault situation within this group will result in a short-circuit current as in TN system.

For final circuits supplying electrical equipment with a rated current not exceeding 32 A and having their exposed-conductive-parts connected to an independent earth electrode electrically separated from the substation earth electrode, the maximum tripping time is given in Figure F13. For the other circuits within the same group of non interconnected exposed-conductive-parts, the maximum disconnecting time is 1s. This is due to the fact that any double fault situation resulting from one insulation fault within this group and another insulation fault from another group will generate a fault current limited by the different earth electrode resistances as in TT system.

*The simultaneous existence of two earth faults (if not both on the same phase) is dangerous, and rapid clearance by fuses or automatic circuit-breaker tripping depends on the type of earth-bonding scheme, and whether separate earthing electrodes are used or not, in the installation concerned*

(1) Based on the "conventional method" noted in the first example of Sub-clause 3.3.





**Fig. F18 :** Circuit-breaker tripping on double fault situation when exposed-conductive-parts are connected to a common protective conductor

- Protection by circuit-breaker

In the case shown in Figure F18, the adjustments of instantaneous and short-time delay overcurrent trip unit must be decided. The times recommended here above can be readily complied with. The short-circuit protection provided by the NSX160 circuit-breaker is suitable to clear a phase to phase short-circuit occurring at the load ends of the circuits concerned.

Reminder: In an IT system, the two circuits involved in a phase to phase short-circuit are assumed to be of equal length, with the same cross sectional area conductors, the PE conductors being the same cross sectional area as the phase conductors. In such a case, the impedance of the circuit loop when using the “conventional method” (sub clause 6.2) will be twice that calculated for one of the circuits in the TN case, shown in Chapter F sub clause 3.3.

The resistance of circuit loop FGHJ =  $2R_{LH} = 2\rho \frac{L}{A}$  in mΩ where:

$\rho$  = resistance of copper rod 1 meter long of cross sectional area 1 mm<sup>2</sup>, in m $\Omega$

L = length of the circuit in meters

a = cross sectional area of the conductor in mm<sup>2</sup>

$$FGHJ = 2 \times 22.5 \times 50/35 = 64.3 \text{ m}\Omega$$

and the loop resistance B, C, D, E, F, G, H, J will be  $2 \times 64.3 = 129 \text{ m}\Omega$ .

The fault current will therefore be  $0.8 \times \sqrt{3} \times 230 \times 10^3 / 129 = 2.470 \text{ A}$ .

- Protection by fuses

The current  $I_a$  for which fuse operation must be assured in a time specified according to here above can be found from fuse operating curves, as described in figure F15.

The current indicated should be significantly lower than the fault currents calculated for the circuit concerned.

### ■ Protection by Residual current circuit-breakers (RCCBs)

For low values of short-circuit current, RCCBs are necessary. Protection against indirect contact hazards can be achieved then by using one RCCB for each circuit.

## 2<sup>nd</sup> case

- It concerns exposed conductive parts which are earthed either individually (each part having its own earth electrode) or in separate groups (one electrode for each group).

If all exposed conductive parts are not bonded to a common electrode system, then it is possible for the second earth fault to occur in a different group or in a separately earthed individual apparatus. Additional protection to that described above for case 1, is required, and consists of a RCD placed at the circuit-breaker controlling each group and each individually-earthed apparatus.



### 3 Protection against indirect contact

The reason for this requirement is that the separate-group electrodes are “bonded” through the earth so that the phase to phase short-circuit current will generally be limited when passing through the earth bond by the electrode contact resistances with the earth, thereby making protection by overcurrent devices unreliable. The more sensitive RCDs are therefore necessary, but the operating current of the RCDs must evidently exceed that which occurs for a first fault (see **Fig. F19**).

Leakage capacitance (μF)	First fault current (A)
1	0.07
5	0.36
30	2.17

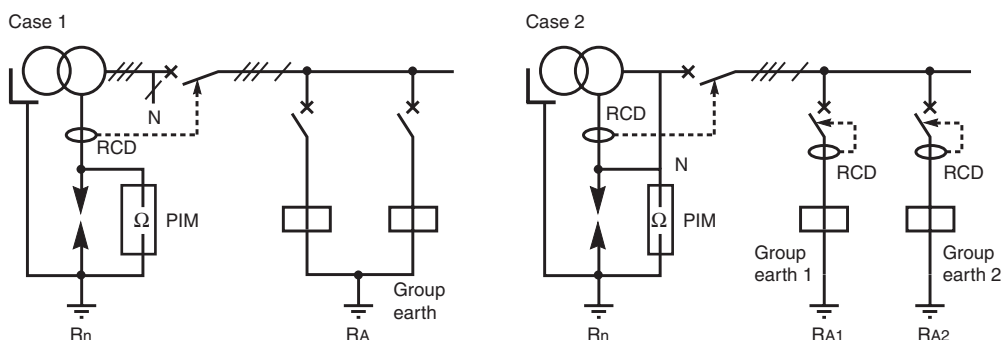
**Note:** 1 μF is the 1 km typical leakage capacitance for 4-conductor cable.

**Fig. F19 :** Correspondence between the earth leakage capacitance and the first fault current

For a second fault occurring within a group having a common earth-electrode system, the overcurrent protection operates, as described above for case 1.

**Note 1:** See also Chapter G Sub-clause 7.2, protection of the neutral conductor.

**Note 2:** In 3-phase 4-wire installations, protection against overcurrent in the neutral conductor is sometimes more conveniently achieved by using a ring-type current transformer over the single-core neutral conductor (see **Fig. F20**).



**Fig. F20 :** Application of RCDs when exposed-conductive-parts are earthed individually or by group on IT system

*Extra-low voltage is used where the risks are great: swimming pools, wandering-lead hand lamps, and other portable appliances for outdoor use, etc.*

#### 3.5 Measures of protection against direct or indirect contact without automatic disconnection of supply

##### The use of SELV (Safety Extra-Low Voltage)

Safety by extra low voltage SELV is used in situations where the operation of electrical equipment presents a serious hazard (swimming pools, amusement parks, etc.). This measure depends on supplying power at extra-low voltage from the secondary windings of isolating transformers especially designed according to national or to international (IEC 60742) standard. The impulse withstand level of insulation between the primary and secondary windings is very high, and/or an earthed metal screen is sometimes incorporated between the windings. The secondary voltage never exceeds 50 V rms.

Three conditions of exploitation must be respected in order to provide satisfactory protection against indirect contact:

- No live conductor at SELV must be connected to earth
- Exposed-conductive-parts of SELV supplied equipment must not be connected to earth, to other exposed conductive parts, or to extraneous-conductive-parts
- All live parts of SELV circuits and of other circuits of higher voltage must be separated by a distance at least equal to that between the primary and secondary windings of a safety isolating transformer.

### 3 Protection against indirect contact

F14

These measures require that:

- SELV circuits must use conduits exclusively provided for them, unless cables which are insulated for the highest voltage of the other circuits are used for the SELV circuits
- Socket outlets for the SELV system must not have an earth-pin contact. The SELV circuit plugs and sockets must be special, so that inadvertent connection to a different voltage level is not possible.

**Note:** In normal conditions, when the SELV voltage is less than 25 V, there is no need to provide protection against direct contact hazards. Particular requirements are indicated in Chapter P, Clause 3: "special locations".

#### The use of PELV (Protection by Extra Low Voltage) (see Fig. F21)

This system is for general use where low voltage is required, or preferred for safety reasons, other than in the high-risk locations noted above. The conception is similar to that of the SELV system, but the secondary circuit is earthed at one point.

IEC 60364-4-41 defines precisely the significance of the reference PELV. Protection against direct contact hazards is generally necessary, except when the equipment is in the zone of equipotential bonding, and the nominal voltage does not exceed 25 V rms, and the equipment is used in normally dry locations only, and large-area contact with the human body is not expected. In all other cases, 6 V rms is the maximum permitted voltage, where no direct contact protection is provided.

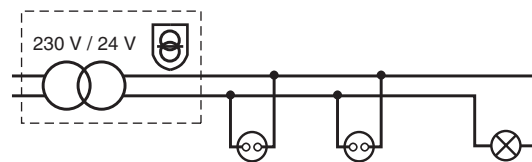


Fig. F21 : Low-voltage supplies from a safety isolating transformer

#### FELV system (Functional Extra-Low Voltage)

Where, for functional reasons, a voltage of 50 V or less is used, but not all of the requirements relating to SELV or PELV are fulfilled, appropriate measures described in IEC 60364-4-41 must be taken to ensure protection against both direct and indirect contact hazards, according to the location and use of these circuits.

**Note:** Such conditions may, for example, be encountered when the circuit contains equipment (such as transformers, relays, remote-control switches, contactors) insufficiently insulated with respect to circuits at higher voltages.

#### The electrical separation of circuits (see Fig. F22)

The principle of the electrical separation of circuits (generally single-phase circuits) for safety purposes is based on the following rationale.

The two conductors from the unearthed single-phase secondary winding of a separation transformer are insulated from earth.

If a direct contact is made with one conductor, a very small current only will flow into the person making contact, through the earth and back to the other conductor, via the inherent capacitance of that conductor with respect to earth. Since the conductor capacitance to earth is very small, the current is generally below the level of perception. As the length of circuit cable increases, the direct contact current will progressively increase to a point where a dangerous electric shock will be experienced.

Even if a short length of cable precludes any danger from capacitive current, a low value of insulation resistance with respect to earth can result in danger, since the current path is then via the person making contact, through the earth and back to the other conductor through the low conductor-to-earth insulation resistance.

For these reasons, relatively short lengths of well insulated cables are essential in separation systems.

Transformers are specially designed for this duty, with a high degree of insulation between primary and secondary windings, or with equivalent protection, such as an earthed metal screen between the windings. Construction of the transformer is to class II insulation standards.

*The electrical separation of circuits is suitable for relatively short cable lengths and high levels of insulation resistance. It is preferably used for an individual appliance*

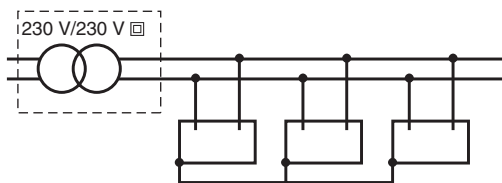


Fig. F22 : Safety supply from a class II separation transformer

### 3 Protection against indirect contact

As indicated before, successful exploitation of the principle requires that:

- No conductor or exposed conductive part of the secondary circuit must be connected to earth,
  - The length of secondary cabling must be limited to avoid large capacitance values<sup>(1)</sup>,
  - A high insulation-resistance value must be maintained for the cabling and appliances.
- These conditions generally limit the application of this safety measure to an individual appliance.

In the case where several appliances are supplied from a separation transformer, it is necessary to observe the following requirements:

- The exposed conductive parts of all appliances must be connected together by an insulated protective conductor, but not connected to earth,
- The socket outlets must be provided with an earth-pin connection. The earth-pin connection is used in this case only to ensure the interconnection (bonding) of all exposed conductive parts.

In the case of a second fault, overcurrent protection must provide automatic disconnection in the same conditions as those required for an IT system of power system earthing.

Class II equipment symbol:



#### Class II equipment

These appliances are also referred to as having “double insulation” since in class II appliances a supplementary insulation is added to the basic insulation (see Fig. F23).

No conductive parts of a class II appliance must be connected to a protective conductor:

- Most portable or semi-fixed equipment, certain lamps, and some types of transformer are designed to have double insulation. It is important to take particular care in the exploitation of class II equipment and to verify regularly and often that the class II standard is maintained (no broken outer envelope, etc.). Electronic devices, radio and television sets have safety levels equivalent to class II, but are not formally class II appliances
- Supplementary insulation in an electrical installation: IEC 60364-4-41 (Sub-clause 413-2) and some national standards such as NF C 15-100 (France) describe in more detail the necessary measures to achieve the supplementary insulation during installation work.

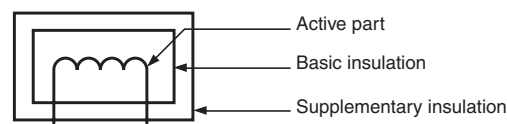


Fig. F23 : Principle of class II insulation level

A simple example is that of drawing a cable into a PVC conduit. Methods are also described for distribution switchboards.

- For distribution switchboards and similar equipment, IEC 60439-1 describes a set of requirements, for what is referred to as “total insulation”, equivalent to class II
- Some cables are recognised as being equivalent to class II by many national standards

*In principle, safety by placing simultaneously-accessible conductive parts out-of-reach, or by interposing obstacles, requires also a non-conducting floor, and so is not an easily applied principle*

#### Out-of-arm's reach or interposition of obstacles

By these means, the probability of touching a live exposed-conductive-part, while at the same time touching an extraneous-conductive-part at earth potential, is extremely low (see Fig. F24 next page). In practice, this measure can only be applied in a dry location, and is implemented according to the following conditions:

- The floor and the wall of the chamber must be non-conducting, i.e. the resistance to earth at any point must be:
  - > 50 kΩ (installation voltage ≤ 500 V)
  - > 100 kΩ (500 V < installation voltage ≤ 1000 V)

Resistance is measured by means of “MEGGER” type instruments (hand-operated generator or battery-operated electronic model) between an electrode placed on the floor or against the wall, and earth (i.e. the nearest protective earth conductor). The electrode contact area pressure must be evidently be the same for all tests.

Different instruments suppliers provide electrodes specific to their own product, so that care should be taken to ensure that the electrodes used are those supplied with the instrument.

(1) It is recommended in IEC 364-4-41 that the product of the nominal voltage of the circuit in volts and length in metres of the wiring system should not exceed 100,000, and that the length of the wiring system should not exceed 500 m.

### 3 Protection against indirect contact

- The placing of equipment and obstacles must be such that simultaneous contact with two exposed-conductive-parts or with an exposed conductive-part and an extraneous-conductive-part by an individual person is not possible.
- No exposed protective conductor must be introduced into the chamber concerned.
- Entrances to the chamber must be arranged so that persons entering are not at risk, e.g. a person standing on a conducting floor outside the chamber must not be able to reach through the doorway to touch an exposed-conductive-part, such as a lighting switch mounted in an industrial-type cast-iron conduit box, for example.

F16

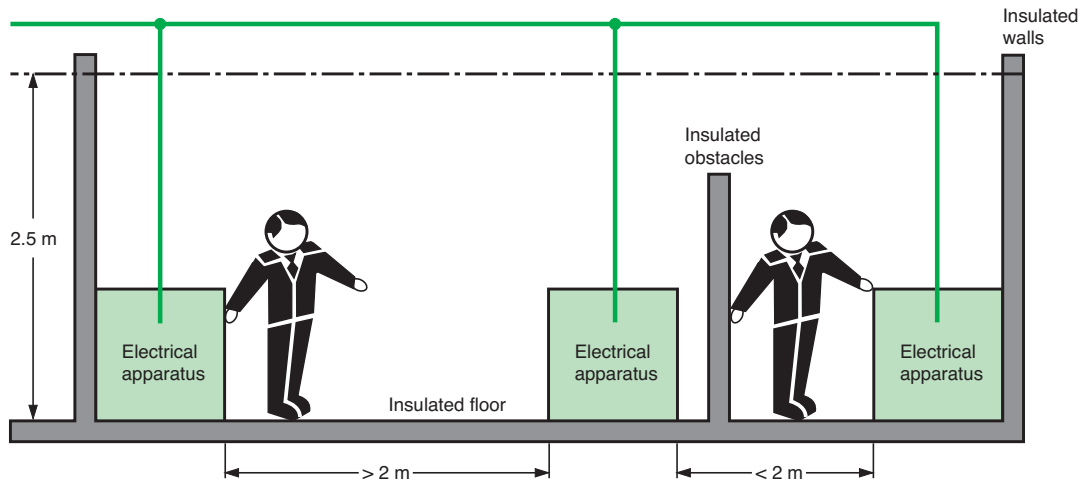


Fig. F24 : Protection by out-of arm's reach arrangements and the interposition of non-conducting obstacles

*Earth-free equipotential chambers are associated with particular installations (laboratories, etc.) and give rise to a number of practical installation difficulties*

#### Earth-free equipotential chambers

In this scheme, all exposed-conductive-parts, including the floor <sup>(1)</sup> are bonded by suitably large conductors, such that no significant difference of potential can exist between any two points. A failure of insulation between a live conductor and the metal envelope of an appliance will result in the whole "cage" being raised to phase-to-earth voltage, but no fault current will flow. In such conditions, a person entering the chamber would be at risk (since he/she would be stepping on to a live floor).

Suitable precautions must be taken to protect personnel from this danger (e.g. non-conducting floor at entrances, etc.). Special protective devices are also necessary to detect insulation failure, in the absence of significant fault current.

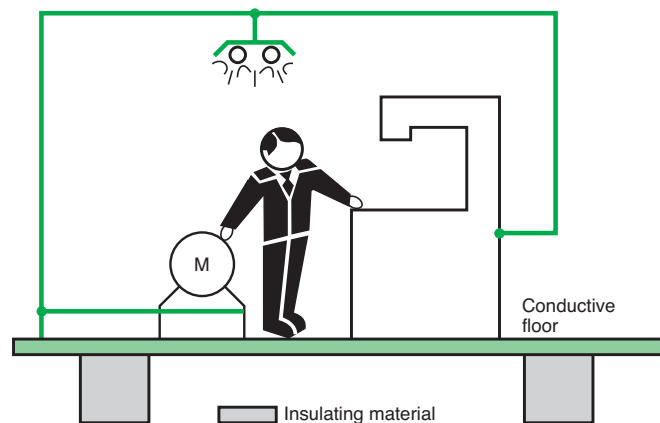


Fig. F25 : Equipotential bonding of all exposed-conductive-parts simultaneously accessible

(1) Extraneous conductive parts entering (or leaving) the equipotential space (such as water pipes, etc.) must be encased in suitable insulating material and excluded from the equipotential network, since such parts are likely to be bonded to protective (earthed) conductors elsewhere in the installation.

## 4 Protection of goods in case of insulation fault

The standards consider the damage (mainly fire) of goods due to insulation faults to be high. Therefore, for location with high risk of fire, 300 mA Residual Current Devices must be used. For the other locations, some standards relies on technique called « Ground Fault Protection » (GFP).

### 4.1 Measures of protection against fire risk with RCDs

*RCDs are very effective devices to provide protection against fire risk due to insulation fault because they can detect leakage current (ex : 300 mA) which are too low for the other protections, but sufficient to cause a fire*

RCDs are very effective devices to provide protection against fire risk due to insulation fault. This type of fault current is actually too low to be detected by the other protection (overcurrent, reverse time).

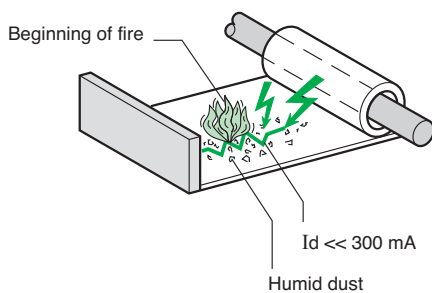
For TT, IT TN-S systems in which leakage current can appear, the use of 300 mA sensitivity RCDs provides a good protection against fire risk due to this type of fault. An investigation has shown that the cost of the fires in industrial and tertiary buildings can be very great.

The analysis of the phenomena shows that fire risk due to electricity is linked to overheating due to a bad coordination between the maximum rated current of the cable (or isolated conductor) and the overcurrent protection setting.

Overheating can also be due to the modification of the initial method of installation (addition of cables on the same support).

This overheating can be the origin of electrical arc in humid environment. These electrical arcs evolve when the fault current-loop impedance is greater than  $0.6 \Omega$  and exist only when an insulation fault occurs. Some tests have shown that a 300 mA fault current can induce a real risk of fire (see Fig. F26).

F17



Some tests have shown that a very low leakage current (a few mA) can evolve and, from 300 mA, induce a fire in humid and dusty environment.

Fig. F26 : Origin of fires in buildings

### 4.2 Ground Fault Protection (GFP)

**Different type of ground fault protections** (see Fig. F27)

Three types of GFP are possible depending on the measuring device installed :

#### ■ “Residual Sensing” RS

The “insulation fault” current is calculated using the vectorial sum of currents of current transformers secondaries. The current transformer on the neutral conductor is often outside the circuit-breaker.

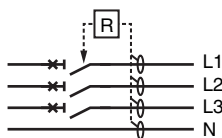
#### ■ “Source Ground Return” SGR

The « insulation fault current » is measured in the neutral – earth link of the LV transformer. The current transformer is outside the circuit-breaker.

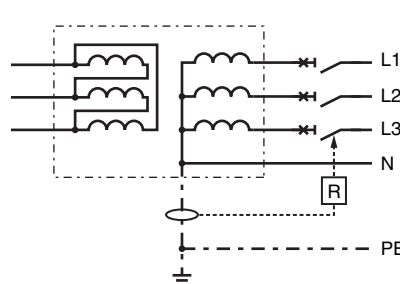
#### ■ “Zero Sequence” ZS

The « insulation fault » is directly measured at the secondary of the current transformer using the sum of currents in live conductors. This type of GFP is only used with low fault current values.

RS system



SGR system



ZS system

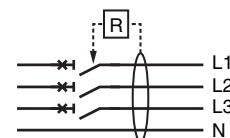


Fig. F27 : Different types of ground fault protections

## 4 Protection of goods in case of insulation fault

### Positioning GFP devices in the installation

Type / installation level	Main-distribution	Sub-distribution	Comments
Source Ground Return (SGR)	□		Used
Residual Sensing (RS) (SGR)	□	■	Often used
Zero Sequence (SGR)	□	■	Rarely used

□ Possible

■ Recommended or required

## 5.1 Protective measures

### Protection against indirect contact

#### General case

Protection against indirect contact is assured by RCDs, the sensitivity  $I\Delta n$  of which complies with the condition  $I\Delta n \leq \frac{50 \text{ V}}{R_A}$  <sup>(1)</sup>

The choice of sensitivity of the residual current device is a function of the resistance  $R_A$  of the earth electrode for the installation, and is given in **Figure F28**.

$I\Delta n$	Maximum resistance of the earth electrode	
	(50 V)	(25 V)
3 A	16 $\Omega$	8 $\Omega$
1 A	50 $\Omega$	25 $\Omega$
500 mA	100 $\Omega$	50 $\Omega$
300 mA	166 $\Omega$	83 $\Omega$
30 mA	1666 $\Omega$	833 $\Omega$

**Fig. F28** : The upper limit of resistance for an installation earthing electrode which must not be exceeded, for given sensitivity levels of RCDs at  $U_L$  voltage limits of 50 V and 25 V

#### Case of distribution circuits (see Fig. F29)

IEC 60364-4-41 and a number of national standards recognize a maximum tripping time of 1 second in installation distribution circuits (as opposed to final circuits). This allows a degree of selective discrimination to be achieved:

- At level A: RCD time-delayed, e.g. "S" type
- At level B: RCD instantaneous

#### Case where the exposed conductive parts of an appliance, or group of appliances, are connected to a separate earth electrode (see Fig. F30)

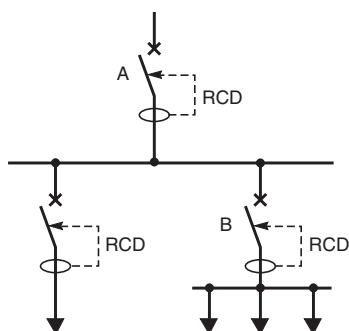
Protection against indirect contact by a RCD at the circuit-breaker level protecting each group or separately-earthed individual appliance.

In each case, the sensitivity must be compatible with the resistance of the earth electrode concerned.

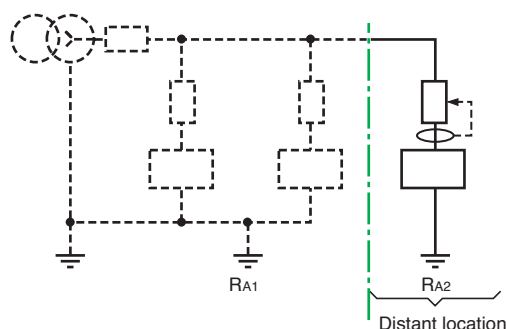
#### High-sensitivity RCDs (see Fig. F31)

According to IEC 60364-4-41, high sensitivity RCDs ( $\leq 30 \text{ mA}$ ) must be used for protection of socket outlets with rated current  $\leq 20 \text{ A}$  in all locations. The use of such RCDs is also recommended in the following cases:

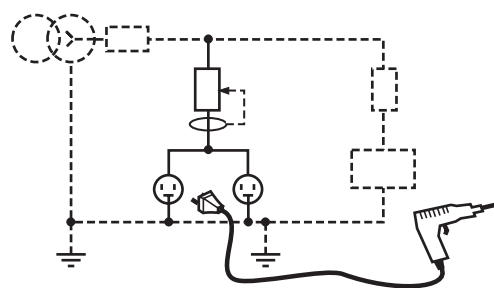
- Socket-outlet circuits in wet locations at all current ratings
  - Socket-outlet circuits in temporary installations
  - Circuits supplying laundry rooms and swimming pools
  - Supply circuits to work-sites, caravans, pleasure boats, and travelling fairs
- See 2.2 and chapter P, section 3



**Fig. F29** : Distribution circuits



**Fig. F30** : Separate earth electrode



**Fig. F31** : Circuit supplying socket-outlets

(1) 25 V for work-site installations, agricultural establishments, etc.

F20

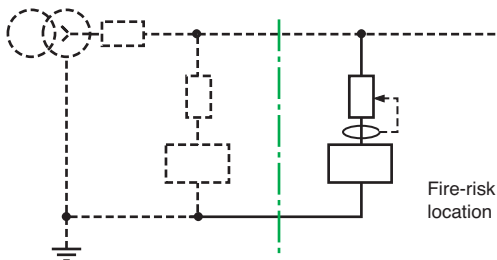


Fig. F32 : Fire-risk location

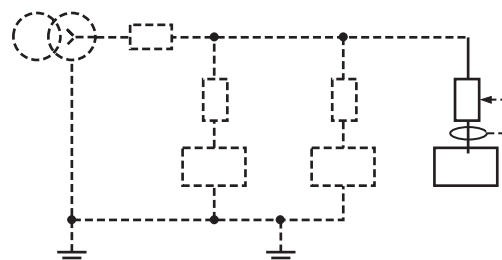


Fig. F33 : Unearthed exposed conductive parts (A)

**In high fire risk locations** (see Fig. F32)

RCD protection at the circuit-breaker controlling all supplies to the area at risk is necessary in some locations, and mandatory in many countries.

The sensitivity of the RCD must be  $\leq 500$  mA, but a 300 mA sensitivity is recommended.

**Protection when exposed conductive parts are not connected to earth** (see Fig. F33)

(In the case of an existing installation where the location is dry and provision of an earthing connection is not possible, or in the event that a protective earth wire becomes broken).

RCDs of high sensitivity ( $\leq 30$  mA) will afford both protection against indirect-contact hazards, and the additional protection against the dangers of direct-contact.

**5.2 Coordination of residual current protective devices**

Discriminative-tripping coordination is achieved either by time-delay or by subdivision of circuits, which are then protected individually or by groups, or by a combination of both methods.

Such discrimination avoids the tripping of any RCD, other than that immediately upstream of a fault position:

■ With equipment currently available, discrimination is possible at three or four different levels of distribution :

- At the main general distribution board
- At local general distribution boards
- At sub-distribution boards
- At socket outlets for individual appliance protection

■ In general, at distribution boards (and sub-distribution boards, if existing) and on individual-appliance protection, devices for automatic disconnection in the event of an indirect-contact hazard occurring are installed together with additional protection against direct-contact hazards.

**Discrimination between RCDs**

The general specification for achieving total discrimination between two RCDs is as follows:

- The ratio between the rated residual operating currents must be  $> 2$
- Time delaying the upstream RCD

Discrimination is achieved by exploiting the several levels of standardized sensitivity: 30 mA, 100 mA, 300 mA and 1 A and the corresponding tripping times, as shown opposite page in **Figure F34**.



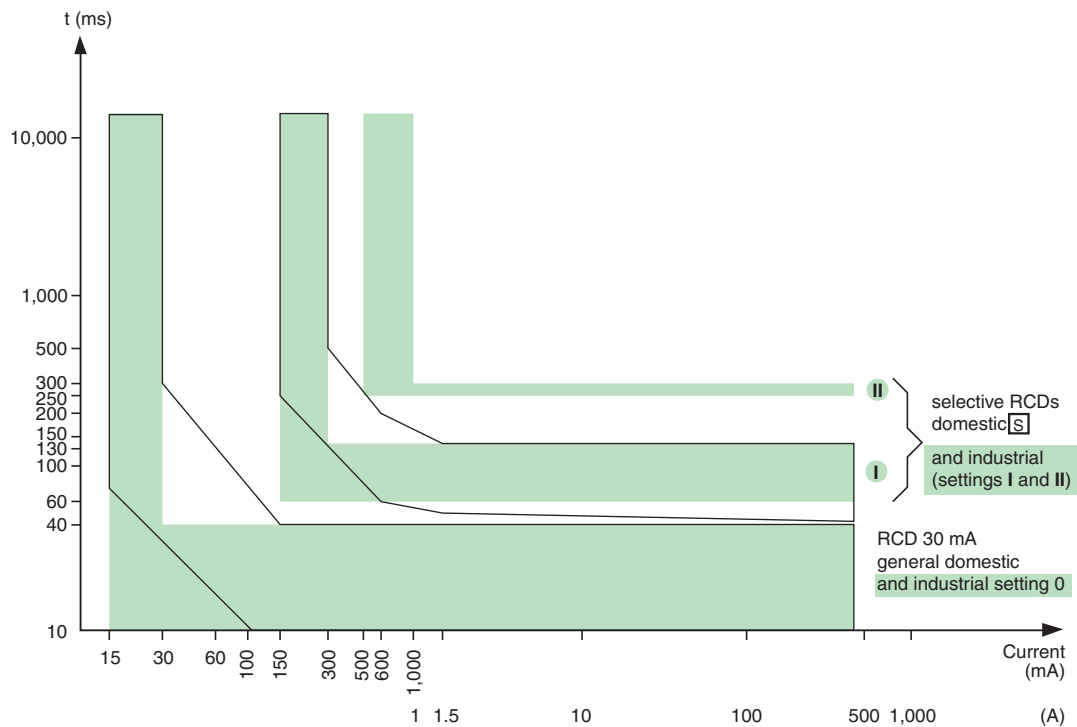


Fig. F34 : Total discrimination at 2 levels

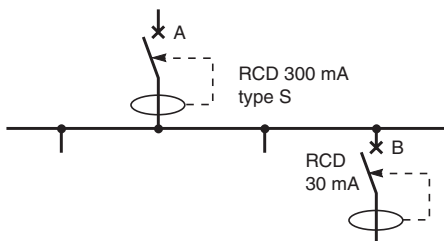


Fig. F35 : Total discrimination at 2 levels

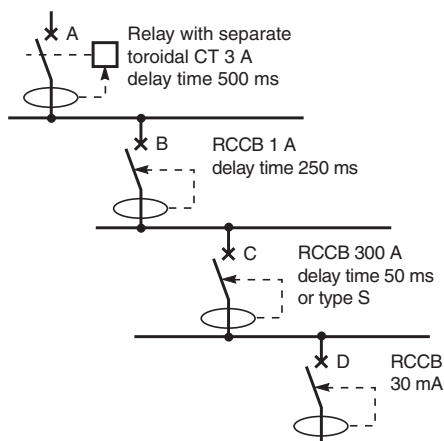


Fig. F36 : Total discrimination at 3 or 4 levels

### Discrimination at 2 levels (see Fig. F35)

#### Protection

- Level A: RCD time-delayed setting I (for industrial device) or type S (for domestic device) for protection against indirect contacts
- Level B: RCD instantaneous, with high sensitivity on circuits supplying socket-outlets or appliances at high risk (washing machines, etc.) See also Chapter P Clause 3

#### Schneider Electric solutions

- Level A: Compact or Multi 9 circuit-breaker with adaptable RCD module (Vigi NSX160 or Vigi NC100), setting I or S type
- Level B: Circuit-breaker with integrated RCD module (DPN Vigi) or adaptable RCD module (e.g. Vigi C60 or Vigi NC100) or Vigicompact

**Note:** The setting of upstream RCCB must comply with selectivity rules and take into account all the downstream earth leakage currents.

### Discrimination at 3 or 4 levels (see Fig. F36)

#### Protection

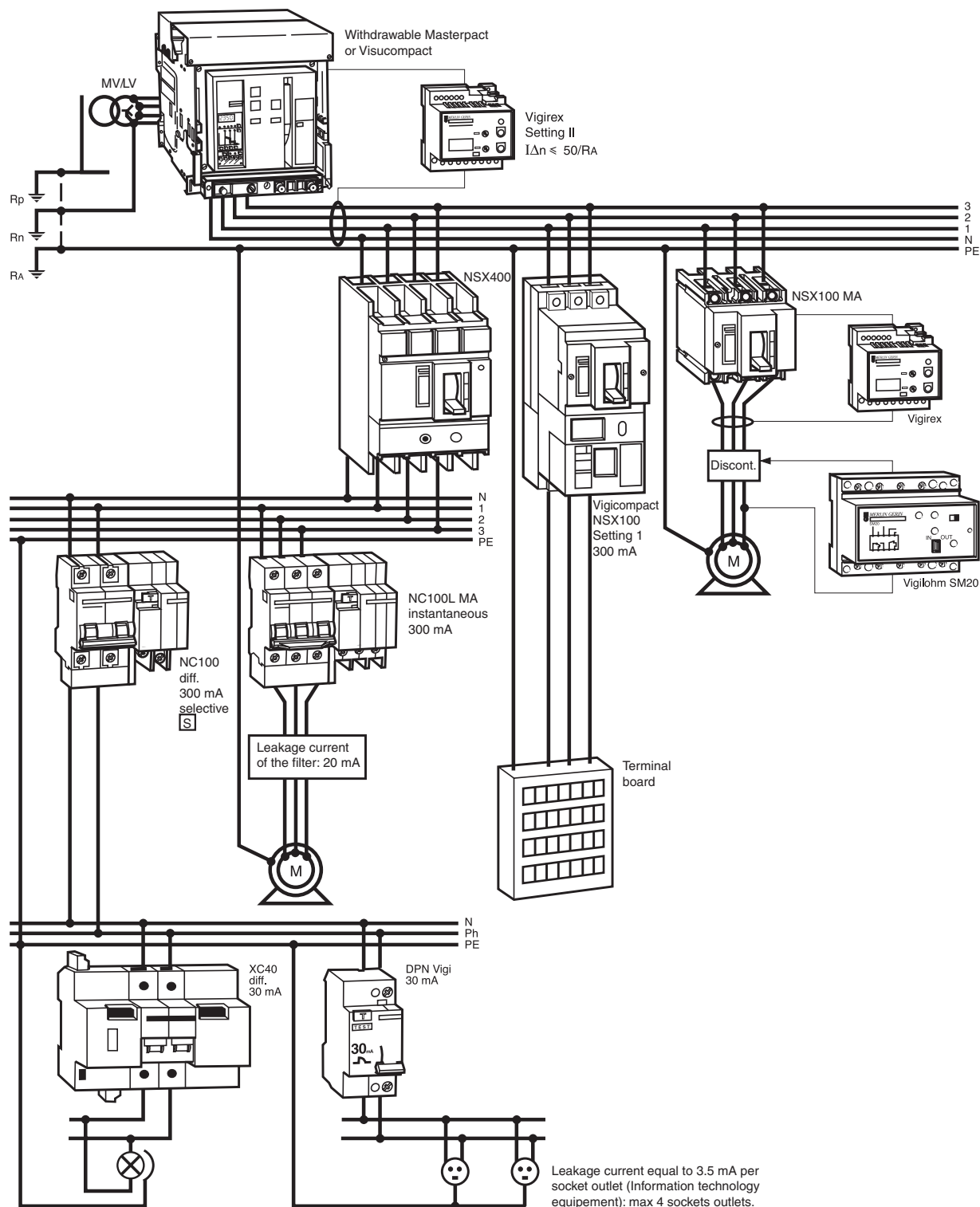
- Level A: RCD time-delayed (setting III)
- Level B: RCD time-delayed (setting II)
- Level C: RCD time-delayed (setting I) or type S
- Level D: RCD instantaneous

#### Schneider Electric solutions

- Level A: Circuit-breaker associated with RCD and separate toroidal transformer (Vigirex RH328AP)
- Level B: Vigicompact or Vigirex
- Level C: Vigirex, Vigicompact or Vigi NC100 or Vigi C60
- Level D:
  - Vigicompact or
  - Vigirex or
  - Multi 9 with integrated or adaptable RCD module : Vigi C60 or DPN Vigi

**Note:** The setting of upstream RCCB must comply with selectivity rules and take into account all the downstream earth leakage currents

## Discriminative protection at three levels (see Fig. F37)



**Fig. F37 :** Typical 3-level installation, showing the protection of distribution circuits in a TT-earthed system. One motor is provided with specific protection

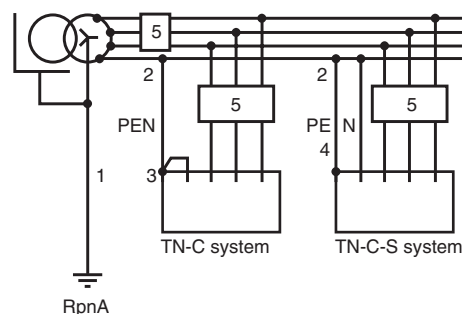
### 6.1 Preliminary conditions

At the design stage, the maximum permitted lengths of cable downstream of a protective circuit-breaker (or set of fuses) must be calculated, while during the installation work certain rules must be fully respected.

Certain conditions must be observed, as listed below and illustrated in **Figure F38**.

1. PE conductor must be regularly connected to earth as much as possible.
2. The PE conductor must not pass through ferro-magnetic conduit, ducts, etc. or be mounted on steel work, since inductive and/or proximity effects can increase the effective impedance of the conductor.
3. In the case of a PEN conductor (a neutral conductor which is also used as a protective conductor), connection must be made directly to the earth terminal of an appliance (see 3 in Figure F38) before being looped to the neutral terminal of the same appliance.
4. Where the conductor  $\leq 6 \text{ mm}^2$  for copper or  $10 \text{ mm}^2$  for aluminium, or where a cable is movable, the neutral and protective conductors should be separated (i.e. a TN-S system should be adopted within the installation).
5. Earth faults may be cleared by overcurrent-protection devices, i.e. by fuses and circuit-breakers.

The foregoing list indicates the conditions to be respected in the implementation of a TN scheme for the protection against indirect contacts.



#### Notes:

- The TN scheme requires that the LV neutral of the MV/LV transformer, the exposed conductive parts of the substation and of the installation, and the extraneous conductive parts in the substation and installation, all be earthed to a common earthing system.
- For a substation in which the metering is at low-voltage, a means of isolation is required at the origin of the LV installation, and the isolation must be clearly visible.
- A PEN conductor must never be interrupted under any circumstances. Control and protective switchgear for the several TN arrangements will be:
  - 3-pole when the circuit includes a PEN conductor,
  - Preferably 4-pole (3 phases + neutral) when the circuit includes a neutral with a separate PE conductor.

**Fig. F38** : Implementation of the TN system of earthing

### 6.2 Protection against indirect contact

#### Methods of determining levels of short-circuit current

In TN-earthed systems, a short-circuit to earth will, in principle, always provide sufficient current to operate an overcurrent device.

The source and supply mains impedances are much lower than those of the installation circuits, so that any restriction in the magnitude of earth-fault currents will be mainly caused by the installation conductors (long flexible leads to appliances greatly increase the "fault-loop" impedance, with a corresponding reduction of short-circuit current).

The most recent IEC recommendations for indirect-contact protection on TN earthing systems only relates maximum allowable tripping times to the nominal system voltage (see Figure F12 in Sub-clause 3.3).

Three methods of calculation are commonly used:

- The method of impedances, based on the trigonometric addition of the system resistances and inductive reactances
- The method of composition
- The conventional method, based on an assumed voltage drop and the use of prepared tables

*For calculations, modern practice is to use software agreed by National Authorities, and based on the method of impedances, such as Ecodial 3. National Authorities generally also publish Guides, which include typical values, conductor lengths, etc.*

The reasoning behind these recommendations is that, for TN systems, the current which must flow in order to raise the potential of an exposed conductive part to 50 V or more is so high that one of two possibilities will occur:

- Either the fault path will blow itself clear, practically instantaneously, or
- The conductor will weld itself into a solid fault and provide adequate current to operate overcurrent devices

To ensure correct operation of overcurrent devices in the latter case, a reasonably accurate assessment of short-circuit earth-fault current levels must be determined at the design stage of a project.

A rigorous analysis requires the use of phase-sequence-component techniques applied to every circuit in turn. The principle is straightforward, but the amount of computation is not considered justifiable, especially since the zero-phase-sequence impedances are extremely difficult to determine with any reasonable degree of accuracy in an average LV installation.

Other simpler methods of adequate accuracy are preferred. Three practical methods are:

- The “**method of impedances**”, based on the summation of all the impedances (positive-phase-sequence only) around the fault loop, for each circuit
- The “**method of composition**”, which is an estimation of short-circuit current at the remote end of a loop, when the short-circuit current level at the near end of the loop is known
- The “**conventional method**” of calculating the minimum levels of earth-fault currents, together with the use of tables of values for obtaining rapid results

These methods are only reliable for the case in which the cables that make up the earth-fault-current loop are in close proximity (to each other) and not separated by ferro-magnetic materials.

### Method of impedances

This method summates the positive-sequence impedances of each item (cable, PE conductor, transformer, etc.) included in the earth-fault loop circuit from which the short-circuit earth-fault current is calculated, using the formula:

$$I = \frac{U}{\sqrt{(\sum R)^2 + (\sum X)^2}}$$

where

$(\sum R)^2$  = (the sum of all resistances in the loop)<sup>2</sup> at the design stage of a project.

and  $(\sum X)^2$  = (the sum of all inductive reactances in the loop)<sup>2</sup>

and U = nominal system phase-to-neutral voltage.

The application of the method is not always easy, because it supposes a knowledge of all parameter values and characteristics of the elements in the loop. In many cases, a national guide can supply typical values for estimation purposes.

### Method of composition

This method permits the determination of the short-circuit current at the end of a loop from the known value of short-circuit at the sending end, by means of the approximate formula:

$$I = I_{sc} \frac{U}{U + Z_s \cdot I_{sc}}$$

where

$I_{sc}$  = upstream short-circuit current

I = end-of-loop short-circuit current

U = nominal system phase voltage

$Z_s$  = impedance of loop

**Note:** in this method the individual impedances are added arithmetically<sup>(1)</sup> as opposed to the previous “method of impedances” procedure.

### Conventional method

This method is generally considered to be sufficiently accurate to fix the upper limit of cable lengths.

#### Principle

The principle bases the short-circuit current calculation on the assumption that the voltage at the origin of the circuit concerned (i.e. at the point at which the circuit protective device is located) remains at 80% or more of the nominal phase to neutral voltage. The 80% value is used, together with the circuit loop impedance, to compute the short-circuit current.

(1) This results in a calculated current value which is less than that it would actually flow. If the overcurrent settings are based on this calculated value, then operation of the relay, or fuse, is assured.

The maximum length of any circuit of a TN-earthed installation is:  $\frac{0.8 U_0 S_{ph}}{\rho(1+m)I_a}$

The following tables give the length of circuit which must not be exceeded, in order that persons be protected against indirect contact hazards by protective devices

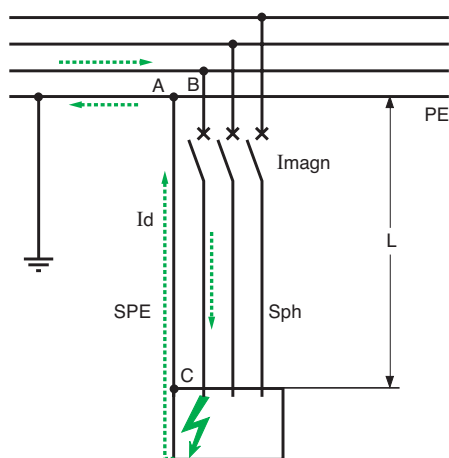


Fig. F39 : Calculation of  $L_{max}$  for a TN-earthed system, using the conventional method

This coefficient takes account of all voltage drops upstream of the point considered. In LV cables, when all conductors of a 3-phase 4-wire circuit are in close proximity (which is the normal case), the inductive reactance internal to and between conductors is negligibly small compared to the cable resistance.

This approximation is considered to be valid for cable sizes up to 120 mm<sup>2</sup>.

Above that size, the resistance value R is increased as follows:

Core size (mm <sup>2</sup> )	Value of resistance
S = 150 mm <sup>2</sup>	R+15%
S = 185 mm <sup>2</sup>	R+20%
S = 240 mm <sup>2</sup>	R+25%

The maximum length of a circuit in a TN-earthed installation is given by the formula:

$$L_{max} = \frac{0.8 U_0 S_{ph}}{\rho(1+m)I_a}$$

where:

$L_{max}$  = maximum length in metres

$U_0$  = phase volts = 230 V for a 230/400 V system

$\rho$  = resistivity at normal working temperature in ohm-mm<sup>2</sup>/metre  
(= 22.5 10<sup>-3</sup> for copper; = 36 10<sup>-3</sup> for aluminium)

$I_a$  = trip current setting for the instantaneous operation of a circuit-breaker, or

$I_a$  = the current which assures operation of the protective fuse concerned, in the specified time.

$$m = \frac{S_{ph}}{S_{PE}}$$

$S_{ph}$  = cross-sectional area of the phase conductors of the circuit concerned in mm<sup>2</sup>

$S_{PE}$  = cross-sectional area of the protective conductor concerned in mm<sup>2</sup>.

(see Fig. F39)

### Tables

The following tables, applicable to TN systems, have been established according to the "conventional method" described above.

The tables give maximum circuit lengths, beyond which the ohmic resistance of the conductors will limit the magnitude of the short-circuit current to a level below that required to trip the circuit-breaker (or to blow the fuse) protecting the circuit, with sufficient rapidity to ensure safety against indirect contact.

#### Correction factor m

Figure F40 indicates the correction factor to apply to the values given in Figures F41 to F44 next pages, according to the ratio  $S_{ph}/S_{PE}$ , the type of circuit, and the conductor materials.

The tables take into account:

- The type of protection: circuit-breakers or fuses
- Operating-current settings
- Cross-sectional area of phase conductors and protective conductors
- Type of system earthing (see Fig. F45 page F27)
- Type of circuit-breaker (i.e. B, C or D)<sup>(1)</sup>

The tables may be used for 230/400 V systems.

Equivalent tables for protection by Compact and Multi 9 circuit-breakers (Merlin Gerin) are included in the relevant catalogues.

Circuit	Conductor material	m = $S_{ph}/S_{PE}$ (or PEN)			
		m = 1	m = 2	m = 3	m = 4
3P + N or P + N	Copper	1	0.67	0.50	0.40
	Aluminium	0.62	0.42	0.31	0.25

Fig. F40 : Correction factor to apply to the lengths given in tables F40 to F43 for TN systems

(1) For the definition of type B, C, D circuit-breakers, refer to chapter H, clause 4.2

Circuits protected by general purpose circuit-breakers (Fig. F41)

Nominal cross-sectional area of conductors	Instantaneous or short-time-delayed tripping current Im (amperes)																														
	mm²	50	63	80	100	125	160	200	250	320	400	500	560	630	700	800	875	1000	1120	1250	1600	2000	2500	3200	4000	5000	6300	8000	10000	12500	
1.5	100	79	63	50	40	31	25	20	16	13	10	9	8	7	6	6	5	4	4												
2.5	167	133	104	83	67	52	42	33	26	21	17	15	13	12	10	10	8	7	7	5	4										
4	267	212	167	133	107	83	67	53	42	33	27	24	21	19	17	15	13	12	11	8	7	5	4								
6	400	317	250	200	160	125	100	80	63	50	40	36	32	29	25	23	20	18	16	13	10	8	6	5	4						
10			417	333	267	208	167	133	104	83	67	60	53	48	42	38	33	30	27	21	17	13	10	8	7	5	4				
16					427	333	267	213	167	133	107	95	85	76	67	61	53	48	43	33	27	21	17	13	11	8	7	5	4		
25						417	333	260	208	167	149	132	119	104	95	83	74	67	52	42	33	26	21	17	13	10	8	7	5	4	
35							467	365	292	233	208	185	167	146	133	117	104	93	73	58	47	36	29	23	19	15	12	9			
50								495	396	317	283	251	226	198	181	158	141	127	99	79	63	49	40	32	25	20	16	13			
70									417	370	333	292	267	233	208	187	146	117	93	73	58	47	37	29	23	19					
95										452	396	362	317	283	263	198	158	127	99	79	63	50	40	32	25						
120															457	400	357	320	250	200	160	125	100	80	63	50	40	32			
150																435	388	348	272	217	174	136	109	87	69	54	43	35			
185																	459	411	321	257	206	161	128	103	82	64	51	41			
240																			400	320	256	200	160	128	102	80	64	51			

**Fig. F41** : Maximum circuit lengths (in metres) for different sizes of copper conductor and instantaneous-tripping-current settings for general-purpose circuit-breakers in 230/240 V TN system with  $m = 1$

Circuits protected by Compact or Multi 9 circuit-breakers for industrial or domestic use (Fig. F42 to Fig. F44)

Sph	Rated current (A)															
mm²	1	2	3	4	6	10	16	20	25	32	40	50	63	80	100	125
1.5	1200	600	400	300	200	120	75	60	48	37	30	24	19	15	12	10
2.5		1000	666	500	333	200	125	100	80	62	50	40	32	25	20	16
4			1066	800	533	320	200	160	128	100	80	64	51	40	32	26
6				1200	800	480	300	240	192	150	120	96	76	60	48	38
10						800	500	400	320	250	200	160	127	100	80	64
16							800	640	512	400	320	256	203	160	128	102
25									800	625	500	400	317	250	200	160
35										875	700	560	444	350	280	224
50												760	603	475	380	304

**Fig. F42** : Maximum circuit lengths (in meters) for different sizes of copper conductor and rated currents for type B<sup>(1)</sup> circuit-breakers in a 230/240 V single-phase or three-phase TN system with  $m = 1$

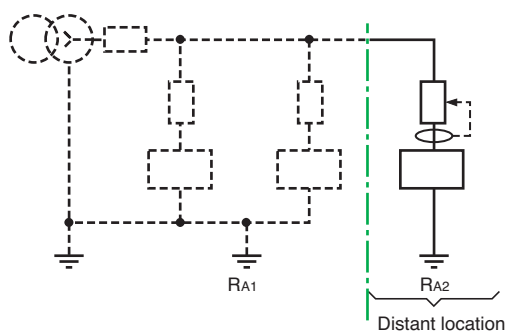
Sph mm <sup>2</sup>	Rated current (A)															
	1	2	3	4	6	10	16	20	25	32	40	50	63	80	100	125
1.5	600	300	200	150	100	60	37	30	24	18	15	12	9	7	6	5
2.5		500	333	250	167	100	62	50	40	31	25	20	16	12	10	8
4			533	400	267	160	100	80	64	50	40	32	25	20	16	13
6				600	400	240	150	120	96	75	60	48	38	30	24	19
10					667	400	250	200	160	125	100	80	63	50	40	32
16						640	400	320	256	200	160	128	101	80	64	51
25							625	500	400	312	250	200	159	125	100	80
35							875	700	560	437	350	280	222	175	140	112
50									760	594	475	380	301	237	190	152

**Fig. F43** : Maximum circuit lengths (in metres) for different sizes of copper conductor and rated currents for type C<sup>(1)</sup> circuit-breakers in a 230/240 V single-phase or three-phase TN system with  $m = 1$

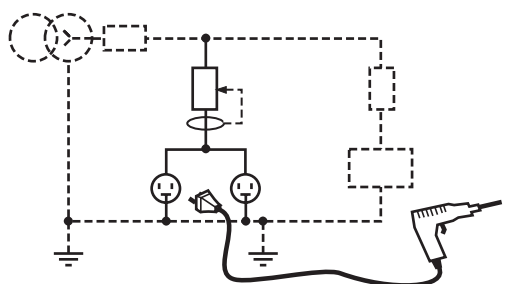
(1) For the definition of type B and C circuit-breakers refer to chapter H clause 4.2.

Sph mm <sup>2</sup>	Rated current (A)															
	1	2	3	4	6	10	16	20	25	32	40	50	63	80	100	125
1.5	429	214	143	107	71	43	27	21	17	13	11	9	7	5	4	3
2.5	714	357	238	179	119	71	45	36	29	22	18	14	11	9	7	6
4		571	381	286	190	114	71	80	46	36	29	23	18	14	11	9
6		857	571	429	286	171	107	120	69	54	43	34	27	21	17	14
10			952	714	476	286	179	200	114	89	71	57	45	36	29	23
16					762	457	286	320	183	143	114	91	73	57	46	37
25						714	446	500	286	223	179	143	113	89	71	57
35							625	700	400	313	250	200	159	125	80	100
50								848	543	424	339	271	215	170	136	109

**Fig. F44** : Maximum circuit lengths (in metres) for different sizes of copper conductor and rated currents for type D<sup>(1)</sup> circuit-breakers in a 230/240 V single-phase or three-phase TN system with  $m = 1$



**Fig. F45** : Separate earth electrode



**Fig. F46** : Circuit supplying socket-outlets

### Example

A 3-phase 4-wire (230/400 V) installation is TN-C earthed. A circuit is protected by a type B circuit-breaker rated at 63 A, and consists of an aluminium cored cable with 50 mm<sup>2</sup> phase conductors and a neutral conductor (PEN) of 25 mm<sup>2</sup>.

What is the maximum length of circuit, below which protection of persons against indirect-contact hazards is assured by the instantaneous magnetic tripping relay of the circuit-breaker?

Figure F42 gives, for 50 mm<sup>2</sup> and a 63 A type B circuit-breaker, 603 metres, to which must be applied a factor of 0.42 (Figure F40 for  $m = \frac{S_{ph}}{S_{PE}} = 2$ ).

The maximum length of circuit is therefore:

$603 \times 0.42 = 253$  metres.

### Particular case where one or more exposed conductive part(s) is (are) earthed to a separate earth electrode

Protection must be provided against indirect contact by a RCD at the origin of any circuit supplying an appliance or group of appliances, the exposed conductive parts of which are connected to an independent earth electrode.

The sensitivity of the RCD must be adapted to the earth electrode resistance (RA2 in Figure F45). See specifications applicable to TT system.

### 6.3 High-sensitivity RCDs (see Fig. F31)

According to IEC 60364-4-41, high sensitivity RCDs ( $\leq 30$  mA) must be used for protection of socket outlets with rated current  $\leq 20$  A in all locations. The use of such RCDs is also recommended in the following cases:

- Socket-outlet circuits in wet locations at all current ratings
  - Socket-outlet circuits in temporary installations
  - Circuits supplying laundry rooms and swimming pools
  - Supply circuits to work-sites, caravans, pleasure boats, and travelling fairs
- See 2.2 and chapter P, al section 3.

(1) For the definition of type D circuit-breaker refer to chapter H Sub-clause 4.2.

F28

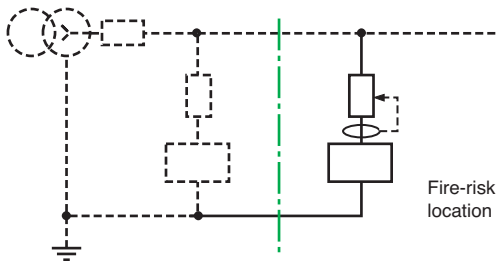


Fig. F47 : Fire-risk location

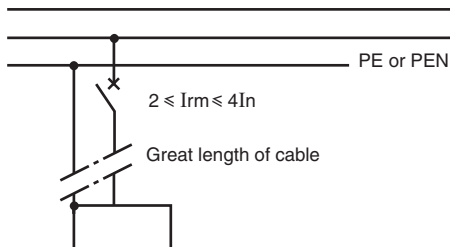


Fig. F48 : Circuit-breaker with low-set instantaneous magnetic tripping

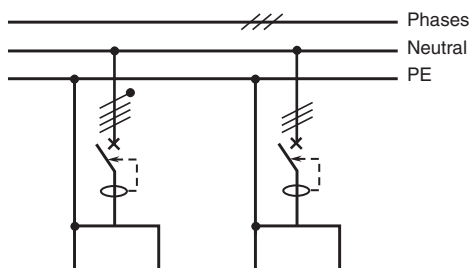


Fig. F49 : RCD protection on TN systems with high earth-fault-loop impedance

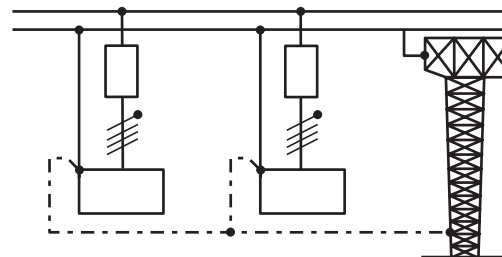


Fig. F50 : Improved equipotential bonding

## 6.4 Protection in high fire-risk location

According to IEC 60364-422-3.10, circuits in high fire-risk locations must be protected by RCDs of sensitivity  $\leq 500$  mA. This excludes the TN-C arrangement and TN-S must be adopted.

A preferred sensitivity of 300 mA is mandatory in some countries (see Fig. F47).

## 6.5 When the fault current-loop impedance is particularly high

When the earth-fault current is limited due to an inevitably high fault-loop impedance, so that the overcurrent protection cannot be relied upon to trip the circuit within the prescribed time, the following possibilities should be considered:

### Suggestion 1 (see Fig. F48)

■ Install a circuit-breaker which has a lower instantaneous magnetic tripping level, for example:

$$2I_n \leq I_{rm} \leq 4I_n$$

This affords protection for persons on circuits which are abnormally long. It must be checked, however, that high transient currents such as the starting currents of motors will not cause nuisance trip-outs.

### ■ Schneider Electric solutions

□ Type G Compact ( $2I_n \leq I_{rm} \leq 4I_n$ )

□ Type B Multi 9 circuit-breaker

### Suggestion 2 (see Fig. F49)

■ Install a RCD on the circuit. The device does not need to be highly-sensitive (HS) (several amps to a few tens of amps). Where socket-outlets are involved, the particular circuits must, in any case, be protected by HS ( $\leq 30$  mA) RCDs; generally one RCD for a number of socket outlets on a common circuit.

### ■ Schneider Electric solutions

□ RCD Multi 9 NG125 :  $I_{\Delta n} = 1$  or 3 A

□ Vigicompact REH or REM:  $I_{\Delta n} = 3$  to 30 A

□ Type B Multi 9 circuit-breaker

### Suggestion 3

Increase the size of the PE or PEN conductors and/or the phase conductors, to reduce the loop impedance.

### Suggestion 4

Add supplementary equipotential conductors. This will have a similar effect to that of suggestion 3, i.e. a reduction in the earth-fault-loop resistance, while at the same time improving the existing touch-voltage protection measures. The effectiveness of this improvement may be checked by a resistance test between each exposed conductive part and the local main protective conductor.

For TN-C installations, bonding as shown in Figure F50 is not allowed, and suggestion 3 should be adopted.



The basic feature of the IT earthing system is that, in the event of a short-circuit to earth fault, the system can continue to operate without interruption. Such a fault is referred to as a "first fault".

In this system, all exposed conductive parts of an installation are connected via PE conductors to an earth electrode at the installation, while the neutral point of the supply transformer is:

- Either isolated from earth
- Or connected to earth through a high resistance (commonly 1,000 ohms or more)

This means that the current through an earth fault will be measured in milli-amps, which will not cause serious damage at the fault position, or give rise to dangerous touch voltages, or present a fire hazard. The system may therefore be allowed to operate normally until it is convenient to isolate the faulty section for repair work. This enhances continuity of service.

In practice, the system earthing requires certain specific measures for its satisfactory exploitation:

- Permanent monitoring of the insulation with respect to earth, which must signal (audibly or visually) the occurrence of the first fault
- A device for limiting the voltage which the neutral point of the supply transformer can reach with respect to earth
- A "first-fault" location routine by an efficient maintenance staff. Fault location is greatly facilitated by automatic devices which are currently available
- Automatic high-speed tripping of appropriate circuit-breakers must take place in the event of a "second fault" occurring before the first fault is repaired. The second fault (by definition) is an earth fault affecting a different live conductor than that of the first fault (can be a phase or neutral conductor)<sup>(1)</sup>.

The second fault results in a short-circuit through the earth and/or through PE bonding conductors.

F29

## 7.1 Preliminary conditions (see Fig. F51 and Fig. F52)

Minimum functions required	Components and devices	Examples
Protection against overvoltages at power frequency	(1) Voltage limiter	Cardew C
Neutral earthing resistor (for impedance earthing variation)	(2) Resistor	Impedance Zx
Overall earth-fault monitor with alarm for first fault condition	(3) Permanent insulation monitor PIM with alarm feature	Vigilohm TR22A or XM 200
Automatic fault clearance on second fault and protection of the neutral conductor against overcurrent	(4) Four-pole circuit-breakers (if the neutral is distributed) all 4 poles trip	Compact circuit-breaker or RCD-MS
Location of first fault	(5) With device for fault-location on live system, or by successive opening of circuits	Vigilohm system

Fig. F51 : Essential functions in IT schemes and examples with Merlin Gerin products

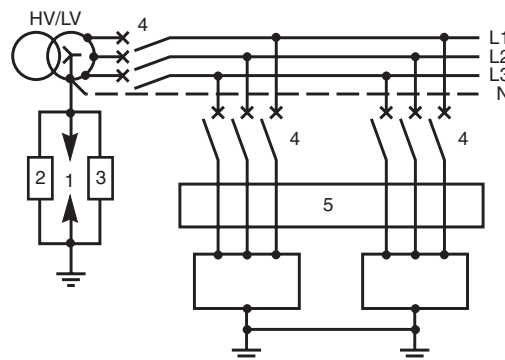


Fig. F52 : Positions of essential functions in 3-phase 3-wire IT-earthed system

(1) On systems where the neutral is distributed, as shown in Figure F56.

Modern monitoring systems greatly facilitate first-fault location and repair

F30

Fault-location systems comply with IEC 61157-9 standard

## 7.2 Protection against indirect contact

### First-fault condition

The earth-fault current which flows under a first-fault condition is measured in milliamps.

The fault voltage with respect to earth is the product of this current and the resistance of the installation earth electrode and PE conductor (from the faulted component to the electrode). This value of voltage is clearly harmless and could amount to several volts only in the worst case (1,000  $\Omega$  earthing resistor will pass 230 mA<sup>(1)</sup> and a poor installation earth-electrode of 50 ohms, would give 11.5 V, for example).

An alarm is given by the permanent insulation monitoring device.

### Principle of earth-fault monitoring

A generator of very low frequency a.c. current, or of d.c. current, (to reduce the effects of cable capacitance to negligible levels) applies a voltage between the neutral point of the supply transformer and earth. This voltage causes a small current to flow according to the insulation resistance to earth of the whole installation, plus that of any connected appliance.

Low-frequency instruments can be used on a.c. systems which generate transient d.c. components under fault conditions. Certain versions can distinguish between resistive and capacitive components of the leakage current.

Modern equipment allow the measurement of leakage-current evolution, so that prevention of a first fault can be achieved.

### Examples of equipment

#### ■ Manual fault-location (see Fig. F53)

The generator may be fixed (example: XM100) or portable (example: GR10X) permitting the checking of dead circuits) and the receiver, together with the magnetic clamp-type pick-up sensor, are portable.

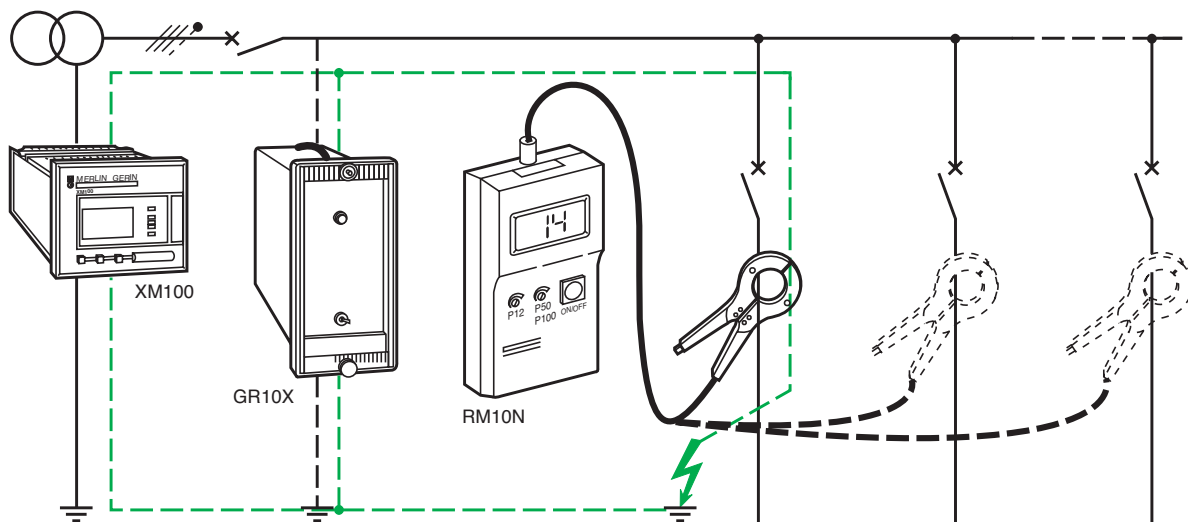


Fig. F53 : Non-automatic (manual) fault location

#### ■ Fixed automatic fault location (see Fig. F54 next page)

The monitoring relay XM100, together with the fixed detectors XD1 or XD12 (each connected to a toroidal CT embracing the conductors of the circuit concerned) provide a system of automatic fault location on a live installation.

Moreover, the level of insulation is indicated for each monitored circuit, and two levels are checked: the first level warns of unusually low insulation resistance so that preventive measures may be taken, while the second level indicates a fault condition and gives an alarm.

(1) On a 230/400 V 3-phase system.

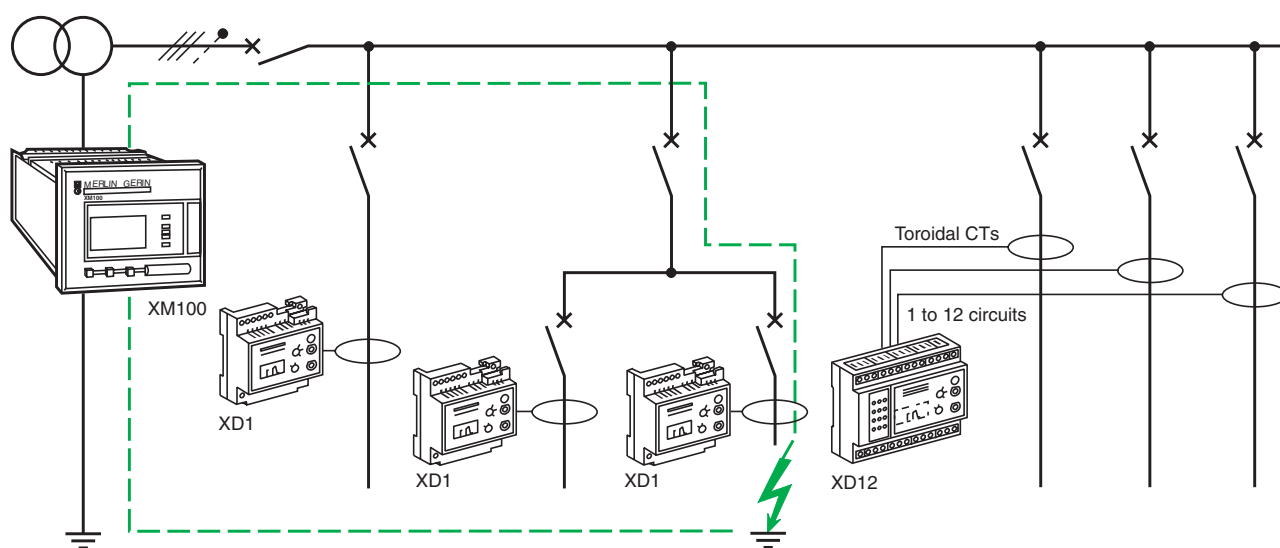


Fig. F54 : Fixed automatic fault location

■ Automatic monitoring, logging, and fault location (see Fig. F55)

The Vigilohm System also allows access to a printer and/or a PC which provides a global review of the insulation level of an entire installation, and records the chronological evolution of the insulation level of each circuit.

The central monitor XM100, together with the localization detectors XD08 and XD16, associated with toroidal CTs from several circuits, as shown below in Figure F55, provide the means for this automatic exploitation.

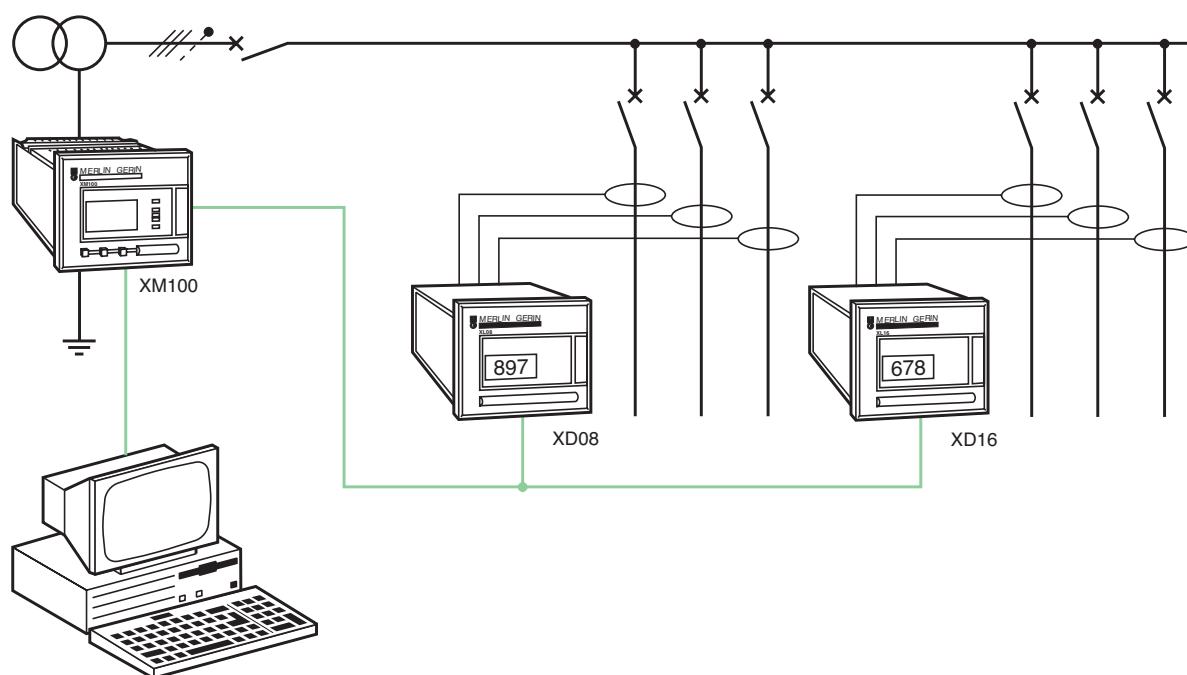


Fig. F55 : Automatic fault location and insulation-resistance data logging

**Implementation of permanent insulation-monitoring (PIM) devices****■ Connection**

The PIM device is normally connected between the neutral (or artificial neutral) point of the power-supply transformer and its earth electrode.

**■ Supply**

Power supply to the PIM device should be taken from a highly reliable source. In practice, this is generally directly from the installation being monitored, through overcurrent protective devices of suitable short-circuit current rating.

**■ Level settings**

Certain national standards recommend a first setting at 20% below the insulation level of the new installation. This value allows the detection of a reduction of the insulation quality, necessitating preventive maintenance measures in a situation of incipient failure.

The detection level for earth-fault alarm will be set at a much lower level.

By way of an example, the two levels might be:

- New installation insulation level: 100 k $\Omega$
- Leakage current without danger: 500 mA (fire risk at > 500 mA)
- Indication levels set by the consumer:
  - Threshold for preventive maintenance:  $0.8 \times 100 = 80 \text{ k}\Omega$
  - Threshold for short-circuit alarm: 500  $\Omega$

**Notes:**

- Following a long period of shutdown, during which the whole, or part of the installation remains de-energized, humidity can reduce the general level of insulation resistance. This situation, which is mainly due to leakage current over the damp surface of healthy insulation, does not constitute a fault condition, and will improve rapidly as the normal temperature rise of current-carrying conductors reduces the surface humidity.
- The PIM device (XM) can measure separately the resistive and the capacitive current components of the leakage current to earth, thereby deriving the true insulation resistance from the total permanent leakage current.

**The case of a second fault**

A second earth fault on an IT system (unless occurring on the same conductor as the first fault) constitutes a phase-phase or phase-to-neutral fault, and whether occurring on the same circuit as the first fault, or on a different circuit, overcurrent protective devices (fuses or circuit-breakers) would normally operate an automatic fault clearance.

The settings of overcurrent tripping relays and the ratings of fuses are the basic parameters that decide the maximum practical length of circuit that can be satisfactorily protected, as discussed in Sub-clause 6.2.

**Note:** In normal circumstances, the fault current path is through common PE conductors, bonding all exposed conductive parts of an installation, and so the fault loop impedance is sufficiently low to ensure an adequate level of fault current.

Where circuit lengths are unavoidably long, and especially if the appliances of a circuit are earthed separately (so that the fault current passes through two earth electrodes), reliable tripping on overcurrent may not be possible.

In this case, an RCD is recommended on each circuit of the installation.

Where an IT system is resistance earthed, however, care must be taken to ensure that the RCD is not too sensitive, or a first fault may cause an unwanted trip-out. Tripping of residual current devices which satisfy IEC standards may occur at values of  $0.5 I_{\Delta n}$  to  $I_{\Delta n}$ , where  $I_{\Delta n}$  is the nominal residual-current setting level.

**Methods of determining levels of short-circuit current**

A reasonably accurate assessment of short-circuit current levels must be carried out at the design stage of a project.

A rigorous analysis is not necessary, since current magnitudes only are important for the protective devices concerned (i.e. phase angles need not be determined) so that simplified conservatively approximate methods are normally used. Three practical methods are:

- The **method of impedances**, based on the vectorial summation of all the (positive-phase-sequence) impedances around a fault-current loop
- The **method of composition**, which is an approximate estimation of short-circuit current at the remote end of a loop, when the level of short-circuit current at the near end of the loop is known. Complex impedances are combined arithmetically in this method
- The **conventional method**, in which the minimum value of voltage at the origin of a faulty circuit is assumed to be 80% of the nominal circuit voltage, and tables are used based on this assumption, to give direct readings of circuit lengths.

*Three methods of calculation are commonly used:*

- *The method of impedances, based on the trigonometric addition of the system resistances and inductive reactances*
- *The method of composition*
- *The conventional method, based on an assumed voltage drop and the use of prepared tables*

The software Ecodial is based on the "method of impedance"

The maximum length of an IT earthed circuit is:

■ For a 3-phase 3-wire scheme

$$L_{\max} = \frac{0.8 U_0 \sqrt{3} S_{ph}}{2 \rho I_a (1+m)}$$

■ For a 3-phase 4-wire scheme

$$L_{\max} = \frac{0.8 U_0 S_1}{2 \rho I_a (1+m)}$$

These methods are reliable only for the cases in which wiring and cables which make up the fault-current loop are in close proximity (to each other) and are not separated by ferro-magnetic materials.

#### Methods of impedances

This method as described in Sub-clause 6.2, is identical for both the IT and TN systems of earthing.

#### Methods of composition

This method as described in Sub-clause 6.2, is identical for both the IT and TN systems of earthing.

#### Conventional method (see Fig. F56)

The principle is the same for an IT system as that described in Sub-clause 6.2 for a TN system : the calculation of maximum circuit lengths which should not be exceeded downstream of a circuit-breaker or fuses, to ensure protection by overcurrent devices.

It is clearly impossible to check circuit lengths for every feasible combination of two concurrent faults.

All cases are covered, however, if the overcurrent trip setting is based on the assumption that a first fault occurs at the remote end of the circuit concerned, while the second fault occurs at the remote end of an identical circuit, as already mentioned in Sub-clause 3.4. This may result, in general, in one trip-out only occurring (on the circuit with the lower trip-setting level), thereby leaving the system in a first-fault situation, but with one faulty circuit switched out of service.

■ For the case of a 3-phase 3-wire installation the second fault can only cause a phase/phase short-circuit, so that the voltage to use in the formula for maximum circuit length is  $\sqrt{3} U_0$ .

The maximum circuit length is given by:

$$L_{\max} = \frac{0.8 U_0 \sqrt{3} S_{ph}}{2 \rho I_a (1+m)} \text{ metres}$$

■ For the case of a 3-phase 4-wire installation the lowest value of fault current will occur if one of the faults is on a neutral conductor. In this case,  $U_0$  is the value to use for computing the maximum cable length, and

$$L_{\max} = \frac{0.8 U_0 S_1}{2 \rho I_a (1+m)} \text{ metres}$$

i.e. 50% only of the length permitted for a TN scheme <sup>(1)</sup>

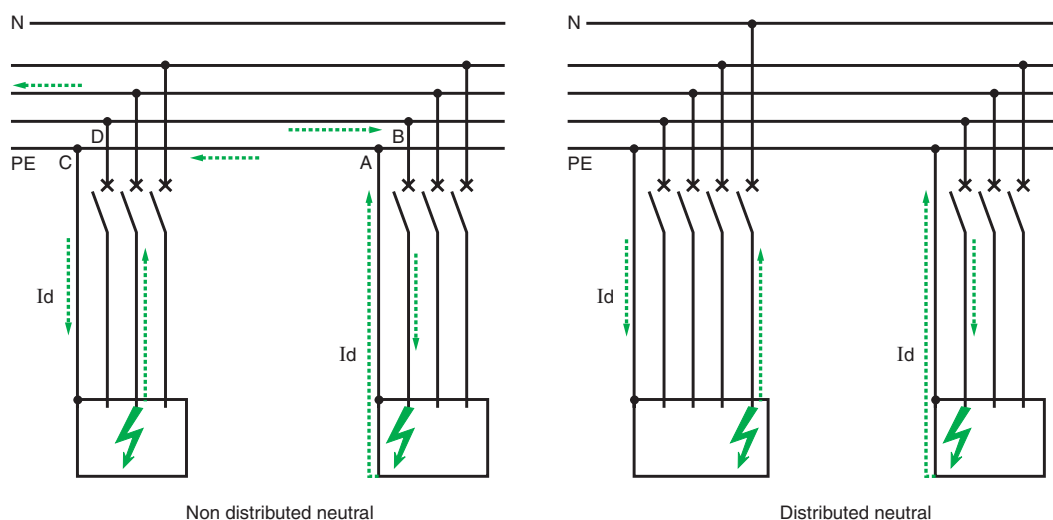


Fig. F56 : Calculation of  $L_{\max}$  for an IT-earthed system, showing fault-current path for a double-fault condition

(1) Reminder: There is no length limit for earth-fault protection on a TT scheme, since protection is provided by RCDs of high sensitivity.

F34

The following tables<sup>(1)</sup> give the length of circuit which must not be exceeded, in order that persons be protected against indirect contact hazards by protective devices

In the preceding formulae:

$L_{\max}$  = longest circuit in metres

$U_0$  = phase-to-neutral voltage (230 V on a 230/400 V system)

$\rho$  = resistivity at normal operating temperature ( $22.5 \times 10^{-3}$  ohms-mm<sup>2</sup>/m for copper,  $36 \times 10^{-3}$  ohms-mm<sup>2</sup>/m for aluminium)

$I_a$  = overcurrent trip-setting level in amps, or  $I_a$  = current in amps required to clear the fuse in the specified time

$$m = \frac{S_{ph}}{S_{PE}}$$

$S_{PE}$  = cross-sectional area of PE conductor in mm<sup>2</sup>

$S_1$  = S neutral if the circuit includes a neutral conductor

$S_1$  =  $S_{ph}$  if the circuit does not include a neutral conductor

### Tables

The following tables have been established according to the "conventional method" described above.

The tables give maximum circuit lengths, beyond which the ohmic resistance of the conductors will limit the magnitude of the short-circuit current to a level below that required to trip the circuit-breaker (or to blow the fuse) protecting the circuit, with sufficient rapidity to ensure safety against indirect contact. The tables take into account:

- The type of protection: circuit-breakers or fuses, operating-current settings
- Cross-sectional area of phase conductors and protective conductors
- Type of earthing scheme
- Correction factor: **Figure F57** indicates the correction factor to apply to the lengths given in tables F40 to F43, when considering an IT system

Circuit	Conductor material	m = $S_{ph}/S_{PE}$ (or PEN)			
		m = 1	m = 2	m = 3	m = 4
3 phases	Copper	0.86	0.57	0.43	0.34
	Aluminium	0.54	0.36	0.27	0.21
3ph + N or 1ph + N	Copper	0.50	0.33	0.25	0.20
	Aluminium	0.31	0.21	0.16	0.12

**Fig. F57** : Correction factor to apply to the lengths given in tables F41 to F44 for TN systems

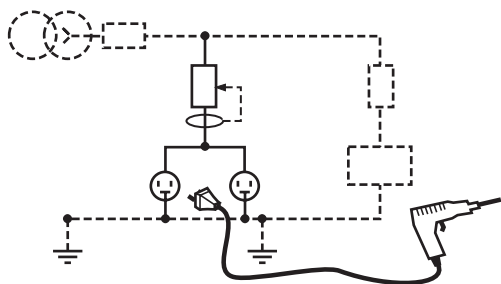
### Example

A 3-phase 3-wire 230/400 V installation is IT-earthed.

One of its circuits is protected by a circuit-breaker rated at 63 A, and consists of an aluminium-cored cable with 50 mm<sup>2</sup> phase conductors. The 25 mm<sup>2</sup> PE conductor is also aluminium. What is the maximum length of circuit, below which protection of persons against indirect-contact hazards is assured by the instantaneous magnetic tripping relay of the circuit-breaker?

Figure F42 indicates 603 metres, to which must be applied a correction factor of 0.36 ( $m = 2$  for aluminium cable).

The maximum length is therefore 217 metres.



**Fig. F62** : Circuit supplying socket-outlets

## 7.3 High-sensitivity RCDs

According to IEC 60364-4-41, high sensitivity RCDs ( $\leq 30$  mA) must be used for protection of socket outlets with rated current  $\leq 20$  A in all locations. The use of such RCDs is also recommended in the following cases:

- Socket-outlet circuits in wet locations at all current ratings
  - Socket-outlet circuits in temporary installations
  - Circuits supplying laundry rooms and swimming pools
  - Supply circuits to work-sites, caravans, pleasure boats, and travelling fairs
- See 2.2 and chapter P, al section 3

(1) The tables are those shown in Sub-clause 6.2 (Figures F41 to F44). However, the table of correction factors (Figure F57) which takes into account the ratio  $S_{ph}/S_{PE}$ , and of the type of circuit (3-ph 3-wire; 3-ph 4-wire; 1-ph 2-wire) as well as conductor material, is specific to the IT system, and differs from that for TN.

## 7.4 Protection in high fire-risk locations

Protection by a RCD of sensitivity  $\leq 500$  mA at the origin of the circuit supplying the fire-risk locations is mandatory in some countries (see Fig. F59).

A preferred sensitivity of 300 mA may be adopted.

## 7.5 When the fault current-loop impedance is particularly high

When the earth-fault current is restricted due to an inevitably high fault-loop impedance, so that the overcurrent protection cannot be relied upon to trip the circuit within the prescribed time, the following possibilities should be considered:

### Suggestion 1 (see Fig. F60)

■ Install a circuit-breaker which has an instantaneous magnetic tripping element with an operation level which is lower than the usual setting, for example:

$$2I_n \leq I_{rm} \leq 4I_n$$

This affords protection for persons on circuits which are abnormally long. It must be checked, however, that high transient currents such as the starting currents of motors will not cause nuisance trip-outs.

#### ■ Schneider Electric solutions

- Compact NSX with G trip unit or Micrologic trip unit ( $2I_n \leq I_{rm} \leq 4I_n$ )
- Type B Multi 9 circuit-breaker

### Suggestion 2 (see Fig. F61)

Install a RCD on the circuit. The device does not need to be highly-sensitive (HS) (several amps to a few tens of amps). Where socket-outlets are involved, the particular circuits must, in any case, be protected by HS ( $\leq 30$  mA) RCDs; generally one RCD for a number of socket outlets on a common circuit.

#### ■ Schneider Electric solutions

- RCD Multi 9 NG125 :  $I_{\Delta n} = 1$  or 3 A
- Vigicompact MH or ME:  $I_{\Delta n} = 3$  to 30 A

### Suggestion 3

Increase the size of the PE conductors and/or the phase conductors, to reduce the loop impedance.

### Suggestion 4 (see Fig. F62)

Add supplementary equipotential conductors. This will have a similar effect to that of suggestion 3, i.e. a reduction in the earth-fault-loop resistance, while at the same time improving the existing touch-voltage protection measures. The effectiveness of this improvement may be checked by a resistance test between each exposed conductive part and the local main protective conductor.

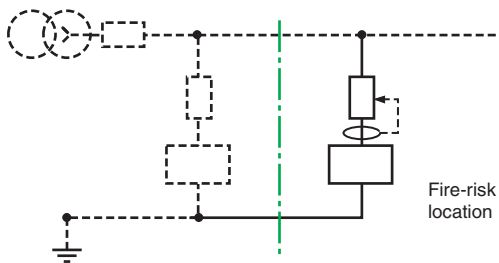


Fig. F59 : Fire-risk location

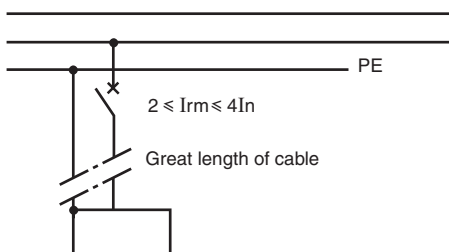


Fig. F60 : A circuit-breaker with low-set instantaneous magnetic trip

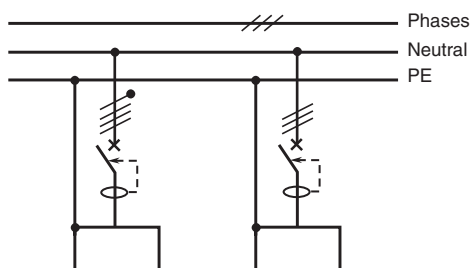


Fig. F61 : RCD protection

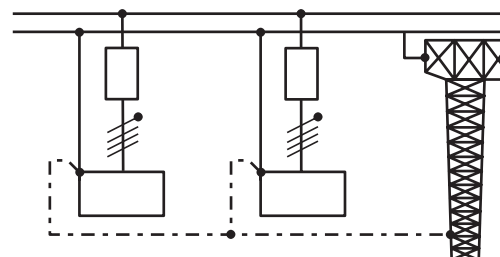


Fig. F62 : Improved equipotential bonding



### 8.1 Types of RCDs

Residual current devices (RCD) are commonly incorporated in or associated with the following components:

- Industrial-type moulded-case circuit-breakers (MCCB) and air circuit-breakers (ACB) conforming to IEC 60947-2 and its appendix B and M
- Industrial type miniature circuit-breakers (MCB) conforming to IEC 60947-2 and its appendix B and M
- Household and similar miniature circuit-breakers (MCB) complying with IEC 60898, IEC 61008, IEC 61009
- Residual load switch conforming to particular national standards
- Relays with separate toroidal (ring-type) current transformers, conforming to IEC 60947-2 Appendix M

RCDs are mandatorily used at the origin of TT-earthed installations, where their ability to discriminate with other RCDs allows selective tripping, thereby ensuring the level of service continuity required.

F36

*Industrial circuit-breakers with an integrated RCD are covered in IEC 60947-2 and its appendix B*

#### Industrial type circuit-breakers with integrated or adaptable RCD module (see Fig. F63)



Industrial type circuit-breaker  
Vigi Compact



Multi 9 DIN-rail industrial  
Circuit-breaker with adaptable Vigi RCD module

**Fig. F63 :** Industrial-type CB with RCD module

Adaptable residual current circuit-breakers, including DIN-rail mounted units (e.g. Compact or Multi 9), are available, to which may be associated an auxiliary RCD module (e.g. Vigi).

The ensemble provides a comprehensive range of protective functions (isolation, protection against short-circuit, overload, and earth-fault).

*Household or domestic circuit-breakers with an integrated RCD are covered in IEC 60898, IEC 61008 and IEC 61009*

#### Household and similar miniature circuit-breakers with RCD (see Fig. F64)



The incoming-supply circuit-breaker can also have time-delayed characteristics and integrate a RCD (type S).



"Monobloc" Déclit Vigi residual current circuit-breakers intended for protection of terminal socket-outlet circuits in domestic and tertiary sector applications.

**Fig. F64 :** Domestic residual current circuit-breakers (RCCBs) for earth leakage protection



Residual current load break switches are covered by particular national standards. RCDs with separate toroidal current transformers are standardized in IEC 60947-2 appendix M

### Residual current circuit-breakers and RCDs with separate toroidal current transformer (see Fig. F65)

RCDs with separate toroidal CTs can be used in association with circuit-breakers or contactors.



Fig. F65 : RCDs with separate toroidal current transformers (Vigirex)

F37

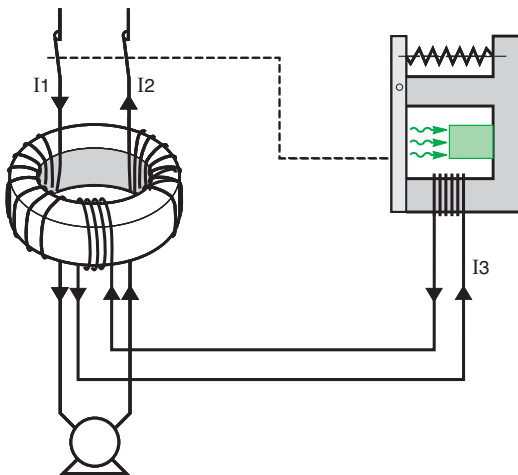


Fig. F66 : The principle of RCD operation

## 8.2 Description

### Principle

The essential features are shown schematically in **Figure F66** below.

A magnetic core encompasses all the current-carrying conductors of an electric circuit and the magnetic flux generated in the core will depend at every instant on the arithmetical sum of the currents; the currents passing in one direction being considered as positive ( $I_1$ ), while those passing in the opposite direction will be negative ( $I_2$ ).

In a normally healthy circuit  $I_1 + I_2 = 0$  and there will be no flux in the magnetic core, and zero e.m.f. in its coil.

An earth-fault current  $I_d$  will pass through the core to the fault, but will return to the source via the earth, or via protective conductors in a TN-earthed system.

The current balance in the conductors passing through the magnetic core therefore no longer exists, and the difference gives rise to a magnetic flux in the core.

The difference current is known as the “residual” current and the principle is referred to as the “residual current” principle.

The resultant alternating flux in the core induces an e.m.f. in its coil, so that a current  $I_3$  flows in the tripping-device operating coil. If the residual current exceeds the value required to operate the tripping device either directly or via an electronic relay, then the associated circuit-breaker will trip.

## 8.3 Sensitivity of RCDs to disturbances

In certain cases, aspects of the environment can disturb the correct operation of RCDs:

- **“nuisance” tripping:** Break in power supply without the situation being really hazardous. This type of tripping is often repetitive, causing major inconvenience and detrimental to the quality of the user's electrical power supply.
- **non-tripping, in the event of a hazard.** Less perceptible than nuisance tripping, these malfunctions must still be examined carefully since they undermine user safety. This is why international standards define 3 categories of RCDs according to their immunity to this type of disturbance (see below).

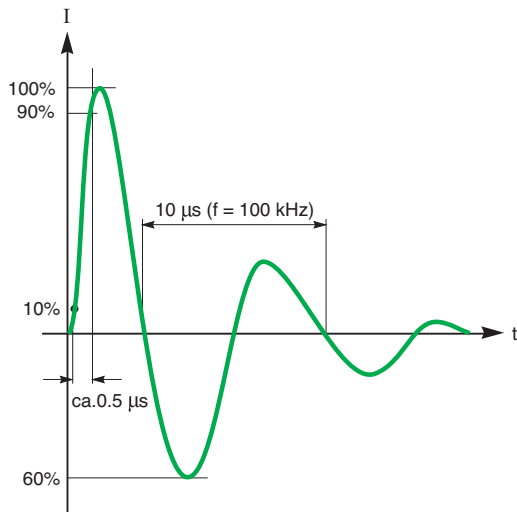


Fig. F67 : Standardized 0.5 μs/100 kHz current transient wave

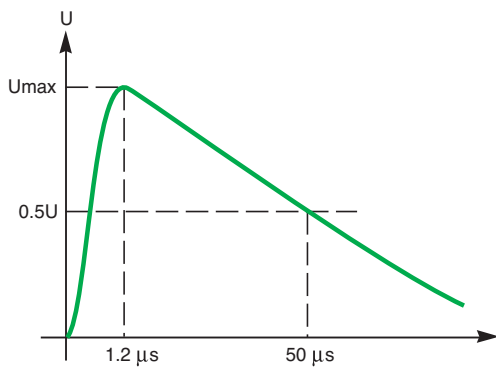


Fig. F68 : Standardized 1.2/50 μs voltage transient wave

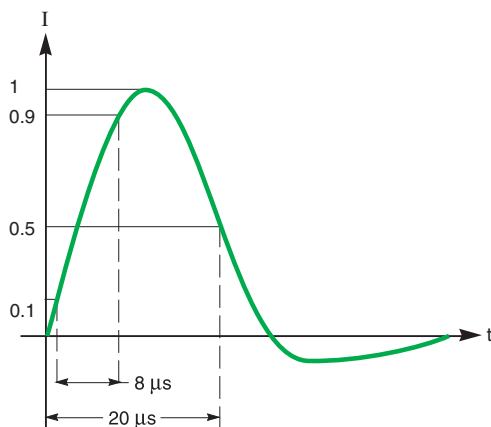


Fig. F69 : Standardized current-impulse wave 8/20 μs

## Main disturbance types

### Permanent earth leakage currents

Every LV installation has a permanent leakage current to earth, which is either due to:

- Unbalance of the intrinsic capacitance between live conductors and earth for three-phase circuits or
  - Capacitance between live conductors and earth for single-phase circuits
- The larger the installation the greater its capacitance with consequently increased leakage current.

The capacitive current to earth is sometimes increased significantly by filtering capacitors associated with electronic equipment (automation, IT and computer-based systems, etc.).

In the absence of more precise data, permanent leakage current in a given installation can be estimated from the following values, measured at 230 V 50 Hz:

Single-phase or three-phase line: 1.5 mA /100m

- Heating floor: 1mA / kW
- Fax terminal, printer: 1 mA
- Microcomputer, workstation: 2 mA
- Copy machine: 1.5 mA

Since RCDs complying with IEC and many national standards may operate under the limitation of permanent leakage current to 0.25 I<sub>Δn</sub>, by sub-division of circuits will, in practice, eliminate any unwanted tripping.

For very particular cases, such as the extension, or partial renovation of extended IT-earthed installations, the manufacturers must be consulted.

**High frequency components** (harmonics, transients, etc.), are generated by computer equipment power supplies, converters, motors with speed regulators, fluorescent lighting systems and in the vicinity of high power switching devices and reactive energy compensation banks.

Part of these high frequency currents may flow to earth through parasitic capacitances. Although not hazardous for the user, these currents can still cause the tripping of differential devices.

### Energization

The initial energization of the capacitances mentioned above gives rise to high frequency transient currents of very short duration, similar to that shown in **Figure F67**.

The sudden occurrence of a first-fault on an IT-earthed system also causes transient earth-leakage currents at high frequency, due to the sudden rise of the two healthy phases to phase/phase voltage above earth.

### Common mode overvoltages

Electrical networks are subjected to overvoltages due to lightning strikes or to abrupt changes of system operating conditions (faults, fuse operation, switching, etc.). These sudden changes often cause large transient voltages and currents in inductive and capacitive circuits. Records have established that, on LV systems, overvoltages remain generally below 6 kV, and that they can be adequately represented by the conventional 1.2/50 μs impulse wave (see **Fig. F68**).

These overvoltages give rise to transient currents represented by a current impulse wave of the conventional 8/20 μs form, having a peak value of several tens of amperes (see **Fig. F69**).

The transient currents flow to earth via the capacitances of the installation.

### Non-sinusoidal fault currents

#### Type AC, A, B

Standard IEC 60755 (General requirements for residual current operated protective devices) defines three types of RCD depending on the characteristics of the fault current:

- Type AC  
RCD for which tripping is ensured for residual sinusoidal alternating currents.
- Type A  
RCD for which tripping is ensured:
  - for residual sinusoidal alternating currents,
  - for residual pulsating direct currents,

### ■ Type B

RCD for which tripping is ensured:

- as for type A,
- for pure direct residual currents which may result from three-phase rectifying circuits.

**Cold:** in the cases of temperatures under - 5 °C, very high sensitivity electromechanical relays in the RCD may be “welded” by the condensation – freezing action.

Type “Si” devices can operate under temperatures down to - 25 °C.

**Atmospheres with high concentrations of chemicals or dust:** the special alloys used to make the RCDs can be notably damaged by corrosion. Dust can also block the movement of mechanical parts.





See the measures to be taken according to the levels of severity defined by standards in **Fig. F70**.

Regulations define the choice of earth leakage protection and its implementation. The main reference texts are as follows:

### ■ Standard IEC 60364-3:

- This gives a classification (AFx) for external influences in the presence of corrosive or polluting substances.
- It defines the choice of materials to be used according to extreme influences.

F39

Disturbed network	Super-immunized residual current protections <b>Type A if:</b> 	SiE  residual current protections	SiE  residual current protections	SiE  residual current protections
Influence of the electrical network			+	+
Clean network	Standard immunized residual current protections <b>Type AC</b>		Appropriate additional protection (sealed cabinet or unit)	Appropriate additional protection (sealed cabinet or unit + overpressure)
	AF1	AF2	AF3	AF4
	■ External influences: negligible,	■ External influences: presence of corrosive or polluting atmospheric agents,	■ External influences: intermittent or accidental action of certain common chemicals,	■ External influences: permanent action of corrosive or polluting chemicals
	■ Equipment characteristics: normal.	■ Equipment characteristics: e.g. conformity with salt mist or atmospheric pollution tests.	■ Equipment characteristics: corrosion protection.	■ Equipment characteristics: specifically studied according to the type of products.

Examples of exposed sites	External influences
Iron and steel works.	Presence of sulfur, sulfur vapor, hydrogen sulfide.
Marinas, trading ports, boats, sea edges, naval shipyards.	Salt atmospheres, humid outside, low temperatures.
Swimming pools, hospitals, food & beverage.	Chlorinated compounds.
Petrochemicals.	Hydrogen, combustion gases, nitrogen oxides.
Breeding facilities, tips.	Hydrogen sulfide.

**Fig. F70** : External influence classification according to IEC 60364-3 standard

**Immunity level for Merlin Gerin residual current devices**

The Merlin Gerin range comprises various types of RCDs allowing earth leakage protection to be adapted to each application. The table below indicates the choices to be made according to the type of probable disturbances at the point of installation.

Device type	Nuisance trippings	Non-trippings			
	High frequency leakage current	Fault current		Low temperatures (down to - 25 °C)	Corrosion Dust
		Rectified alternating	Pure direct		
AC	■				
A	■	■		■	
SI	■ ■ ■	■		■	
SiE	■ ■ ■	■		■	■
B	■ ■ ■	■	■	■	

**Fig. F71** : Immunity level of Merlin Gerin RCDs

**Immunity to nuisance tripping**

Type Si/SiE RCDs have been designed to avoid nuisance tripping or non-tripping in case of polluted network , lightning effect, high frequency currents, RF waves, etc.

**Figure F72** below indicates the levels of tests undergone by this type of RCDs.

Disturbance type	Rated test wave	Immunity
		<b>Multi9 :</b> <b>ID-RCCB, DPN Vigi, Vigi C60, Vigi C120, Vigi NG125</b> <b>SI / SiE type</b>
<b>Continuous disturbances</b>		
Harmonics	1 kHz	Earth leakage current = 8 x I <sub>Δn</sub>
<b>Transient disturbances</b>		
Lightning induced overvoltage	1.2 / 50 μs pulse (IEC/EN 61000-4-5)	4.5 kV between conductors 5.5 kV / earth
Lightning induced current	8 / 20 μs pulse (IEC/EN 61008)	5 kA peak
Switching transient, indirect lightning currents	0.5 μs / 100 kHz " ring wave " (IEC/EN 61008)	400 A peak
Downstream surge arrester operation, capacitance loading	10 ms pulse	500 A
<b>Electromagnetic compatibility</b>		
Inductive load switchings fluorescent lights, motors, etc.)	Repeated bursts (IEC 61000-4-4)	4 kV / 400 kHz
Fluorescent lights, thyristor controlled circuits, etc.	RF conducted waves (IEC 61000-4-6)	66 mA (15 kHz to 150 kHz) 30 V (150 kHz to 230 MHz)
RF waves (TV& radio, broadcast, telecommunications,etc.)	RF radiated waves 80 MHz to 1 GHz (IEC 61000-4-3)	30 V / m

**Fig. F72** : Immunity to nuisance tripping tests undergone by Merlin Gerin RCDs

Recommendations concerning the installation of RCDs with separate toroidal current transformers

The detector of residual current is a closed magnetic circuit (usually circular) of very high magnetic permeability, on which is wound a coil of wire, the ensemble constituting a toroidal (or ring-type) current transformer.

Because of its high permeability, any small deviation from perfect symmetry of the conductors encompassed by the core, and the proximity of ferrous material (steel enclosure, chassis members, etc.) can affect the balance of magnetic forces sufficiently, at times of large load currents (motor-starting current, transformer energizing current surge, etc.) to cause unwanted tripping of the RCD.

Unless particular measures are taken, the ratio of operating current  $I\Delta n$  to maximum phase current  $I_{ph}$  (max.) is generally less than 1/1,000.

This limit can be increased substantially (i.e. the response can be desensitized) by adopting the measures shown in **Figure F73**, and summarized in **Figure F74**.

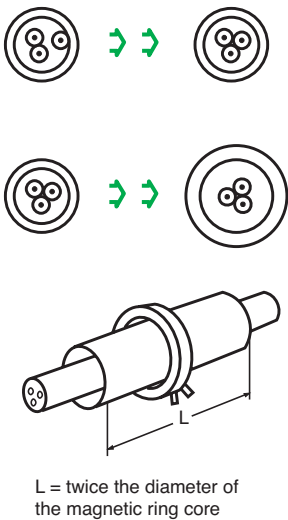


Fig. F73 : Three measures to reduce the ratio  $I\Delta n/I_{ph}$  (max.)

Measures	Diameter (mm)	Sensitivity diminution factor
Careful centralizing of cables through the ring core		3
Oversizing of the ring core	ø 50 → ø 100	2
	ø 80 → ø 200	2
	ø 120 → ø 300	6
Use of a steel or soft-iron shielding sleeve	ø 50	4
■ Of wall thickness 0.5 mm	ø 80	3
■ Of length 2 x inside diameter of ring core	ø 120	3
■ Completely surrounding the conductors and overlapping the circular core equally at both ends	ø 200	2

These measures can be combined. By carefully centralizing the cables in a ring core of 200 mm diameter, where a 50 mm core would be large enough, and using a sleeve, the ratio 1/1,000 could become 1/30,000.

Fig. F74 : Means of reducing the ratio  $I\Delta n/I_{ph}$  (max.)

F41

F42

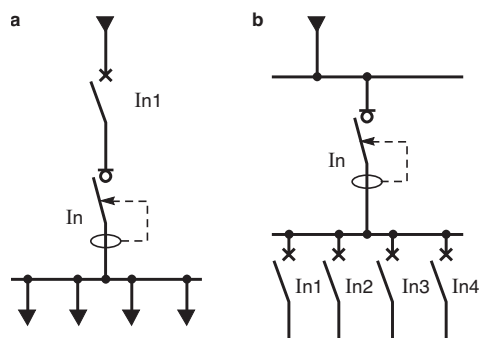


Fig. F75 : Residual current circuit-breakers (RCCBs)

### Choice of characteristics of a residual-current circuit-breaker (RCCB - IEC 61008)

#### Rated current

The rated current of a RCCB is chosen according to the maximum sustained load current it will carry.

■ If the RCCB is connected in series with, and downstream of a circuit-breaker, the rated current of both items will be the same, i.e.  $I_n \geq I_{n1}$  (see Fig. F75a)

■ If the RCCB is located upstream of a group of circuits, protected by circuit-breakers, as shown in Figure F75b, then the RCCB rated current will be given by:

$$I_n \geq k_u \times k_s (I_{n1} + I_{n2} + I_{n3} + I_{n4})$$

#### Electrodynamic withstand requirements

Protection against short-circuits must be provided by an upstream SCPD (Short-Circuit Protective Device) but it is considered that where the RCCB is located in the same distribution box (complying with the appropriate standards) as the downstream circuit-breakers (or fuses), the short-circuit protection afforded by these (outgoing-circuit) SCPDs is an adequate alternative. Coordination between the RCCB and the SCPDs is necessary, and manufacturers generally provide tables associating RCCBs and circuit-breakers or fuses (see Fig. F76).

Circuit-breaker and RCCB association – maxi  $I_{sc}$  (r.m.s) value in kA

Upstream circuit-breaker			DT40	DT40N	C60N	C60H	C60L	C120N	C120H	NG125N	NG125H
Downstream RCCB	2P 230V	I 20A	6.5	6.5	6.5	6.5	6.5	3	4.5	4.5	4.5
		IN-A 40A	6	10	20	30	30	10	10	15	15
		IN-A 63A	6	10	20	30	30	10	10	15	15
		I 100A						15	15	15	15
	4P 400V	I 20A	4.5	4.5	4.5	4.5	4.5	2	3	3	3
		IN-A 40A	6	10	10	15	15	7	7	15	15
		IN-A 63A	6	10	10	15	15	7	7	15	15
		NG 125NA						10	16	25	50

Fuses and RCCB association – maxi  $I_{sc}$  (r.m.s) value in kA

gG upstream fuse			20A	63A	100A	125A
Downstream RCCB	2P 230V	I 20A	8			
		IN-A 40A		30	20	
		IN-A 63A		30	20	
		I 100A			6	
	4P 400V	I 20A	8			
		IN-A 40A		30	20	
		IN-A 63A		30	20	
		NG 125NA				50

Fig. F76 : Typical manufacturers coordination table for RCCBs, circuit-breakers, and fuses (Merlin Gerin products)

# Chapter G

## Sizing and protection of conductors

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G1

*Component parts of an electric circuit and its protection are determined such that all normal and abnormal operating conditions are satisfied*

G2

## 1.1 Methodology and definition

### Methodology (see Fig. G1 )

Following a preliminary analysis of the power requirements of the installation, as described in Chapter B Clause 4, a study of cabling<sup>(1)</sup> and its electrical protection is undertaken, starting at the origin of the installation, through the intermediate stages to the final circuits.

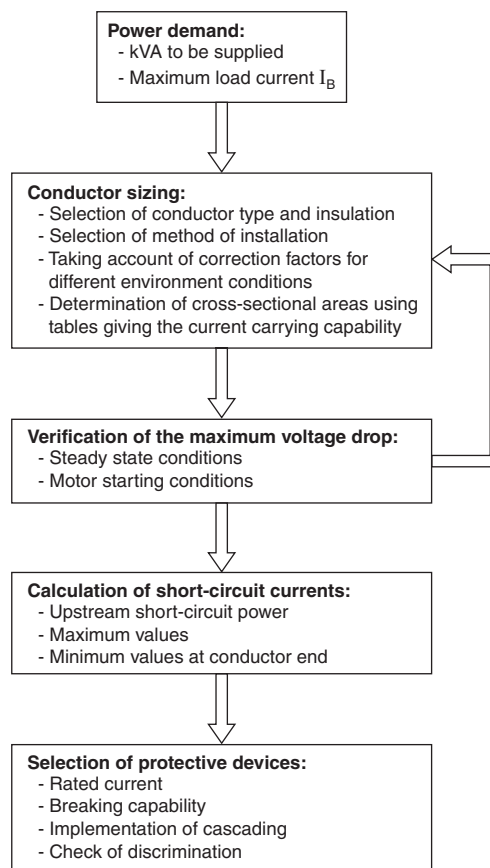
The cabling and its protection at each level must satisfy several conditions at the same time, in order to ensure a safe and reliable installation, e.g. it must:

- Carry the permanent full load current, and normal short-time overcurrents
- Not cause voltage drops likely to result in an inferior performance of certain loads, for example: an excessively long acceleration period when starting a motor, etc.

Moreover, the protective devices (circuit-breakers or fuses) must:

- Protect the cabling and busbars for all levels of overcurrent, up to and including short-circuit currents
- Ensure protection of persons against indirect contact hazards, particularly in TN- and IT- earthed systems, where the length of circuits may limit the magnitude of short-circuit currents, thereby delaying automatic disconnection (it may be remembered that TT- earthed installations are necessarily protected at the origin by a RCD, generally rated at 300 mA).

The cross-sectional areas of conductors are determined by the general method described in Sub-clause 2 of this Chapter. Apart from this method some national standards may prescribe a minimum cross-sectional area to be observed for reasons of mechanical endurance. Particular loads (as noted in Chapter N) require that the cable supplying them be oversized, and that the protection of the circuit be likewise modified.



**Fig. G1** : Flow-chart for the selection of cable size and protective device rating for a given circuit

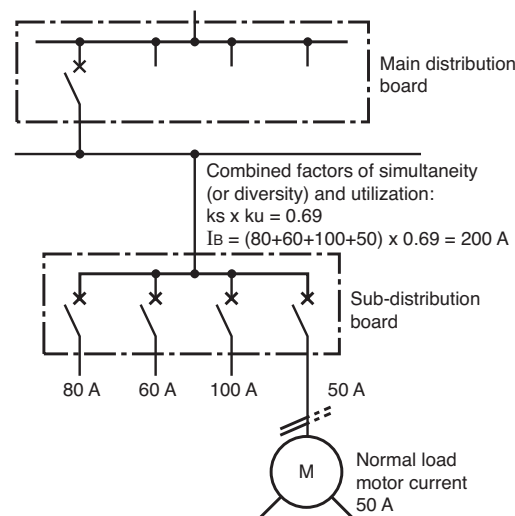
(1) The term "cabling" in this chapter, covers all insulated conductors, including multi-core and single-core cables and insulated wires drawn into conduits, etc.



## Definitions

### Maximum load current: $I_b$

- At the final circuits level, this current corresponds to the rated kVA of the load. In the case of motor-starting, or other loads which take a high in-rush current, particularly where frequent starting is concerned (e.g. lift motors, resistance-type spot welding, and so on) the cumulative thermal effects of the overcurrents must be taken into account. Both cables and thermal type relays are affected.
- At all upstream circuit levels this current corresponds to the kVA to be supplied, which takes account of the factors of simultaneity (diversity) and utilization,  $k_s$  and  $k_u$  respectively, as shown in **Figure G2**.



**Fig. G2** : Calculation of maximum load current  $I_b$

### Maximum permissible current: $I_z$

This is the maximum value of current that the cabling for the circuit can carry indefinitely, without reducing its normal life expectancy.

The current depends, for a given cross sectional area of conductors, on several parameters:

- Constitution of the cable and cable-way (Cu or Alu conductors; PVC or EPR etc. insulation; number of active conductors)
- Ambient temperature
- Method of installation
- Influence of neighbouring circuits

### Overcurrents

An overcurrent occurs each time the value of current exceeds the maximum load current  $I_b$  for the load concerned.

This current must be cut off with a rapidity that depends upon its magnitude, if permanent damage to the cabling (and appliance if the overcurrent is due to a defective load component) is to be avoided.

Overcurrents of relatively short duration can however, occur in normal operation; two types of overcurrent are distinguished:

#### Overloads

These overcurrents can occur in healthy electric circuits, for example, due to a number of small short-duration loads which occasionally occur co-incidentally: motor starting loads, and so on. If either of these conditions persists however beyond a given period (depending on protective-relay settings or fuse ratings) the circuit will be automatically cut off.

#### Short-circuit currents

These currents result from the failure of insulation between live conductors or/and between live conductors and earth (on systems having low-impedance-earthed neutrals) in any combination, viz:

- 3 phases short-circuited (and to neutral and/or earth, or not)
- 2 phases short-circuited (and to neutral and/or earth, or not)
- 1 phase short-circuited to neutral (and/or to earth)

## 1.2 Overcurrent protection principles

A protective device is provided at the origin of the circuit concerned (see **Fig. G3** and **Fig. G4**).

- Acting to cut-off the current in a time shorter than that given by the  $I^2t$  characteristic of the circuit cabling
- But allowing the maximum load current  $I_B$  to flow indefinitely

The characteristics of insulated conductors when carrying short-circuit currents can, for periods up to 5 seconds following short-circuit initiation, be determined approximately by the formula:

$I^2t = k^2 S^2$  which shows that the allowable heat generated is proportional to the squared cross-sectional-area of the conductor.

where

t: Duration of short-circuit current (seconds)

S: Cross sectional area of insulated conductor ( $\text{mm}^2$ )

I: Short-circuit current (A r.m.s.)

k: Insulated conductor constant (values of  $k^2$  are given in Figure G52 )

For a given insulated conductor, the maximum permissible current varies according to the environment. For instance, for a high ambient temperature ( $\theta_{a1} > \theta_{a2}$ ),  $I_{z1}$  is less than  $I_{z2}$  (see **Fig. G5**).  $\theta$  means "temperature".

**Note:**

- $I_{sc}$ : 3-phase short-circuit current
- $I_{scB}$ : rated 3-ph. short-circuit breaking current of the circuit-breaker
- $I_r$  (or  $I_{rth}^{(1)}$ ): regulated "nominal" current level; e.g. a 50 A nominal circuit-breaker can be regulated to have a protective range, i.e. a conventional overcurrent tripping level (see **Fig. G6** opposite page) similar to that of a 30 A circuit-breaker.

## 1.3 Practical values for a protective scheme

The following methods are based on rules laid down in the IEC standards, and are representative of the practices in many countries.

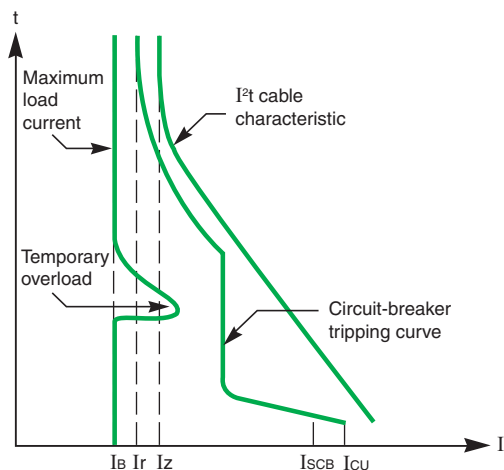
### General rules

A protective device (circuit-breaker or fuse) functions correctly if:

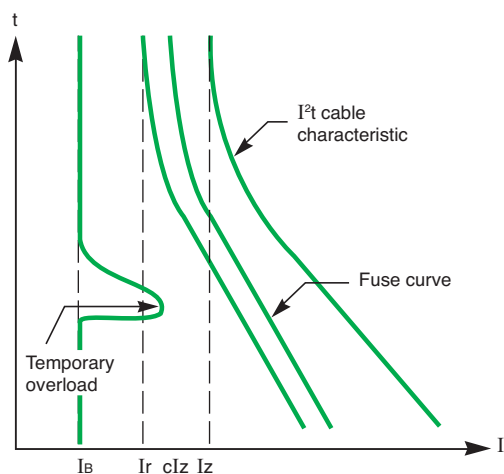
- Its nominal current or its setting current  $I_n$  is greater than the maximum load current  $I_B$  but less than the maximum permissible current  $I_z$  for the circuit, i.e.  $I_B \leq I_n \leq I_z$  corresponding to zone "a" in Figure G6
- Its tripping current  $I_2$  "conventional" setting is less than  $1.45 I_z$  which corresponds to zone "b" in Figure G6

The "conventional" setting tripping time may be 1 hour or 2 hours according to local standards and the actual value selected for  $I_2$ . For fuses,  $I_2$  is the current (denoted  $I_f$ ) which will operate the fuse in the conventional time.

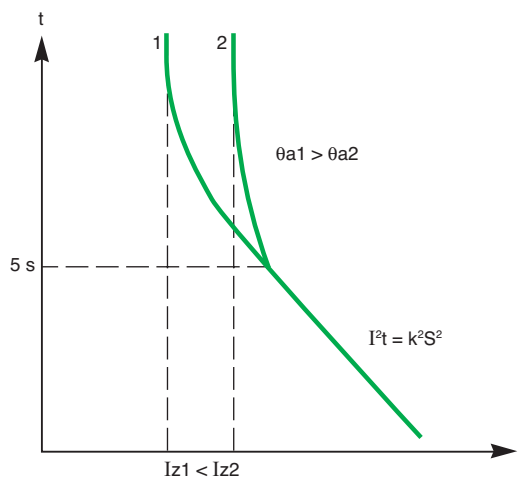
G4



**Fig. G3** : Circuit protection by circuit-breaker



**Fig. G4** : Circuit protection by fuses



**Fig. G5** :  $I^2t$  characteristic of an insulated conductor at two different ambient temperatures

(1) Both designations are commonly used in different standards.

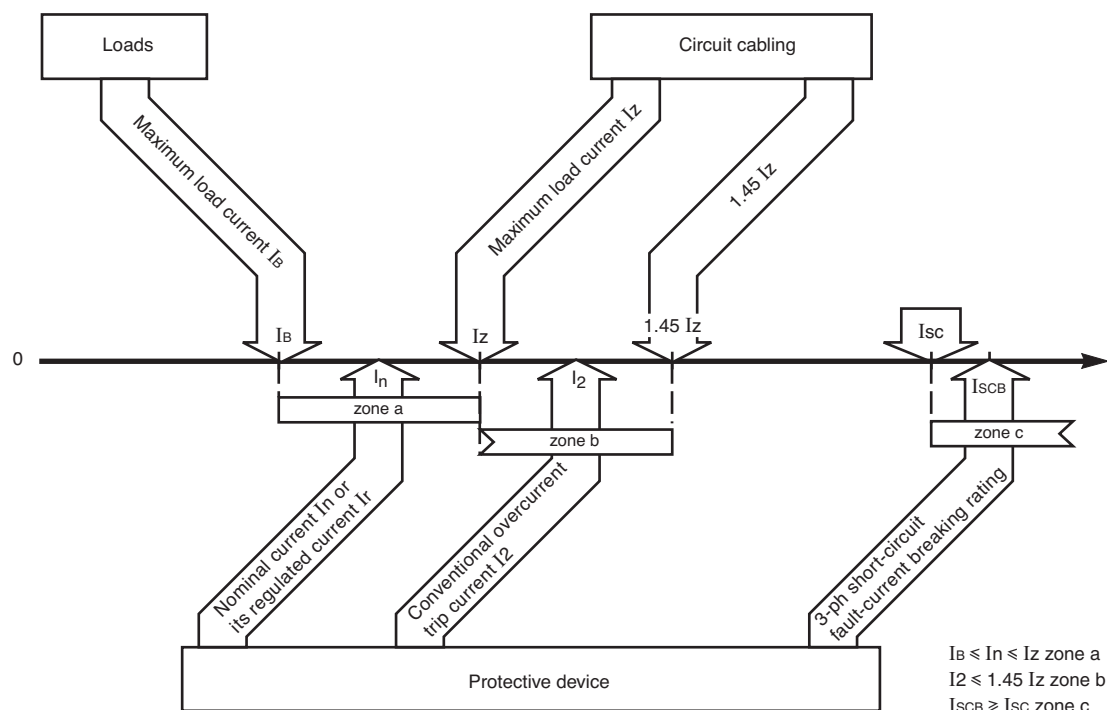


Fig. G6 : Current levels for determining circuit breaker or fuse characteristics

■ Its 3-phase short-circuit fault-current breaking rating is greater than the 3-phase short-circuit current existing at its point of installation. This corresponds to zone "c" in Figure G6.

## Applications

### ■ Protection by circuit-breaker

By virtue of its high level of precision the current  $I_2$  is always less than  $1.45 I_n$  (or  $1.45 I_r$ ) so that the condition  $I_2 \leq 1.45 I_z$  (as noted in the "general rules" above) will always be respected.

#### □ Particular case

If the circuit-breaker itself does not protect against overloads, it is necessary to ensure that, at a time of lowest value of short-circuit current, the overcurrent device protecting the circuit will operate correctly. This particular case is examined in Sub-clause 5.1.

### ■ Protection by fuses

The condition  $I_2 \leq 1.45 I_z$  must be taken into account, where  $I_2$  is the fusing (melting level) current, equal to  $k_2 \times I_n$  ( $k_2$  ranges from 1.6 to 1.9) depending on the particular fuse concerned.

A further factor  $k_3$  has been introduced ( $k_3 = \frac{k_2}{1.45}$ ) such that  $I_2 \leq 1.45 I_z$  will be valid if  $I_n \leq I_z/k_3$ .

For fuses type gG:

$I_n < 16 \text{ A} \rightarrow k_3 = 1.31$

$I_n \geq 16 \text{ A} \rightarrow k_3 = 1.10$

Moreover, the short-circuit current breaking capacity of the fuse  $I_{scf}$  must exceed the level of 3-phase short-circuit current at the point of installation of the fuse(s).

### ■ Association of different protective devices

The use of protective devices which have fault-current ratings lower than the fault level existing at their point of installation are permitted by IEC and many national standards in the following conditions:

- There exists upstream, another protective device which has the necessary short-circuit rating, and
- The amount of energy allowed to pass through the upstream device is less than that which can be withstood without damage by the downstream device and all associated cabling and appliances.

#### Criteria for circuit-breakers:

$I_B \leq I_n \leq I_z$  and  $I_{scB} \geq I_{sc}$ .

#### Criteria for fuses:

$I_B \leq I_n \leq I_z/k_3$  and  $I_{scf} \geq I_{sc}$ .

A protective device is, in general, required at the origin of each circuit

In practice this arrangement is generally exploited in:

- The association of circuit-breakers/fuses
- The technique known as “cascading” or “series rating” in which the strong current-limiting performance of certain circuit-breakers effectively reduces the severity of downstream short-circuits

Possible combinations which have been tested in laboratories are indicated in certain manufacturers catalogues.

## 1.4 Location of protective devices

### General rule (see Fig. G7a)

A protective device is necessary at the origin of each circuit where a reduction of permissible maximum current level occurs.

### Possible alternative locations in certain circumstances (see Fig. G7b)

The protective device may be placed part way along the circuit:

- If AB is not in proximity to combustible material, and
- If no socket-outlets or branch connections are taken from AB

Three cases may be useful in practice:

- Consider case (1) in the diagram
- $AB \leq 3$  metres, and
- AB has been installed to reduce to a practical minimum the risk of a short-circuit (wires in heavy steel conduit for example)
- Consider case (2)
- The upstream device P1 protects the length AB against short-circuits in accordance with Sub-clause 5.1
- Consider case (3)
- The overload device (S) is located adjacent to the load. This arrangement is convenient for motor circuits. The device (S) constitutes the control (start/stop) and overload protection of the motor while (SC) is: either a circuit-breaker (designed for motor protection) or fuses type aM
- The short-circuit protection (SC) located at the origin of the circuit conforms with the principles of Sub-clause 5.1

### Circuits with no protection (see Fig. G7c)

Either

- The protective device P1 is calibrated to protect the cable S2 against overloads and short-circuits

Or

- Where the breaking of a circuit constitutes a risk, e.g.
  - Excitation circuits of rotating machines
  - circuits of large lifting electromagnets
  - the secondary circuits of current transformers

No circuit interruption can be tolerated, and the protection of the cabling is of secondary importance.

## 1.5 Conductors in parallel

Conductors of the same cross-sectional-area, the same length, and of the same material, can be connected in parallel.

The maximum permissible current is the sum of the individual-core maximum currents, taking into account the mutual heating effects, method of installation, etc. Protection against overload and short-circuits is identical to that for a single-cable circuit.

The following precautions should be taken to avoid the risk of short-circuits on the paralleled cables:

- Additional protection against mechanical damage and against humidity, by the introduction of supplementary protection
- The cable route should be chosen so as to avoid close proximity to combustible materials

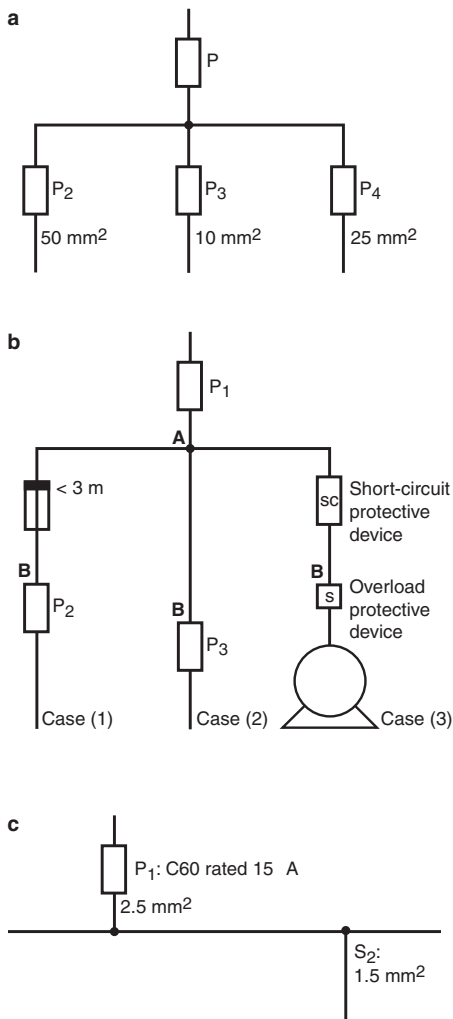


Fig. G7 : Location of protective devices

## 2 Practical method for determining the smallest allowable cross-sectional area of circuit conductors

### 2.1 General

The reference international standard for the study of cabling is IEC 60364-5-52: "Electrical installation of buildings - Part 5-52: Selection and erection of electrical equipment - Wiring system".

A summary of this standard is presented here, with examples of the most commonly used methods of installation. The current-carrying capacities of conductors in all different situations are given in annex A of the standard. A simplified method for use of the tables of annex A is proposed in informative annex B of the standard.

### 2.2 General method for cables

#### Possible methods of installation for different types of conductors or cables

The different admissible methods of installation are listed in **Figure G8**, in conjunction with the different types of conductors and cables.

Conductors and cables		Method of installation							
		Without fixings	Clipped direct	Conduit	Cable trunking (including skirting trunking, flush floor trunking)	Cable ducting	Cable ladder Cable tray Cable brackets	On insulators	Support wire
Bare conductors		–	–	–	–	–	–	+	–
Insulated conductors		–	–	+	+	+	–	+	–
Sheathed cables (including armoured and mineral insulated)	Multi-core	+	+	+	+	+	+	0	+
	Single-core	0	+	+	+	+	+	0	+

+ Permitted.

– Not permitted.

0 Not applicable, or not normally used in practice.

**Fig. G8** : Selection of wiring systems (table 52-1 of IEC 60364-5-52)

## 2 Practical method for determining the smallest allowable cross-sectional area of circuit conductors

### Possible methods of installation for different situations:

Different methods of installation can be implemented in different situations. The possible combinations are presented in **Figure G9**.

The number given in this table refer to the different wiring systems considered. (see also **Fig. G10**)

Situations	Method of installation							
	Without fixings	With fixings	Conduit	Cable trunking (including skirting trunking, flush floor trunking)	Cable ducting	Cable ladder cable tray, cable brackets	On insulators	Support wire
Building voids	40, 46, 15, 16	0	15, 16, 41, 42	–	43	30, 31, 32, 33, 34	–	–
Cable channel	56	56	54, 55	0	44, 45	30, 31, 32, 33, 34	–	–
Buried in ground	72, 73	0	70, 71	–		70, 71	0	–
Embedded in structure	57, 58	3	1, 2, 59, 60	50, 51, 52, 53	44, 45	0	–	–
Surface mounted	–	20, 21	4, 5	6, 7, 8, 9, 12, 13, 14, 22, 23	6, 7, 8, 9	30, 31, 32, 33, 34	36	–
Overhead	–	–	0	10, 11	–	30, 31, 32, 33, 34	36	35
Immersed	80	80	0	–	0	0	–	–

– Not permitted.

0 Not applicable, or not normally used in practice.

**Fig. G9** : Erection of wiring systems (table 52-2 of IEC 60364-5-52)

## 2 Practical method for determining the smallest allowable cross-sectional area of circuit conductors

### Examples of wiring systems and reference methods of installations

An illustration of some of the many different wiring systems and methods of installation is provided in Figure G10.

Several reference methods are defined (with code letters A to G), grouping installation methods having the same characteristics relative to the current-carrying capacities of the wiring systems.

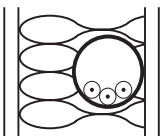
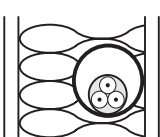
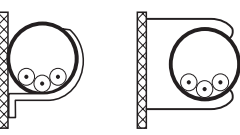
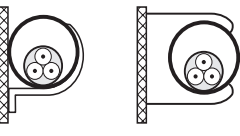
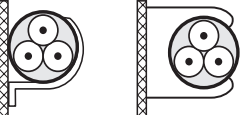
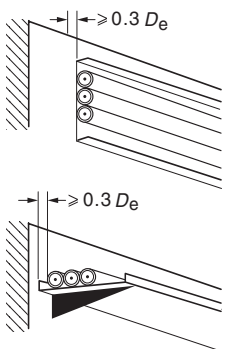
Item No.	Methods of installation	Description	Reference method of installation to be used to obtain current-carrying capacity
1	 Room	Insulated conductors or single-core cables in conduit in a thermally insulated wall	A1
2	 Room	Multi-core cables in conduit in a thermally insulated wall	A2
4		Insulated conductors or single-core cables in conduit on a wooden, or masonry wall or spaced less than 0,3 x conduit diameter from it	B1
5		Multi-core cable in conduit on a wooden, or masonry wall or spaced less than 0,3 x conduit diameter from it	B2
20		Single-core or multi-core cables: - fixed on, or spaced less than 0.3 x cable diameter from a wooden wall	C
30		On unperforated tray	C

Fig. G10 : Examples of methods of installation (part of table 52-3 of IEC 60364-5-52) (continued on next page)

## 2 Practical method for determining the smallest allowable cross-sectional area of circuit conductors

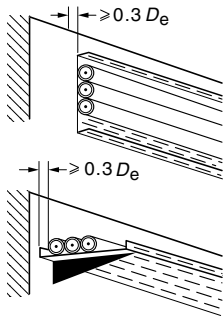

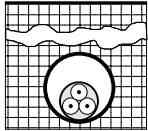
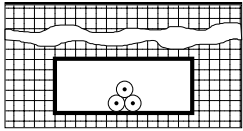
Item No.	Methods of installation	Description	Reference method of installation to be used to obtain current-carrying capacity
31		On perforated tray	E or F
36		Bare or insulated conductors on insulators	G
70		Multi-core cables in conduit or in cable ducting in the ground	D
71		Single-core cable in conduit or in cable ducting in the ground	D

Fig. G10 : Examples of methods of installation (part of table 52-3 of IEC 60364-5-52)

### Maximum operating temperature:

The current-carrying capacities given in the subsequent tables have been determined so that the maximum insulation temperature is not exceeded for sustained periods of time.

For different type of insulation material, the maximum admissible temperature is given in **Figure G11**.

Type of insulation	Temperature limit °C
Polyvinyl-chloride (PVC)	70 at the conductor
Cross-linked polyethylene (XLPE) and ethylene propylene rubber (EPR)	90 at the conductor
Mineral (PVC covered or bare exposed to touch)	70 at the sheath
Mineral (bare not exposed to touch and not in contact with combustible material)	105 at the sheath

Fig. G11 : Maximum operating temperatures for types of insulation (table 52-4 of IEC 60364-5-52)

### Correction factors:

In order to take environment or special conditions of installation into account, correction factors have been introduced.

The cross sectional area of cables is determined using the rated load current  $I_B$  divided by different correction factors,  $k_1$ ,  $k_2$ , ...:

$$I'_B = \frac{I_B}{k_1 \cdot k_2 \dots}$$

$I'_B$  is the corrected load current, to be compared to the current-carrying capacity of the considered cable.



## 2 Practical method for determining the smallest allowable cross-sectional area of circuit conductors

### ■ Ambient temperature

The current-carrying capacities of cables in the air are based on an average air temperature equal to 30 °C. For other temperatures, the correction factor is given in **Figure G12** for PVC, EPR and XLPE insulation material.

The related correction factor is here noted  $k_1$ .

Ambient temperature °C	Insulation	
	PVC	XLPE and EPR
10	1.22	1.15
15	1.17	1.12
20	1.12	1.08
25	1.06	1.04
35	0.94	0.96
40	0.87	0.91
45	0.79	0.87
50	0.71	0.82
55	0.61	0.76
60	0.50	0.71
65	-	0.65
70	-	0.58
75	-	0.50
80	-	0.41

**Fig. G12** : Correction factors for ambient air temperatures other than 30 °C to be applied to the current-carrying capacities for cables in the air (from table A.52-14 of IEC 60364-5-52)

The current-carrying capacities of cables in the ground are based on an average ground temperature equal to 20 °C. For other temperatures, the correction factor is given in **Figure G13** for PVC, EPR and XLPE insulation material.

The related correction factor is here noted  $k_2$ .

Ground temperature °C	Insulation	
	PVC	XLPE and EPR
10	1.10	1.07
15	1.05	1.04
25	0.95	0.96
30	0.89	0.93
35	0.84	0.89
40	0.77	0.85
45	0.71	0.80
50	0.63	0.76
55	0.55	0.71
60	0.45	0.65
65	-	0.60
70	-	0.53
75	-	0.46
80	-	0.38

**Fig. G13** : Correction factors for ambient ground temperatures other than 20 °C to be applied to the current-carrying capacities for cables in ducts in the ground (from table A.52-15 of IEC 60364-5-52)

G11

## 2 Practical method for determining the smallest allowable cross-sectional area of circuit conductors

### ■ Soil thermal resistivity

The current-carrying capacities of cables in the ground are based on a ground resistivity equal to 2.5 K.m/W. For other values, the correction factor is given in **Figure G14**.

The related correction factor is here noted  $k_3$ .

Thermal resistivity, K.m/W	1	1.5	2	2.5	3
Correction factor	1.18	1.1	1.05	1	0.96

**Fig. G14** : Correction factors for cables in buried ducts for soil thermal resistivities other than 2.5 K.m/W to be applied to the current-carrying capacities for reference method D (table A52.16 of IEC 60364-5-52)

Based on experience, a relationship exist between the soil nature and resistivity. Then, empiric values of correction factors  $k_3$  are proposed in **Figure G15**, depending on the nature of soil.

Nature of soil	$k_3$
Very wet soil (saturated)	1.21
Wet soil	1.13
Damp soil	1.05
Dry soil	1.00
Very dry soil (sunbaked)	0.86

**Fig. G15** : Correction factor  $k_3$  depending on the nature of soil

### ■ Grouping of conductors or cables

The current-carrying capacities given in the subsequent tables relate to single circuits consisting of the following numbers of loaded conductors:

- Two insulated conductors or two single-core cables, or one twin-core cable (applicable to single-phase circuits);
- Three insulated conductors or three single-core cables, or one three-core cable (applicable to three-phase circuits).

Where more insulated conductors or cables are installed in the same group, a group reduction factor (here noted  $k_4$ ) shall be applied.

Examples are given in **Figures G16 to G18** for different configurations (installation methods, in free air or in the ground).

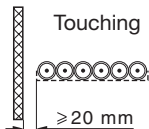
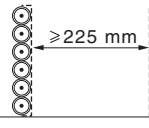
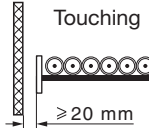
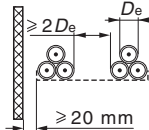
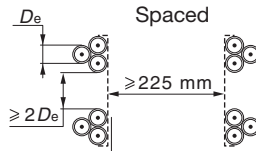
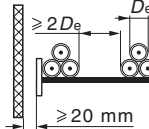
**Figure G16** gives the values of correction factor  $k_4$  for different configurations of unbundled cables or conductors, grouping of more than one circuit or multi-core cables.

Arrangement (cables touching)	Number of circuits or multi-core cables												Reference methods
	1	2	3	4	5	6	7	8	9	12	16	20	
Bunched in air, on a surface, embedded or enclosed	1.00	0.80	0.70	0.65	0.60	0.57	0.54	0.52	0.50	0.45	0.41	0.38	Methods A to F
Single layer on wall, floor or unperforated tray	1.00	0.85	0.79	0.75	0.73	0.72	0.72	0.71	0.70	No further reduction factor for more than nine circuits or multi-core cables			Method C
Single layer fixed directly under a wooden ceiling	0.95	0.81	0.72	0.68	0.66	0.64	0.63	0.62	0.61				Methods E and F
Single layer on a perforated horizontal or vertical tray	1.00	0.88	0.82	0.77	0.75	0.73	0.73	0.72	0.72				
Single layer on ladder support or cleats etc.	1.00	0.87	0.82	0.80	0.80	0.79	0.79	0.78	0.78				

**Fig. G16** : Reduction factors for groups of more than one circuit or of more than one multi-core cable (table A.52-17 of IEC 60364-5-52)

## 2 Practical method for determining the smallest allowable cross-sectional area of circuit conductors

**Figure G17** gives the values of correction factor  $k_4$  for different configurations of unburied cables or conductors, for groups of more than one circuit of single-core cables in free air.

Method of installation			Number of tray	Number of three-phase circuits			Use as a multiplier to rating for
				1	2	3	
Perforated trays	31		1	0.98	0.91	0.87	Three cables in horizontal formation
			2	0.96	0.87	0.81	
			3	0.95	0.85	0.78	
Vertical perforated trays	31		1	0.96	0.86		Three cables in vertical formation
			2	0.95	0.84		
Ladder supports, cleats, etc...	32		1	1.00	0.97	0.96	Three cables in horizontal formation
	33		2	0.98	0.93	0.89	
	34		3	0.97	0.90	0.86	
Perforated trays	31		1	1.00	0.98	0.96	Three cables in trefoil formation
			2	0.97	0.93	0.89	
			3	0.96	0.92	0.86	
Vertical perforated trays	31		1	1.00	0.91	0.89	
			2	1.00	0.90	0.86	
Ladder supports, cleats, etc...	32		1	1.00	1.00	1.00	
	33		2	0.97	0.95	0.93	
	34		3	0.96	0.94	0.90	

**Fig. G17** : Reduction factors for groups of more than one circuit of single-core cables to be applied to reference rating for one circuit of single-core cables in free air - Method of installation F. (table A.52.21 of IEC 60364-5-52)

## 2 Practical method for determining the smallest allowable cross-sectional area of circuit conductors

**Figure G18** gives the values of correction factor  $k_4$  for different configurations of cables or conductors laid directly in the ground.

Number of circuits	Cable to cable clearance ( $a$ ) <sup>a</sup>				
	Nil (cables touching)	One cable diameter	0.125 m	0.25 m	0.5 m
2	0.75	0.80	0.85	0.90	0.90
3	0.65	0.70	0.75	0.80	0.85
4	0.60	0.60	0.70	0.75	0.80
5	0.55	0.55	0.65	0.70	0.80
6	0.50	0.55	0.60	0.70	0.80

<sup>a</sup> Multi-core cables



<sup>a</sup> Single-core cables



**Fig. G18** : Reduction factors for more than one circuit, single-core or multi-core cables laid directly in the ground. Installation method D. (table 52-18 of IEC 60364-5-52)

### ■ Harmonic current

The current-carrying capacity of three-phase, 4-core or 5-core cables is based on the assumption that only 3 conductors are fully loaded.

However, when harmonic currents are circulating, the neutral current can be significant, and even higher than the phase currents. This is due to the fact that the 3<sup>rd</sup> harmonic currents of the three phases do not cancel each other, and sum up in the neutral conductor.

This of course affects the current-carrying capacity of the cable, and a correction factor noted here  $k_5$  shall be applied.

In addition, if the 3<sup>rd</sup> harmonic percentage  $h_3$  is greater than 33%, the neutral current is greater than the phase current and the cable size selection is based on the neutral current. The heating effect of harmonic currents in the phase conductors has also to be taken into account.

The values of  $k_5$  depending on the 3<sup>rd</sup> harmonic content are given in **Figure G19**.

Third harmonic content of phase current %	Correction factor	
	Size selection is based on phase current	Size selection is based on neutral current
0 - 15	1.0	
15 - 33	0.86	
33 - 45		0.86
> 45		1.0

**Fig. G19** : Correction factors for harmonic currents in four-core and five-core cables (table D.52.1 of IEC 60364-5-52)

### Admissible current as a function of nominal cross-sectional area of conductors

IEC standard 60364-5-52 proposes extensive information in the form of tables giving the admissible currents as a function of cross-sectional area of cables. Many parameters are taken into account, such as the method of installation, type of insulation material, type of conductor material, number of loaded conductors.

## 2 Practical method for determining the smallest allowable cross-sectional area of circuit conductors

As an example, **Figure G20** gives the current-carrying capacities for different methods of installation of PVC insulation, three loaded copper or aluminium conductors, free air or in ground.

Nominal cross-sectional area of conductors (mm <sup>2</sup> )	Installation methods					
	A1	A2	B1	B2	C	D
1						
2	3	4	5	6	7	8
<b>Copper</b>						
1.5	13.5	13	15.5	15	17.5	18
2.5	18	17.5	21	20	24	24
4	24	23	28	27	32	31
6	31	29	36	34	41	39
10	42	39	50	46	57	52
16	56	52	68	62	76	67
25	73	68	89	80	96	86
35	89	83	110	99	119	103
50	108	99	134	118	144	122
70	136	125	171	149	184	151
95	164	150	207	179	223	179
120	188	172	239	206	259	203
150	216	196	-	-	299	230
185	245	223	-	-	341	258
240	286	261	-	-	403	297
300	328	298	-	-	464	336
<b>Aluminium</b>						
2.5	14	13.5	16.5	15.5	18.5	18.5
4	18.5	17.5	22	21	25	24
6	24	23	28	27	32	30
10	32	31	39	36	44	40
16	43	41	53	48	59	52
25	57	53	70	62	73	66
35	70	65	86	77	90	80
50	84	78	104	92	110	94
70	107	98	133	116	140	117
95	129	118	161	139	170	138
120	149	135	186	160	197	157
150	170	155	-	-	227	178
185	194	176	-	-	259	200
240	227	207	-	-	305	230
300	261	237	-	-	351	260

**Fig. G20** : Current-carrying capacities in amperes for different methods of installation, PVC insulation, three loaded conductors, copper or aluminium, conductor temperature: 70 °C, ambient temperature: 30 °C in air, 20 °C in ground (table A.52.4 of IEC 60364-5-52)

## 2 Practical method for determining the smallest allowable cross-sectional area of circuit conductors

### 2.3 Recommended simplified approach for cables

In order to facilitate the selection of cables, 2 simplified tables are proposed, for unburied and buried cables.

These tables summarize the most commonly used configurations and give easier access to the information.

■ Unburied cables:

Reference methods	Number of loaded conductors and type of insulation											
A1		2 PVC	3 PVC		3 XLPE	2 XLPE						
A2	3 PVC	2 PVC		3 XLPE	2 XLPE							
B1				3 PVC	2 PVC		3 XLPE		2 XLPE			
B2			3 PVC	2 PVC		3 XLPE	2 XLPE					
C					3 PVC	2 PVC	3 XLPE		2 XLPE			
E						3 PVC	2 PVC	3 XLPE		2 XLPE		
F							3 PVC		2 PVC	3 XLPE		2 XLPE
1	2	3	4	5	6	7	8	9	10	11	12	13
<b>Size (mm<sup>2</sup>)</b>												
<b>Copper</b>												
1.5	13	13.5	14.5	15.5	17	18.5	19.5	22	23	24	26	-
2.5	17.5	18	19.5	21	23	25	27	30	31	33	36	-
4	23	24	26	28	31	34	36	40	42	45	49	-
6	29	31	34	36	40	43	46	51	54	58	63	-
10	39	42	46	50	54	60	63	70	75	80	86	-
16	52	56	61	68	73	80	85	94	100	107	115	-
25	68	73	80	89	95	101	110	119	127	135	149	161
35	-	-	-	110	117	126	137	147	158	169	185	200
50	-	-	-	134	141	153	167	179	192	207	225	242
70	-	-	-	171	179	196	213	229	246	268	289	310
95	-	-	-	207	216	238	258	278	298	328	352	377
120	-	-	-	239	249	276	299	322	346	382	410	437
150	-	-	-	-	285	318	344	371	395	441	473	504
185	-	-	-	-	324	362	392	424	450	506	542	575
240	-	-	-	-	380	424	461	500	538	599	641	679
<b>Aluminium</b>												
2.5	13.5	14	15	16.5	18.5	19.5	21	23	24	26	28	-
4	17.5	18.5	20	22	25	26	28	31	32	35	38	-
6	23	24	26	28	32	33	36	39	42	45	49	-
10	31	32	36	39	44	46	49	54	58	62	67	-
16	41	43	48	53	58	61	66	73	77	84	91	-
25	53	57	63	70	73	78	83	90	97	101	108	121
35	-	-	-	86	90	96	103	112	120	126	135	150
50	-	-	-	104	110	117	125	136	146	154	164	184
70	-	-	-	133	140	150	160	174	187	198	211	237
95	-	-	-	161	170	183	195	211	227	241	257	289
120	-	-	-	186	197	212	226	245	263	280	300	337
150	-	-	-	-	226	245	261	283	304	324	346	389
185	-	-	-	-	256	280	298	323	347	371	397	447
240	-	-	-	-	300	330	352	382	409	439	470	530

Fig. G21a : Current-carrying capacity in amperes (table B.52-1 of IEC 60364-5-52)

## 2 Practical method for determining the smallest allowable cross-sectional area of circuit conductors

Correction factors are given in **Figure G21b** for groups of several circuits or multi-core cables:

Arrangement	Number of circuits or multi-core cables								
	1	2	3	4	6	9	12	16	20
Embedded or enclosed	1.00	0.80	0.70	0.70	0.55	0.50	0.45	0.40	0.40
Single layer on walls, floors or on unperforatedtrays	1.00	0.85	0.80	0.75	0.70	0.70	-	-	-
Single layer fixed directly under a ceiling	0.95	0.80	0.70	0.70	0.65	0.60	-	-	-
Single layer on perforated horizontal trays or on vertical trays	1.00	0.90	0.80	0.75	0.75	0.70	-	-	-
Single layer on cable ladder supports or cleats, etc...	1.00	0.85	0.80	0.80	0.80	0.80	-	-	-

**Fig. G21b** : Reduction factors for groups of several circuits or of several multi-core cables (table B.52-3 of IEC 60364-5-52)

### ■ Buried cables:

Installation method	Size mm <sup>2</sup>	Number of loaded conductors and type of insulation			
		Two PVC	Three PVC	Two XLPE	Three XLPE
D	<b>Copper</b>				
	1.5	22	18	26	22
	2.5	29	24	34	29
	4	38	31	44	37
	6	47	39	56	46
	10	63	52	73	61
	16	81	67	95	79
	25	104	86	121	101
	35	125	103	146	122
	50	148	122	173	144
	70	183	151	213	178
	95	216	179	252	211
	120	246	203	287	240
	150	278	230	324	271
	185	312	258	363	304
	240	361	297	419	351
	300	408	336	474	396
D	<b>Aluminium</b>				
	2.5	22	18.5	26	22
	4	29	24	34	29
	6	36	30	42	36
	10	48	40	56	47
	16	62	52	73	61
	25	80	66	93	78
	35	96	80	112	94
	50	113	94	132	112
	70	140	117	163	138
	95	166	138	193	164
	120	189	157	220	186
	150	213	178	249	210
	185	240	200	279	236
	240	277	230	322	272
	300	313	260	364	308

**Fig. G22** : Current-carrying capacity in amperes (table B.52-1 of IEC 60364-5-52)

## 2 Practical method for determining the smallest allowable cross-sectional area of circuit conductors

### 2.4 Busbar trunking systems

The selection of busbar trunking systems is very straightforward, using the data provided by the manufacturer. Methods of installation, insulation materials, correction factors for grouping are not relevant parameters for this technology.

The cross section area of any given model has been determined by the manufacturer based on:

- The rated current,
- An ambient air temperature equal to 35 °C,
- 3 loaded conductors.

#### Rated current

The rated current can be calculated taking account of:

- The layout,
- The current absorbed by the different loads connected along the trunking system.

#### Ambient temperature

A correction factor has to be applied for temperature higher than 35 °C. The correction factor applicable to medium and high power range (up to 4,000 A) is given in **Figure G23a**.

G18

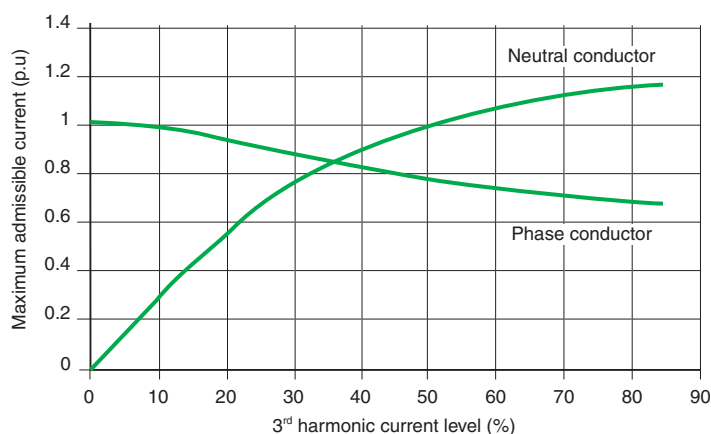
°C	35	40	45	50	55
Correction factor	1	0.97	0.93	0.90	0.86

**Fig. G23a** : Correction factor for air temperature higher than 35 °C

#### Neutral current

Where 3<sup>rd</sup> harmonic currents are circulating, the neutral conductor may be carrying a significant current and the corresponding additional power losses must be taken into account.

**Figure G23b** represents the maximum admissible phase and neutral currents (per unit) in a high power busbar trunking system as functions of 3<sup>rd</sup> harmonic level.



**Fig. G23b** : Maximum admissible currents (p.u.) in a busbar trunking system as functions of the 3<sup>rd</sup> harmonic level.



## 2 Practical method for determining the smallest allowable cross-sectional area of circuit conductors

The layout of the trunking system depends on the position of the current consumers, the location of the power source and the possibilities for fixing the system.

- One single distribution line serves a 4 to 6 meter area
- Protection devices for current consumers are placed in tap-off units, connected directly to usage points.
- One single feeder supplies all current consumers of different powers.

Once the trunking system layout is established, it is possible to calculate the absorbed current  $I_n$  on the distribution line.

$I_n$  is equal to the sum of absorbed currents by the current  $I_n$  consumers:  $I_n = \Sigma I_B$ .

The current consumers do not all work at the same time and are not permanently on full load, so we have to use a clustering coefficient  $k_s$ :  $I_n = \Sigma (I_B \cdot k_s)$ .

Application	Number of current consumers	Ks Coefficient
Lighting, Heating		1
Distribution (engineering workshop)	2...3	0.9
	4...5	0.8
	6...9	0.7
	10...40	0.6
	40 and over	0.5

*Note : for industrial installations, remember to take account of upgrading of the machine equipment base. As for a switchboard, a 20 % margin is recommended:*

$$I_n \leq I_B \times k_s \times 1.2.$$

**Fig G24** : Clustering coefficient according to the number of current consumers

G19

## 3 Determination of voltage drop

The impedance of circuit conductors is low but not negligible: when carrying load current there is a voltage drop between the origin of the circuit and the load terminals. The correct operation of a load (a motor, lighting circuit, etc.) depends on the voltage at its terminals being maintained at a value close to its rated value. It is necessary therefore to determine the circuit conductors such that at full-load current, the load terminal voltage is maintained within the limits required for correct performance.

This section deals with methods of determining voltage drops, in order to check that:

- They comply with the particular standards and regulations in force
- They can be tolerated by the load
- They satisfy the essential operational requirements

### 3.1 Maximum voltage drop

Maximum allowable voltage-drop vary from one country to another. Typical values for LV installations are given below in **Figure G25**.

G20

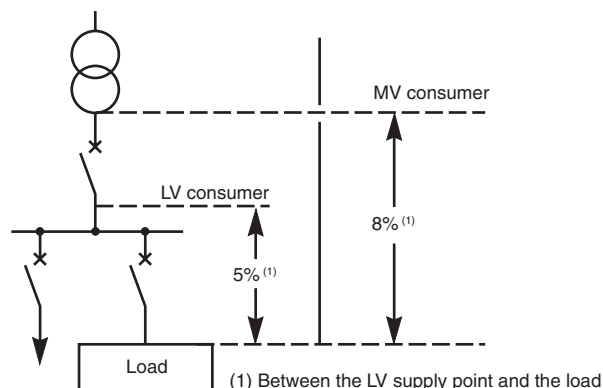
Type of installations	Lighting circuits	Other uses (heating and power)
A low-voltage service connection from a LV public power distribution network	3%	5%
Consumers MV/LV substation supplied from a public distribution MV system	6%	8%

**Fig. G25** : Maximum voltage-drop between the service-connection point and the point of utilization

These voltage-drop limits refer to normal steady-state operating conditions and do not apply at times of motor starting, simultaneous switching (by chance) of several loads, etc. as mentioned in Chapter A Sub-clause 4.3 (factor of simultaneity, etc.). When voltage drops exceed the values shown in Figure G25, larger cables (wires) must be used to correct the condition.

The value of 8%, while permitted, can lead to problems for motor loads; for example:

- In general, satisfactory motor performance requires a voltage within  $\pm 5\%$  of its rated nominal value in steady-state operation,
- Starting current of a motor can be 5 to 7 times its full-load value (or even higher). If an 8% voltage drop occurs at full-load current, then a drop of 40% or more will occur during start-up. In such conditions the motor will either:
  - Stall (i.e. remain stationary due to insufficient torque to overcome the load torque) with consequent over-heating and eventual trip-out
  - Or accelerate very slowly, so that the heavy current loading (with possibly undesirable low-voltage effects on other equipment) will continue beyond the normal start-up period
- Finally an 8% voltage drop represents a continuous power loss, which, for continuous loads will be a significant waste of (metered) energy. For these reasons it is recommended that the maximum value of 8% in steady operating conditions should not be reached on circuits which are sensitive to under-voltage problems (see **Fig. G26**).



**Fig. G26** : Maximum voltage drop

### 3.2 Calculation of voltage drop in steady load conditions

#### Use of formulae

**Figure G27** below gives formulae commonly used to calculate voltage drop in a given circuit per kilometre of length.

If:

- $I_B$ : The full load current in amps
- $L$ : Length of the cable in kilometres
- $R$ : Resistance of the cable conductor in  $\Omega/\text{km}$

$$R = \frac{22.5 \Omega \text{ mm}^2 / \text{km}}{S(\text{c.s.a. in mm}^2)} \text{ for copper}$$

$$R = \frac{36 \Omega \text{ mm}^2 / \text{km}}{S(\text{c.s.a. in mm}^2)} \text{ for aluminium}$$

**Note:**  $R$  is negligible above a c.s.a. of 500  $\text{mm}^2$

- $X$ : inductive reactance of a conductor in  $\Omega/\text{km}$

**Note:**  $X$  is negligible for conductors of c.s.a. less than 50  $\text{mm}^2$ . In the absence of any other information, take  $X$  as being equal to 0.08  $\Omega/\text{km}$ .

- $\varphi$ : phase angle between voltage and current in the circuit considered, generally:

□ Incandescent lighting:  $\cos \varphi = 1$

□ Motor power:

- At start-up:  $\cos \varphi = 0.35$

- In normal service:  $\cos \varphi = 0.8$

- $U_n$ : phase-to-phase voltage

- $V_n$ : phase-to-neutral voltage

For prefabricated pre-wired ducts and bustrunking, resistance and inductive reactance values are given by the manufacturer.

G21

Circuit	Voltage drop ( $\Delta U$ )	
	in volts	in %
Single phase: phase/phase	$\Delta U = 2 I_B (R \cos \varphi + X \sin \varphi) L$	$\frac{100 \Delta U}{U_n}$
Single phase: phase/neutral	$\Delta U = 2 I_B (R \cos \varphi + X \sin \varphi) L$	$\frac{100 \Delta U}{V_n}$
Balanced 3-phase: 3 phases (with or without neutral)	$\Delta U = \sqrt{3} I_B (R \cos \varphi + X \sin \varphi) L$	$\frac{100 \Delta U}{U_n}$

**Fig. G27** : Voltage-drop formulae

#### Simplified table

Calculations may be avoided by using **Figure G28** next page, which gives, with an adequate approximation, the phase-to-phase voltage drop per km of cable per ampere, in terms of:

- Kinds of circuit use: motor circuits with  $\cos \varphi$  close to 0.8, or lighting with a  $\cos \varphi$  close to 1.

- Type of cable; single-phase or 3-phase

Voltage drop in a cable is then given by:

$$K \times I_B \times L$$

$K$  is given by the table,

$I_B$  is the full-load current in amps,

$L$  is the length of cable in km.

The column motor power " $\cos \varphi = 0.35$ " of Figure G28 may be used to compute the voltage drop occurring during the start-up period of a motor (see example no. 1 after the Figure G28).

c.s.a. in mm <sup>2</sup>		Single-phase circuit			Balanced three-phase circuit		
		Motor power		Lighting	Motor power		Lighting
		Normal service	Start-up		Normal service	Start-up	
Cu	Al	cos $\varphi = 0.8$	cos $\varphi = 0.35$	cos $\varphi = 1$	cos $\varphi = 0.8$	cos $\varphi = 0.35$	cos $\varphi = 1$
1.5		24	10.6	30	20	9.4	25
2.5		14.4	6.4	18	12	5.7	15
4		9.1	4.1	11.2	8	3.6	9.5
6	10	6.1	2.9	7.5	5.3	2.5	6.2
10	16	3.7	1.7	4.5	3.2	1.5	3.6
16	25	2.36	1.15	2.8	2.05	1	2.4
25	35	1.5	0.75	1.8	1.3	0.65	1.5
35	50	1.15	0.6	1.29	1	0.52	1.1
50	70	0.86	0.47	0.95	0.75	0.41	0.77
70	120	0.64	0.37	0.64	0.56	0.32	0.55
95	150	0.48	0.30	0.47	0.42	0.26	0.4
120	185	0.39	0.26	0.37	0.34	0.23	0.31
150	240	0.33	0.24	0.30	0.29	0.21	0.27
185	300	0.29	0.22	0.24	0.25	0.19	0.2
240	400	0.24	0.2	0.19	0.21	0.17	0.16
300	500	0.21	0.19	0.15	0.18	0.16	0.13

Fig. G28 : Phase-to-phase voltage drop  $\Delta U$  for a circuit, in volts per ampere per km

G22

### Examples

#### Example 1 (see Fig. G29)

A three-phase 35 mm<sup>2</sup> copper cable 50 metres long supplies a 400 V motor taking:

■ 100 A at a cos  $\varphi = 0.8$  on normal permanent load

■ 500 A (5 In) at a cos  $\varphi = 0.35$  during start-up

The voltage drop at the origin of the motor cable in normal circumstances (i.e. with the distribution board of Figure G29 distributing a total of 1,000 A) is 10 V phase-to-phase.

What is the voltage drop at the motor terminals:

■ In normal service?

■ During start-up?

Solution:

■ Voltage drop in normal service conditions:

$$\Delta U\% = 100 \frac{\Delta U}{U_n}$$

Table G28 shows 1 V/A/km so that:

$$\Delta U \text{ for the cable} = 1 \times 100 \times 0.05 = 5 \text{ V}$$

$$\Delta U \text{ total} = 10 + 5 = 15 \text{ V i.e.}$$

$$\frac{15}{400} \times 100 = 3.75\%$$

This value is less than that authorized (8%) and is satisfactory.

■ Voltage drop during motor start-up:

$$\Delta U_{\text{cable}} = 0.52 \times 500 \times 0.05 = 13 \text{ V}$$

Owing to the additional current taken by the motor when starting, the voltage drop at the distribution board will exceed 10 Volts.

Supposing that the infeed to the distribution board during motor starting is 900 + 500 = 1,400 A then the voltage drop at the distribution board will increase approximately pro rata, i.e.

$$\frac{10 \times 1,400}{1,000} = 14 \text{ V}$$

$$\Delta U \text{ distribution board} = 14 \text{ V}$$

$$\Delta U \text{ for the motor cable} = 13 \text{ V}$$

$$\Delta U \text{ total} = 13 + 14 = 27 \text{ V i.e.}$$

$$\frac{27}{400} \times 100 = 6.75\%$$

a value which is satisfactory during motor starting.

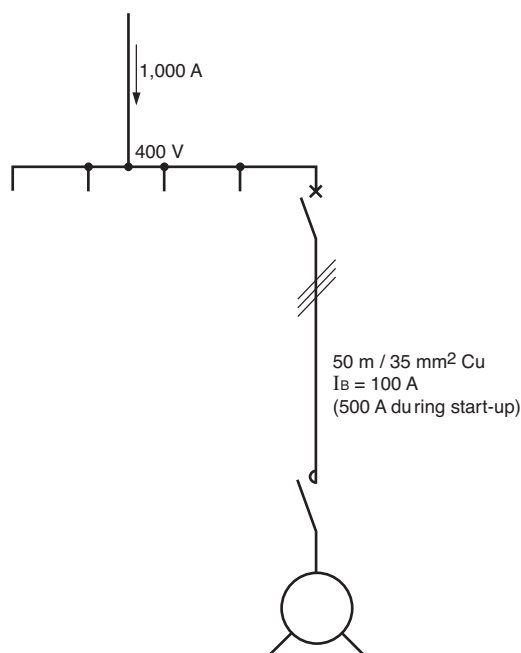


Fig. G29 : Example 1

**Example 2** (see Fig. G30)

A 3-phase 4-wire copper line of 70 mm<sup>2</sup> c.s.a. and a length of 50 m passes a current of 150 A. The line supplies, among other loads, 3 single-phase lighting circuits, each of 2.5 mm<sup>2</sup> c.s.a. copper 20 m long, and each passing 20 A.

It is assumed that the currents in the 70 mm<sup>2</sup> line are balanced and that the three lighting circuits are all connected to it at the same point.

What is the voltage drop at the end of the lighting circuits?

Solution:

■ Voltage drop in the 4-wire line:

$$\Delta U\% = 100 \frac{\Delta U}{U_n}$$

Figure G28 shows 0.55 V/A/km

$$\Delta U_{\text{line}} = 0.55 \times 150 \times 0.05 = 4.125 \text{ V phase-to-phase}$$

$$\text{which gives: } \frac{4.125}{\sqrt{3}} = 2.38 \text{ V phase to neutral.}$$

■ Voltage drop in any one of the lighting single-phase circuits:

$$\Delta U \text{ for a single-phase circuit} = 18 \times 20 \times 0.02 = 7.2 \text{ V}$$

The total voltage drop is therefore

$$7.2 + 2.38 = 9.6 \text{ V}$$

$$\frac{9.6 \text{ V}}{230 \text{ V}} \times 100 = 4.2\%$$

This value is satisfactory, being less than the maximum permitted voltage drop of 6%.

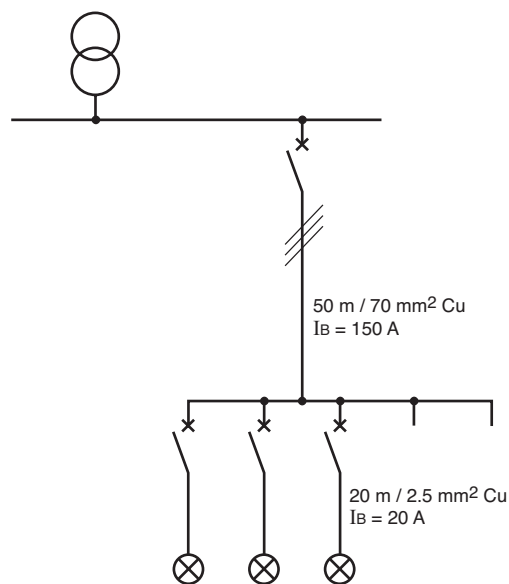


Fig. G30 : Example 2

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Knowing the levels of 3-phase symmetrical short-circuit currents ( $I_{sc}$ ) at different points in an installation is an essential feature of its design

A knowledge of 3-phase symmetrical short-circuit current values ( $I_{sc}$ ) at strategic points of an installation is necessary in order to determine switchgear (fault current rating), cables (thermal withstand rating), protective devices (discriminative trip settings) and so on...

In the following notes a 3-phase short-circuit of zero impedance (the so-called bolted short-circuit) fed through a typical MV/LV distribution transformer will be examined. Except in very unusual circumstances, this type of fault is the most severe, and is certainly the simplest to calculate.

Short-circuit currents occurring in a network supplied from a generator and also in DC systems are dealt with in Chapter N.

The simplified calculations and practical rules which follow give conservative results of sufficient accuracy, in the large majority of cases, for installation design purposes.

## 4.1 Short-circuit current at the secondary terminals of a MV/LV distribution transformer

### The case of one transformer

■ In a simplified approach, the impedance of the MV system is assumed to be

negligibly small, so that:  $I_{sc} = \frac{I_n \times 100}{U_{sc}}$  where  $I_n = \frac{P \times 10^3}{U_{20} \sqrt{3}}$  and:

$P$  = kVA rating of the transformer

$U_{20}$  = phase-to-phase secondary volts on open circuit

$I_n$  = nominal current in amps

$I_{sc}$  = short-circuit fault current in amps

$U_{sc}$  = short-circuit impedance voltage of the transformer in %.

Typical values of  $U_{sc}$  for distribution transformers are given in **Figure G31**.

Transformer rating (kVA)	U <sub>sc</sub> in %	
	Oil-immersed	Cast-resin dry type
50 to 750	4	6
800 to 3,200	6	6

**Fig. G31** : Typical values of  $U_{sc}$  for different kVA ratings of transformers with MV windings  $\leq 20$  kV

### ■ Example

400 kVA transformer, 420 V at no load

$U_{sc} = 4\%$

$$I_n = \frac{400 \times 10^3}{420 \times \sqrt{3}} = 550 \text{ A} \quad I_{sc} = \frac{550 \times 100}{4} = 13.7 \text{ kA}$$

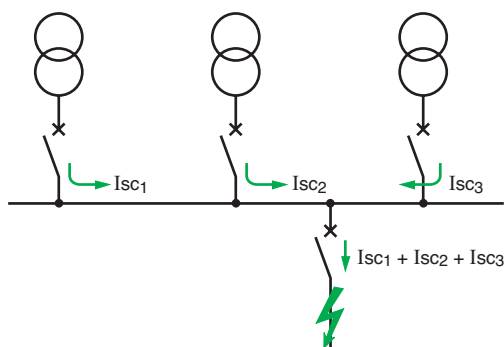
### The case of several transformers in parallel feeding a busbar

The value of fault current on an outgoing circuit immediately downstream of the busbars (see **Fig. G32**) can be estimated as the sum of the  $I_{sc}$  from each transformer calculated separately.

It is assumed that all transformers are supplied from the same MV network, in which case the values obtained from Figure G31 when added together will give a slightly higher fault-level value than would actually occur.

Other factors which have not been taken into account are the impedance of the busbars and of the circuit-breakers.

The conservative fault-current value obtained however, is sufficiently accurate for basic installation design purposes. The choice of circuit-breakers and incorporated protective devices against short-circuit fault currents is described in Chapter H Sub-clause 4.4.



**Fig. G32** : Case of several transformers in parallel

## 4.2 3-phase short-circuit current ( $I_{sc}$ ) at any point within a LV installation

In a 3-phase installation  $I_{sc}$  at any point is given by:

$$I_{sc} = \frac{U_{20}}{\sqrt{3} Z_T} \quad \text{where}$$

$U_{20}$  = phase-to-phase voltage of the open circuited secondary windings of the power supply transformer(s).

$Z_T$  = total impedance per phase of the installation upstream of the fault location (in  $\Omega$ )

### Method of calculating $Z_T$

Each component of an installation (MV network, transformer, cable, circuit-breaker, busbar, and so on...) is characterized by its impedance  $Z$ , comprising an element of resistance ( $R$ ) and an inductive reactance ( $X$ ). It may be noted that capacitive reactances are not important in short-circuit current calculations.

The parameters  $R$ ,  $X$  and  $Z$  are expressed in ohms, and are related by the sides of a right angled triangle, as shown in the impedance diagram of **Figure G33**.

The method consists in dividing the network into convenient sections, and to calculate the  $R$  and  $X$  values for each.

Where sections are connected in series in the network, all the resistive elements in the section are added arithmetically; likewise for the reactances, to give  $R_T$  and  $X_T$ . The impedance ( $Z_T$ ) for the combined sections concerned is then calculated from

$$Z_T = \sqrt{R_T^2 + X_T^2}$$

Any two sections of the network which are connected in parallel, can, if predominantly both resistive (or both inductive) be combined to give a single equivalent resistance (or reactance) as follows:

Let  $R_1$  and  $R_2$  be the two resistances connected in parallel, then the equivalent resistance  $R_3$  will be given by:

$$R_3 = \frac{R_1 \times R_2}{R_1 + R_2} \quad \text{or for reactances } X_3 = \frac{X_1 \times X_2}{X_1 + X_2}$$

It should be noted that the calculation of  $X_3$  concerns only separated circuit without mutual inductance. If the circuits in parallel are close together the value of  $X_3$  will be notably higher.

### Determination of the impedance of each component

#### ■ Network upstream of the MV/LV transformer (see **Fig. G34**)

The 3-phase short-circuit fault level  $P_{sc}$ , in kA or in MVA<sup>(1)</sup> is given by the power supply authority concerned, from which an equivalent impedance can be deduced.

$P_{sc}$	$U_0$ (V)	$R_a$ (m $\Omega$ )	$X_a$ (m $\Omega$ )
250 MVA	420	0.07	0.7
500 MVA	420	0.035	0.351

**Fig. G34** : The impedance of the MV network referred to the LV side of the MV/LV transformer

A formula which makes this deduction and at the same time converts the impedance to an equivalent value at LV is given, as follows:

$$Z_s = \frac{U_0^2}{P_{sc}}$$

where

$Z_s$  = impedance of the MV voltage network, expressed in milli-ohms

$U_0$  = phase-to-phase no-load LV voltage, expressed in volts

$P_{sc}$  = MV 3-phase short-circuit fault level, expressed in kVA

The upstream (MV) resistance  $R_a$  is generally found to be negligible compared with the corresponding  $X_a$ , the latter then being taken as the ohmic value for  $Z_a$ . If more accurate calculations are necessary,  $X_a$  may be taken to be equal to 0.995  $Z_a$  and  $R_a$  equal to 0.1  $X_a$ .

Figure G36 gives values for  $R_a$  and  $X_a$  corresponding to the most common MV<sup>(2)</sup> short-circuit levels in utility power-supply networks, namely, 250 MVA and 500 MVA.

(1) Short-circuit MVA:  $\sqrt{3} E_L I_{sc}$  where:

■  $E_L$  = phase-to-phase nominal system voltage expressed in kV (r.m.s.)

■  $I_{sc}$  = 3-phase short-circuit current expressed in kA (r.m.s.)

(2) up to 36 kV

### ■ Transformers (see Fig. G35)

The impedance  $Z_{tr}$  of a transformer, viewed from the LV terminals, is given by the formula:

$$Z_{tr} = \frac{U_{20}^2}{P_n} \times \frac{U_{sc}}{100}$$

where:

$U_{20}$  = open-circuit secondary phase-to-phase voltage expressed in volts

$P_n$  = rating of the transformer (in kVA)

$U_{sc}$  = the short-circuit impedance voltage of the transformer expressed in %

The transformer windings resistance  $R_{tr}$  can be derived from the total losses as follows:

$$P_{cu} = 3 I_n^2 \times R_{tr} \text{ so that } R_{tr} = \frac{P_{cu} \times 10^3}{3 I_n^2} \text{ in milli-ohms}$$

where

$P_{cu}$  = total losses in watts

$I_n$  = nominal full-load current in amps

$R_{tr}$  = resistance of one phase of the transformer in milli-ohms (the LV and corresponding MV winding for one LV phase are included in this resistance value).

$$X_{tr} = \sqrt{Z_{tr}^2 - R_{tr}^2}$$

For an approximate calculation  $R_{tr}$  may be ignored since  $X \approx Z$  in standard distribution type transformers.

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Rated Power (kVA)	Oil-immersed				Cast-resin			
	Usc (%)	Rtr (mΩ)	Xtr (mΩ)	Ztr (mΩ)	Usc (%)	Rtr (mΩ)	Xtr (mΩ)	Ztr (mΩ)
100	4	37.9	59.5	70.6	6	37.0	99.1	105.8
160	4	16.2	41.0	44.1	6	18.6	63.5	66.2
200	4	11.9	33.2	35.3	6	14.1	51.0	52.9
250	4	9.2	26.7	28.2	6	10.7	41.0	42.3
315	4	6.2	21.5	22.4	6	8.0	32.6	33.6
400	4	5.1	16.9	17.6	6	6.1	25.8	26.5
500	4	3.8	13.6	14.1	6	4.6	20.7	21.2
630	4	2.9	10.8	11.2	6	3.5	16.4	16.8
800	6	2.9	12.9	13.2	6	2.6	13.0	13.2
1,000	6	2.3	10.3	10.6	6	1.9	10.4	10.6
1,250	6	1.8	8.3	8.5	6	1.5	8.3	8.5
1,600	6	1.4	6.5	6.6	6	1.1	6.5	6.6
2,000	6	1.1	5.2	5.3	6	0.9	5.2	5.3

Fig. G35 : Resistance, reactance and impedance values for typical distribution 400 V transformers with MV windings ≤ 20 kV

### ■ Circuit-breakers

In LV circuits, the impedance of circuit-breakers upstream of the fault location must be taken into account. The reactance value conventionally assumed is 0.15 mΩ per CB, while the resistance is neglected.

### ■ Busbars

The resistance of busbars is generally negligible, so that the impedance is practically all reactive, and amounts to approximately 0.15 mΩ/metre<sup>(1)</sup> length for LV busbars (doubling the spacing between the bars increases the reactance by about 10% only).

### ■ Circuit conductors

The resistance of a conductor is given by the formula:  $R_c = \rho \frac{L}{S}$

where

$\rho$  = the resistivity constant of the conductor material at the normal operating temperature being:

□ 22.5 mΩ.mm<sup>2</sup>/m for copper

□ 36 mΩ.mm<sup>2</sup>/m for aluminium

$L$  = length of the conductor in m

$S$  = c.s.a. of conductor in mm<sup>2</sup>

(1) For 50 Hz systems, but 0.18 mΩ/m length at 60 Hz



Cable reactance values can be obtained from the manufacturers. For c.s.a. of less than 50 mm<sup>2</sup> reactance may be ignored. In the absence of other information, a value of 0.08 mΩ/metre may be used (for 50 Hz systems) or 0.096 mΩ/metre (for 60 Hz systems). For prefabricated bus-trunking and similar pre-wired ducting systems, the manufacturer should be consulted.

#### ■ Motors

At the instant of short-circuit, a running motor will act (for a brief period) as a generator, and feed current into the fault.

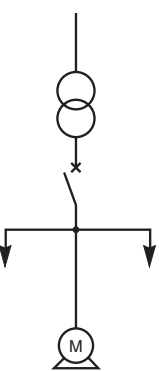
In general, this fault-current contribution may be ignored. However, if the total power of motors running simultaneously is higher than 25% of the total power of transformers, the influence of motors must be taken into account. Their total contribution can be estimated from the formula:

$I_{scm} = 3.5 I_n$  from each motor i.e.  $3.5 m I_n$  for  $m$  similar motors operating concurrently. The motors concerned will be the 3-phase motors only; single-phase-motor contribution being insignificant.

#### ■ Fault-arc resistance

Short-circuit faults generally form an arc which has the properties of a resistance. The resistance is not stable and its average value is low, but at low voltage this resistance is sufficient to reduce the fault-current to some extent. Experience has shown that a reduction of the order of 20% may be expected. This phenomenon will effectively ease the current-breaking duty of a CB, but affords no relief for its fault-current making duty.

■ Recapitulation table (see Fig. G36)

Parts of power-supply system		R (mΩ)	X (mΩ)
	Supply network Figure G34	$R_a$ $X_a = 0.1$	$X_a = 0.995 Z_a$ ; $Z_a = \frac{U_{20}^2}{P_{sc}}$
	Transformer Figure G35	$R_{tr} = \frac{P_{cu} \times 10^3}{3 I_n^2}$  $R_{tr}$ is often negligible compared to $X_{tr}$ for transformers > 100 kVA	$\sqrt{Z_{tr}^2 - R_{tr}^2}$  with $Z_{tr} = \frac{U_{20}^2}{P_n} \times \frac{U_{sc}}{100}$
	Circuit-breaker	Negligible	$X_D = 0.15 \text{ m}\Omega/\text{pole}$
	Busbars	Negligible for $S > 200 \text{ mm}^2$ in the formula: $R = \rho \frac{L}{S}^{(1)}$	$X_B = 0.15 \text{ m}\Omega/\text{m}$
	Circuit conductors <sup>(2)</sup>	$R = \rho \frac{L}{S}^{(1)}$	Cables: $X_c = 0.08 \text{ m}\Omega/\text{m}$
	Motors	See Sub-clause 4.2 Motors (often negligible at LV)	
	<b>Three-phase short circuit current in kA</b>	$I_{sc} = \frac{U_{20}}{\sqrt{3} \sqrt{R_T^2 + X_T^2}}$	

$U_{20}$ : Phase-to-phase no-load secondary voltage of MV/LV transformer (in volts).

$P_{sc}$ : 3-phase short-circuit power at MV terminals of the MV/LV transformers (in kVA).

$P_{cu}$ : 3-phase total losses of the MV/LV transformer (in watts).

$P_n$ : Rating of the MV/LV transformer (in kVA).

$U_{sc}$ : Short-circuit impedance voltage of the MV/LV transformer (in %).

$R_T$ : Total resistance.  $X_T$ : Total reactance

(1)  $\rho$  = resistivity at normal temperature of conductors in service

■  $\rho = 22.5 \text{ m}\Omega \times \text{mm}^2/\text{m}$  for copper

■  $\rho = 36 \text{ m}\Omega \times \text{mm}^2/\text{m}$  for aluminium

(2) If there are several conductors in parallel per phase, then divide the resistance of one conductor by the number of conductors. The reactance remains practically unchanged.

Fig. G36 : Recapitulation table of impedances for different parts of a power-supply system

■ Example of short-circuit calculations (see Fig. G37)

LV installation	R (mΩ)	X (mΩ)	RT (mΩ)	XT (mΩ)	$I_{sc} = \frac{420}{\sqrt{3} \sqrt{R_T^2 + X_T^2}}$
MV network P <sub>sc</sub> = 500 MVA	0.035	0.351			
Transformer 20 kV/420 V P <sub>n</sub> = 1000 kVA U <sub>sc</sub> = 5% P <sub>cu</sub> = 13.3 x 10 <sup>3</sup> watts	2.24	8.10			
Single-core cables 5 m copper 4 x 240 mm <sup>2</sup> /phase	$R_c = \frac{22.5}{4} \times \frac{5}{240} = 0.12$	$X_c = 0.08 \times 5 = 0.40$	2.41	8.85	I <sub>sc1</sub> = 26 kA
Main circuit-breaker	R <sub>D</sub> = 0	X <sub>D</sub> = 0.15			
Busbars 10 m	R <sub>B</sub> = 0	X <sub>B</sub> = 1.5	2.41	10.5	I <sub>sc2</sub> = 22 kA
Three-core cable 100 m 95 mm <sup>2</sup> copper	$R_c = 22.5 \times \frac{100}{95} = 23.68$	$X_c = 100 \times 0.08 = 8$	26.1	18.5	I <sub>sc3</sub> = 7.4 kA
Three-core cable 20 m 10 mm <sup>2</sup> copper final circuits	$R_c = 22.5 \times \frac{20}{10} = 45$	$X_c = 20 \times 0.08 = 1.6$	71.1	20.1	I <sub>sc4</sub> = 3.2 kA

Fig. G37 : Example of short-circuit current calculations for a LV installation supplied at 400 V (nominal) from a 1,000 kVA MV/LV transformer

### 4.3 I<sub>sc</sub> at the receiving end of a feeder as a function of the I<sub>sc</sub> at its sending end

The network shown in **Figure G38** typifies a case for the application of **Figure G39** next page, derived by the «method of composition» (mentioned in Chapter F Sub-clause 6.2). These tables give a rapid and sufficiently accurate value of short-circuit current at a point in a network, knowing:

- The value of short-circuit current upstream of the point considered
- The length and composition of the circuit between the point at which the short-circuit current level is known, and the point at which the level is to be determined

It is then sufficient to select a circuit-breaker with an appropriate short-circuit fault rating immediately above that indicated in the tables.

If more precise values are required, it is possible to make a detailed calculation (see Sub-Clause 4.2) or to use a software package, such as Ecodial. In such a case, moreover, the possibility of using the cascading technique should be considered, in which the use of a current limiting circuit-breaker at the upstream position would allow all circuit-breakers downstream of the limiter to have a short-circuit current rating much lower than would otherwise be necessary (See chapter H Sub-Clause 4.5).

#### Method

Select the c.s.a. of the conductor in the column for copper conductors (in this example the c.s.a. is 47.5 mm<sup>2</sup>).

Search along the row corresponding to 47.5 mm<sup>2</sup> for the length of conductor equal to that of the circuit concerned (or the nearest possible on the low side). Descend vertically the column in which the length is located, and stop at a row in the middle section (of the 3 sections of the Figure) corresponding to the known fault-current level (or the nearest to it on the high side).

In this case 30 kA is the nearest to 28 kA on the high side. The value of short-circuit current at the downstream end of the 20 metre circuit is given at the intersection of the vertical column in which the length is located, and the horizontal row corresponding to the upstream I<sub>sc</sub> (or nearest to it on the high side).

This value in the example is seen to be 14.7 kA.

The procedure for aluminium conductors is similar, but the vertical column must be ascended into the middle section of the table.

In consequence, a DIN-rail-mounted circuit-breaker rated at 63 A and I<sub>sc</sub> of 25 kA (such as a NG 125N unit) can be used for the 55 A circuit in Figure G38.

A Compact rated at 160 A with an I<sub>sc</sub> capacity of 25 kA (such as a NS160 unit) can be used to protect the 160 A circuit.

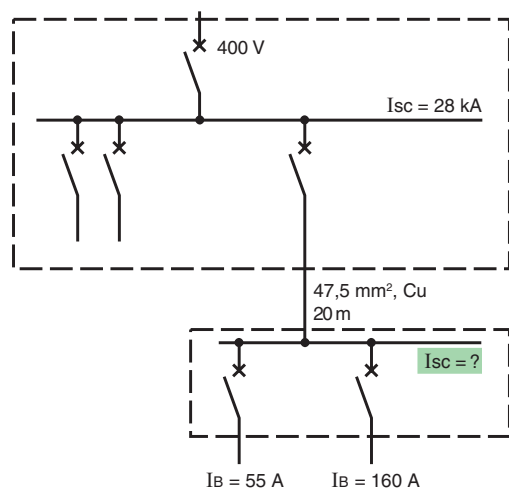


Fig. G38 : Determination of downstream short-circuit current level I<sub>sc</sub> using Figure G39

Copper 230 V / 400 V	
c.s.a. of phase conductors (mm <sup>2</sup> )	Length of circuit (in metres)
1.5	1.3 1.8 2.6 3.6 5.2 7.3 10.3 14.6 21
2.5	1.1 1.5 2.1 3.0 4.3 6.1 8.6 12.1 17.2 24 34
4	1.2 1.7 2.4 3.4 4.9 6.9 9.7 13.7 19.4 27 39 55
6	1.8 2.6 3.6 5.2 7.3 10.3 14.6 21 29 41 58 82
10	2.2 3.0 4.3 6.1 8.6 12.2 17.2 24 34 49 69 97 137
16	1.7 2.4 3.4 4.9 6.9 9.7 13.8 19.4 27 39 55 78 110 155 220
25	1.3 1.9 2.7 3.8 5.4 7.6 10.8 15.2 21 30 43 61 86 121 172 243 343
35	1.9 2.7 3.8 5.3 7.5 10.6 15.1 21 30 43 60 85 120 170 240 340 480
47.5	1.8 2.6 3.6 5.1 7.2 10.2 14.4 20 29 41 58 82 115 163 231 326 461
70	2.7 3.8 5.3 7.5 10.7 15.1 21 30 43 60 85 120 170 240 340
95	2.6 3.6 5.1 7.2 10.2 14.5 20 29 41 58 82 115 163 231 326 461
120	1.6 2.3 3.2 4.6 6.5 9.1 12.9 18.3 26 37 52 73 103 146 206 291 412
150	1.2 1.8 2.5 3.5 5.0 7.0 9.9 14.0 19.8 28 40 56 79 112 159 224 317 448
185	1.5 2.1 2.9 4.2 5.9 8.3 11.7 16.6 23 33 47 66 94 133 187 265 374 529
240	1.8 2.6 3.7 5.2 7.3 10.3 14.6 21 29 41 58 83 117 165 233 330 466 659
300	2.2 3.1 4.4 6.2 8.8 12.4 17.6 25 35 50 70 99 140 198 280 396 561
2x120	2.3 3.2 4.6 6.5 9.1 12.9 18.3 26 37 52 73 103 146 206 292 412 583
2x150	2.5 3.5 5.0 7.0 9.9 14.0 20 28 40 56 79 112 159 224 317 448 634
2x185	2.9 4.2 5.9 8.3 11.7 16.6 23 33 47 66 94 133 187 265 375 530 749
553x120	3.4 4.9 6.9 9.7 13.7 19.4 27 39 55 77 110 155 219 309 438 619
3x150	3.7 5.3 7.5 10.5 14.9 21 30 42 60 84 119 168 238 336 476 672
3x185	4.4 6.2 8.8 12.5 17.6 25 35 50 70 100 141 199 281 398 562
Isc upstream (in kA)	Isc downstream (in kA)
100	93 90 87 82 77 70 62 54 45 37 29 22 17.0 12.6 9.3 6.7 4.9 3.5 2.5 1.8 1.3 0.9
90	84 82 79 75 71 65 58 51 43 35 28 22 16.7 12.5 9.2 6.7 4.8 3.5 2.5 1.8 1.3 0.9
80	75 74 71 68 64 59 54 47 40 34 27 21 16.3 12.2 9.1 6.6 4.8 3.5 2.5 1.8 1.3 0.9
70	66 65 63 61 58 54 49 44 38 32 26 20 15.8 12.0 8.9 6.6 4.8 3.4 2.5 1.8 1.3 0.9
60	57 56 55 53 51 48 44 39 35 29 24 20 15.2 11.6 8.7 6.5 4.7 3.4 2.5 1.8 1.3 0.9
50	48 47 46 45 43 41 38 35 31 27 22 18.3 14.5 11.2 8.5 6.3 4.6 3.4 2.4 1.7 1.2 0.9
40	39 38 38 37 36 34 32 30 27 24 20 16.8 13.5 10.6 8.1 6.1 4.5 3.3 2.4 1.7 1.2 0.9
35	34 34 33 33 32 30 29 27 24 22 18.8 15.8 12.9 10.2 7.9 6.0 4.5 3.3 2.4 1.7 1.2 0.9
30	29 29 29 28 27 27 25 24 22 20 17.3 14.7 12.2 9.8 7.6 5.8 4.4 3.2 2.4 1.7 1.2 0.9
25	25 24 24 24 23 23 22 21 19.1 17.4 15.5 13.4 11.2 9.2 7.3 5.6 4.2 3.2 2.3 1.7 1.2 0.9
20	20 20 19.4 19.2 18.8 18.4 17.8 17.0 16.1 14.9 13.4 11.8 10.1 8.4 6.8 5.3 4.1 3.1 2.3 1.7 1.2 0.9
15	14.8 14.8 14.7 14.5 14.3 14.1 13.7 13.3 12.7 11.9 11.0 9.9 8.7 7.4 6.1 4.9 3.8 2.9 2.2 1.6 1.2 0.9
10	9.9 9.9 9.8 9.8 9.7 9.6 9.4 9.2 8.9 8.5 8.0 7.4 6.7 5.9 5.1 4.2 3.4 2.7 2.0 1.5 1.1 0.8
7	7.0 6.9 6.9 6.9 6.9 6.8 6.7 6.6 6.4 6.2 6.0 5.6 5.2 4.7 4.2 3.6 3.0 2.4 1.9 1.4 1.1 0.8
5	5.0 5.0 5.0 4.9 4.9 4.9 4.9 4.8 4.7 4.6 4.5 4.3 4.0 3.7 3.4 3.0 2.5 2.1 1.7 1.3 1.0 0.8
4	4.0 4.0 4.0 4.0 4.0 3.9 3.9 3.9 3.8 3.7 3.6 3.5 3.3 3.1 2.9 2.6 2.2 1.9 1.6 1.2 1.0 0.7
3	3.0 3.0 3.0 3.0 3.0 3.0 2.9 2.9 2.9 2.8 2.7 2.6 2.5 2.3 2.1 1.9 1.6 1.4 1.1 0.9 0.7
2	2.0 2.0 2.0 2.0 2.0 2.0 2.0 2.0 2.0 1.9 1.9 1.9 1.8 1.8 1.7 1.6 1.4 1.3 1.1 1.0 0.8 0.6
1	1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 0.9 0.9 0.9 0.8 0.8 0.7 0.6 0.5
Aluminium 230 V / 400 V	
c.s.a. of phase conductors (mm <sup>2</sup> )	Length of circuit (in metres)
2.5	1.4 1.9 2.7 3.8 5.4 7.6 10.8 15.3 22
4	1.1 1.5 2.2 3.1 4.3 6.1 8.6 12.2 17.3 24 35
6	1.6 2.3 3.2 4.6 6.5 9.2 13.0 18.3 26 37 52
10	1.9 2.7 3.8 5.4 7.7 10.8 15.3 22 31 43 61 86
16	2.2 3.1 4.3 6.1 8.7 12.2 17.3 24 35 49 69 98 138
25	1.7 2.4 3.4 4.8 6.8 9.6 13.5 19.1 27 38 54 76 108 153 216
35	1.7 2.4 3.4 4.7 6.7 9.5 13.4 18.9 27 38 54 76 107 151 214 302
47.5	1.6 2.3 3.2 4.6 6.4 9.1 12.9 18.2 26 36 51 73 103 145 205 290 410
70	2.4 3.4 4.7 6.7 9.5 13.4 19.0 27 38 54 76 107 151 214 303 428
95	2.3 3.2 4.6 6.4 9.1 12.9 18.2 26 36 51 73 103 145 205 290 411
120	2.9 4.1 5.8 8.1 11.5 16.3 23 32 46 65 92 130 184 259 367
150	3.1 4.4 6.3 8.8 12.5 17.7 25 35 50 71 100 141 199 282 399
185	2.6 3.7 5.2 7.4 10.4 14.8 21 30 42 59 83 118 167 236 333 471
240	1.2 1.6 2.3 3.3 4.6 6.5 9.2 13.0 18.4 26 37 52 73 104 147 208 294 415
300	1.4 2.0 2.8 3.9 5.5 7.8 11.1 15.6 22 31 44 62 88 125 177 250 353 499
2x120	1.4 2.0 2.9 4.1 5.8 8.1 11.5 16.3 23 33 46 65 92 130 184 260 367 519
2x150	1.6 2.2 3.1 4.4 6.3 8.8 12.5 17.7 25 35 50 71 100 141 200 282 399
2x185	1.9 2.6 3.7 5.2 7.4 10.5 14.8 21 30 42 59 83 118 167 236 334 472
2x240	2.3 3.3 4.6 6.5 9.2 13.0 18.4 26 37 52 74 104 147 208 294 415 587
3x120	2.2 3.1 4.3 6.1 8.6 12.2 17.3 24 34 49 69 97 138 195 275 389 551
3x150	2.3 3.3 4.7 6.6 9.4 13.3 18.8 27 37 53 75 106 150 212 299 423 598
3x185	2.8 3.9 5.5 7.8 11.1 15.7 22 31 44 63 89 125 177 250 354 500 707
3x240	3.5 4.9 6.9 9.8 13.8 19.5 28 39 55 78 110 156 220 312 441 623

Note: for a 3-phase system having 230 V between phases, divide the above lengths by  $\sqrt{3}$

**Fig. G39** : Isc at a point downstream, as a function of a known upstream fault-current value and the length and c.s.a. of the intervening conductors, in a 230/400 V 3-phase system

#### 4.4 Short-circuit current supplied by a generator or an inverter: Please refer to Chapter N

## 5 Particular cases of short-circuit current

*If a protective device in a circuit is intended only to protect against short-circuit faults, it is essential that it will operate with certainty at the lowest possible level of short-circuit current that can occur on the circuit*

### 5.1 Calculation of minimum levels of short-circuit current

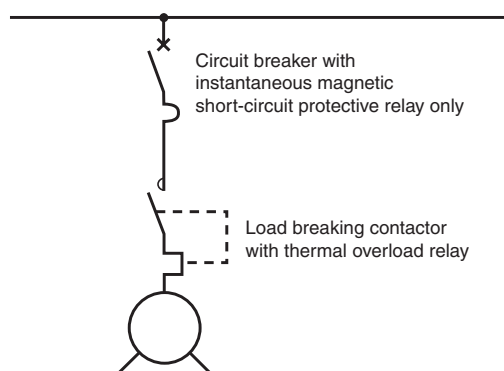
In general, on LV circuits, a single protective device protects against all levels of current, from the overload threshold through the maximum rated short-circuit current-breaking capability of the device.

In certain cases, however, overload protective devices and separate short-circuit protective devices are used.

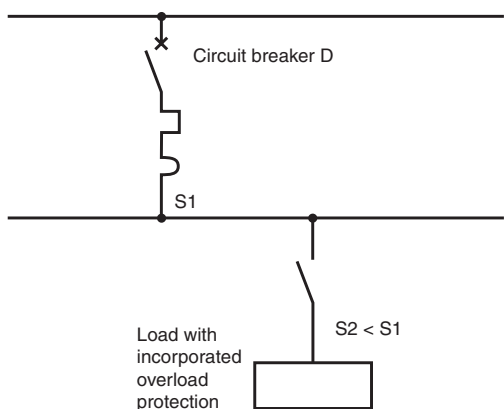
#### Examples of such arrangements

Figures G40 to G42 show some common arrangements where overload and short-circuit protections are achieved by separate devices.

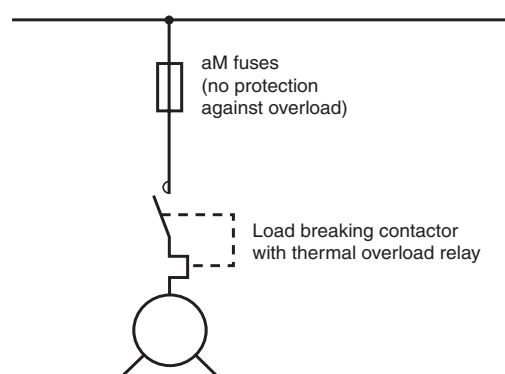
G30



**Fig. G41 :** Circuit protected by circuit-breaker without thermal overload relay



**Fig. G42a :** Circuit-breaker D provides protection against short-circuit faults as far as and including the load



**Fig. G40 :** Circuit protected by aM fuses

As shown in Figures G40 and G41, the most common circuits using separate devices control and protect motors.

Figure G42a constitutes a derogation in the basic protection rules, and is generally used on circuits of prefabricated bustrunking, lighting rails, etc.

#### Variable speed drive

Figure G42b shows the functions provided by the variable speed drive, and if necessary some additional functions provided by devices such as circuit-breaker, thermal relay, RCD.

Protection to be provided	Protection generally provided by the variable speed drive	Additional protection
Cable overload	Yes = (1)	Not necessary if (1)
Motor overload	Yes = (2)	Not necessary if (2)
Downstream short-circuit	Yes	
Variable speed drive overload	Yes	
Overvoltage	Yes	
Undervoltage	Yes	
Loss of phase	Yes	
Upstream short-circuit		Circuit-breaker (short-circuit tripping)
Internal fault		Circuit-breaker (short-circuit and overload tripping)
Downstream earth fault (indirect contact)	(self protection)	RCD $\geq 300$ mA
Direct contact fault		RCD $\leq 30$ mA

**Figure G42b :** Protection to be provided for variable speed drive applications

The protective device must fulfill:

- instantaneous trip setting  $I_m < I_{sc_{min}}$  for a circuit-breaker
- fusion current  $I_a < I_{sc_{min}}$  for a fuse

## Conditions to be fulfilled

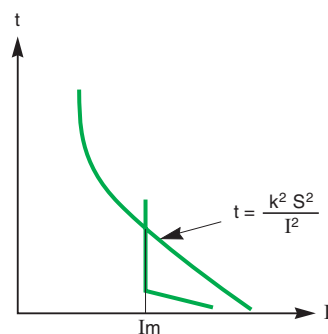
The protective device must therefore satisfy the two following conditions:

- Its fault-current breaking rating must be greater than  $I_{sc}$ , the 3-phase short-circuit current at its point of installation
- Elimination of the minimum short-circuit current possible in the circuit, in a time  $t_c$  compatible with the thermal constraints of the circuit conductors, where:

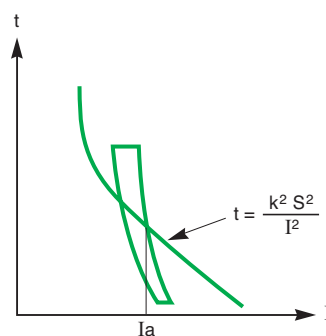
$$t_c \leq \frac{K^2 S^2}{I_{sc_{min}}^2} \quad (\text{valid for } t_c < 5 \text{ seconds})$$

Comparison of the tripping or fusing performance curve of protective devices, with the limit curves of thermal constraint for a conductor shows that this condition is satisfied if:

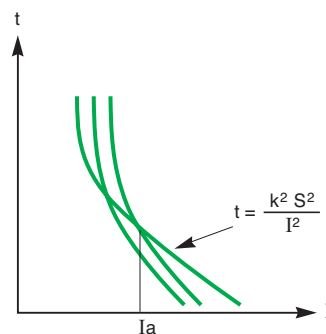
- $I_{sc}(\min) > I_m$  (instantaneous or short timedelay circuit-breaker trip setting current level), (see **Fig. G45**)
- $I_{sc}(\min) > I_a$  for protection by fuses. The value of the current  $I_a$  corresponds to the crossing point of the fuse curve and the cable thermal withstand curve (see **Fig. G44** and **G45**)



**Fig. G45** : Protection by circuit-breaker



**Fig. G46** : Protection by aM-type fuses



**Fig. G47** : Protection by gI-type fuses

In practice this means that the length of circuit downstream of the protective device must not exceed a calculated maximum length:

$$L_{\max} = \frac{0.8 U S_{ph}}{2p I_m}$$

## Practical method of calculating $L_{\max}$

The limiting effect of the impedance of long circuit conductors on the value of short-circuit currents must be checked and the length of a circuit must be restricted accordingly.

The method of calculating the maximum permitted length has already been demonstrated in TN- and IT- earthed schemes for single and double earth faults, respectively (see Chapter F Sub-clauses 6.2 and 7.2). Two cases are considered below:

### 1 - Calculation of $L_{\max}$ for a 3-phase 3-wire circuit

The minimum short-circuit current will occur when two phase wires are short-circuited at the remote end of the circuit (see Fig. G46).



Fig G46 : Definition of  $L$  for a 3-phase 3-wire circuit

Using the “conventional method”, the voltage at the point of protection  $P$  is assumed to be 80% of the nominal voltage during a short-circuit fault, so that  $0.8 U = I_{sc} Z_d$ , where:

$Z_d$  = impedance of the fault loop

$I_{sc}$  = short-circuit current (ph/ph)

$U$  = phase-to-phase nominal voltage

For cables  $\leq 120 \text{ mm}^2$ , reactance may be neglected, so that

$$Z_d = \rho \frac{2L}{S_{ph}} \quad (1)$$

where:

$\rho$  = resistivity of conductor material at the average temperature during a short-circuit,

$S_{ph}$  = c.s.a. of a phase conductor in  $\text{mm}^2$

$L$  = length in metres

The condition for the cable protection is  $I_m \leq I_{sc}$  with  $I_m$  = magnetic trip current setting of the CB.

$$\text{This leads to } I_m \leq \frac{0.8 U}{Z_d} \quad \text{which gives } L \leq \frac{0.8 U S_{ph}}{2p I_m}$$

with  $U = 400 \text{ V}$

$$\rho = 1.25 \times 0.018 = 0.023 \Omega \cdot \text{mm}^2/\text{m}^{(2)} \text{ (Cu)}$$

$L_{\max}$  = maximum circuit length in metres

$$L_{\max} = \frac{k S_{ph}}{I_m}$$

### 2 - Calculation of $L_{\max}$ for a 3-phase 4-wire 230/400 V circuit

The minimum  $I_{sc}$  will occur when the short-circuit is between a phase conductor and the neutral.

A calculation similar to that of example 1 above is required, but using the following formulae (for cable  $\leq 120 \text{ mm}^2$  <sup>(1)</sup>).

■ Where  $S_n$  for the neutral conductor =  $S_{ph}$  for the phase conductor

$$L_{\max} = \frac{3,333 S_{ph}}{I_m}$$

■ If  $S_n$  for the neutral conductor  $< S_{ph}$ , then

$$L_{\max} = 6,666 \frac{S_{ph}}{I_m} \frac{1}{1+m} \quad \text{where } m = \frac{S_{ph}}{S_n}$$

For larger c.s.a.'s than those listed, reactance values must be combined with those of resistance to give an impedance. Reactance may be taken as  $0.08 \text{ m}\Omega/\text{m}$  for cables (at 50 Hz). At 60 Hz the value is  $0.096 \text{ m}\Omega/\text{m}$ .

(1) For larger c.s.a.'s, the resistance calculated for the conductors must be increased to account for the non-uniform current density in the conductor (due to “skin” and “proximity” effects)

Suitable values are as follows:

150  $\text{mm}^2$ :  $R + 15\%$

185  $\text{mm}^2$ :  $R + 20\%$

240  $\text{mm}^2$ :  $R + 25\%$

300  $\text{mm}^2$ :  $R + 30\%$

(2) The high value for resistivity is due to the elevated temperature of the conductor when passing short-circuit current

## 5 Particular cases of short-circuit current

### Tabulated values for L<sub>max</sub>

Figure G47 below gives maximum circuit lengths (L<sub>max</sub>) in metres, for:

■ 3-phase 4-wire 400 V circuits (i.e. with neutral) and

■ 1-phase 2-wire 230 V circuits

protected by general-purpose circuit-breakers.

In other cases, apply correction factors (given in Figure G53) to the lengths obtained. The calculations are based on the above methods, and a short-circuit trip level within  $\pm 20\%$  of the adjusted value I<sub>m</sub>.

For the 50 mm<sup>2</sup> c.s.a., calculation are based on a 47.5 mm<sup>2</sup> real c.s.a.

Operating current level I <sub>m</sub> of the instantaneous magnetic tripping element (in A)	c.s.a. (nominal cross-sectional-area) of conductors (in mm <sup>2</sup> )														
	1.5	2.5	4	6	10	16	25	35	50	70	95	120	150	185	240
50	100	167	267	400											
63	79	133	212	317											
80	63	104	167	250	417										
100	50	83	133	200	333										
125	40	67	107	160	267	427									
160	31	52	83	125	208	333									
200	25	42	67	100	167	267	417								
250	20	33	53	80	133	213	333	467							
320	16	26	42	63	104	167	260	365	495						
400	13	21	33	50	83	133	208	292	396						
500	10	17	27	40	67	107	167	233	317						
560	9	15	24	36	60	95	149	208	283	417					
630	8	13	21	32	63	85	132	185	251	370					
700	7	12	19	29	48	76	119	167	226	333	452				
800	6	10	17	25	42	67	104	146	198	292	396				
875	6	10	15	23	38	61	95	133	181	267	362	457			
1000	5	8	13	20	33	53	83	117	158	233	317	400	435		
1120	4	7	12	18	30	48	74	104	141	208	283	357	388	459	
1250	4	7	11	16	27	43	67	93	127	187	253	320	348	411	
1600		5	8	13	21	33	52	73	99	146	198	250	272	321	400
2000		4	7	10	17	27	42	58	79	117	158	200	217	257	320
2500			5	8	13	21	33	47	63	93	127	160	174	206	256
3200			4	6	10	17	26	36	49	73	99	125	136	161	200
4000				5	8	13	21	29	40	58	79	100	109	128	160
5000				4	7	11	17	23	32	47	63	80	87	103	128
6300					5	8	13	19	25	37	50	63	69	82	102
8000					4	7	10	15	20	29	40	50	54	64	80
10000						5	8	12	16	23	32	40	43	51	64
12500						4	7	9	13	19	25	32	35	41	51

Fig. G47 : Maximum circuit lengths in metres for copper conductors (for aluminium, the lengths must be multiplied by 0.62)

Figures G48 to G50 next page give maximum circuit length (L<sub>max</sub>) in metres for:

■ 3-phase 4-wire 400 V circuits (i.e. with neutral) and

■ 1-phase 2-wire 230 V circuits

protected in both cases by domestic-type circuit-breakers or with circuit-breakers having similar tripping/current characteristics.

In other cases, apply correction factors to the lengths indicated. These factors are given in Figure G51 next page.

# 5 Particular cases of short-circuit current

Rated current of circuit-breakers (in A)	c.s.a. (nominal cross-sectional-area) of conductors (in mm <sup>2</sup> )								
	1.5	2.5	4	6	10	16	25	35	50
6	200	333	533	800					
10	120	200	320	480	800				
16	75	125	200	300	500	800			
20	60	100	160	240	400	640			
25	48	80	128	192	320	512	800		
32	37	62	100	150	250	400	625	875	
40	30	50	80	120	200	320	500	700	
50	24	40	64	96	160	256	400	560	760
63	19	32	51	76	127	203	317	444	603
80	15	25	40	60	100	160	250	350	475
100	12	20	32	48	80	128	200	280	380
125	10	16	26	38	64	102	160	224	304

**Fig. G48** : Maximum length of copper-conductor circuits in metres protected by B-type circuit-breakers

Rated current of circuit-breakers (in A)	c.s.a. (nominal cross-sectional-area) of conductors (in mm <sup>2</sup> )								
	1.5	2.5	4	6	10	16	25	35	50
6	100	167	267	400	667				
10	60	100	160	240	400	640			
16	37	62	100	150	250	400	625	875	
20	30	50	80	120	200	320	500	700	
25	24	40	64	96	160	256	400	560	760
32	18.0	31	50	75	125	200	313	438	594
40	15.0	25	40	60	100	160	250	350	475
50	12.0	20	32	48	80	128	200	280	380
63	9.5	16.0	26	38	64	102	159	222	302
80	7.5	12.5	20	30	50	80	125	175	238
100	6.0	10.0	16.0	24	40	64	100	140	190
125	5.0	8.0	13.0	19.0	32	51	80	112	152

**Fig. G49** : Maximum length of copper-conductor circuits in metres protected by C-type circuit-breakers

Rated current of circuit-breakers (in A)	c.s.a. (nominal cross-sectional-area) of conductors (in mm <sup>2</sup> )								
	1.5	2.5	4	6	10	16	25	35	50
1	429	714							
2	214	357	571	857					
3	143	238	381	571	952				
4	107	179	286	429	714				
6	71	119	190	286	476	762			
10	43	71	114	171	286	457	714		
16	27	45	71	107	179	286	446	625	848
20	21	36	57	86	143	229	357	500	679
25	17.0	29	46	69	114	183	286	400	543
32	13.0	22	36	54	89	143	223	313	424
40	11.0	18.0	29	43	71	114	179	250	339
50	9.0	14.0	23	34	57	91	143	200	271
63	7.0	11.0	18.0	27	45	73	113	159	215
80	5.0	9.0	14.0	21	36	57	89	125	170
100	4.0	7.0	11.0	17.0	29	46	71	100	136
125	3.0	6.0	9.0	14.0	23	37	57	80	109

**Fig. G50** : Maximum length of copper-conductor circuits in metres protected by D-type circuit-breakers

Circuit detail		
3-phase 3-wire 400 V circuit or 1-phase 2-wire 400 V circuit (no neutral)		1.73
1-phase 2-wire (phase and neutral) 230 V circuit		1
3-phase 4-wire 230/400 V circuit or 2-phase 3-wire 230/400 V circuit (i.e with neutral)	Sph / S neutral = 1	1
	Sph / S neutral = 2	0.67

**Fig. G51** : Correction factor to apply to lengths obtained from Figures G47 to G50

**Note:** IEC 60898 accepts an upper short-circuit-current tripping range of 10-50 In for type D circuit-breakers. European standards, and Figure G50 however, are based on a range of 10-20 In, a range which covers the vast majority of domestic and similar installations.



## Examples

### Example 1

In a 1-phase 2-wire installation the protection is provided by a 50 A circuit-breaker type NSX80HMA, the instantaneous short-circuit current trip, is set at 500 A (accuracy of  $\pm 20\%$ ), i.e. in the worst case would require  $500 \times 1,2 = 600$  A to trip. The cable c.s.a. =  $10 \text{ mm}^2$  and the conductor material is copper.

In Figure G47, the row  $I_m = 500$  A crosses the column c.s.a. =  $10 \text{ mm}^2$  at the value for  $L_{\max}$  of 67 m. The circuit-breaker protects the cable against short-circuit faults, therefore, provided that its length does not exceed 67 metres.

### Example 2

In a 3-phase 3-wire 400 V circuit (without neutral), the protection is provided by a 220 A circuit-breaker type NSX250N with an instantaneous short-circuit current trip unit type MA set at 2,000 A ( $\pm 20\%$ ), i.e. a worst case of 2,400 A to be certain of tripping. The cable c.s.a. =  $120 \text{ mm}^2$  and the conductor material is copper.

In Figure G47 the row  $I_m = 2,000$  A crosses the column c.s.a. =  $120 \text{ mm}^2$  at the value for  $L_{\max}$  of 200 m. Being a 3-phase 3-wire 400 V circuit (without neutral), a correction factor from Figure G51 must be applied. This factor is seen to be 1.73. The circuit-breaker will therefore protect the cable against short-circuit current, provided that its length does not exceed  $200 \times 1.73 = 346$  metres.

G35

## 5.2 Verification of the withstand capabilities of cables under short-circuit conditions

*In general, verification of the thermal-withstand capability of a cable is not necessary, except in cases where cables of small c.s.a. are installed close to, or feeding directly from, the main general distribution board*

### Thermal constraints

When the duration of short-circuit current is brief (several tenths of a second up to five seconds maximum) all of the heat produced is assumed to remain in the conductor, causing its temperature to rise. The heating process is said to be adiabatic, an assumption that simplifies the calculation and gives a pessimistic result, i.e. a higher conductor temperature than that which would actually occur, since in practice, some heat would leave the conductor and pass into the insulation.

For a period of 5 seconds or less, the relationship  $I^2t = k^2S^2$  characterizes the time in seconds during which a conductor of c.s.a.  $S$  (in  $\text{mm}^2$ ) can be allowed to carry a current  $I$ , before its temperature reaches a level which would damage the surrounding insulation.

The factor  $k^2$  is given in **Figure G52** below.

Insulation	Conductor copper (Cu)	Conductor aluminium (Al)
PVC	13,225	5,776
XLPE	20,449	8,836

**Fig. G52** : Value of the constant  $k^2$

The method of verification consists in checking that the thermal energy  $I^2t$  per ohm of conductor material, allowed to pass by the protecting circuit-breaker (from manufacturers catalogues) is less than that permitted for the particular conductor (as given in **Figure G53** below).

S ( $\text{mm}^2$ )	PVC		XLPE	
	Copper	Aluminium	Copper	Aluminium
1.5	0.0297	0.0130	0.0460	0.0199
2.5	0.0826	0.0361	0.1278	0.0552
4	0.2116	0.0924	0.3272	0.1414
6	0.4761	0.2079	0.7362	0.3181
10	1.3225	0.5776	2.0450	0.8836
16	3.3856	1.4786	5.2350	2.2620
25	8.2656	3.6100	12.7806	5.5225
35	16.2006	7.0756	25.0500	10.8241
50	29.839	13.032	46.133	19.936

**Fig. G53** : Maximum allowable thermal stress for cables  $I^2t$  (expressed in  $\text{ampere}^2 \times \text{second} \times 10^6$ )

## 5 Particular cases of short-circuit current

### Example

Is a copper-cored XLPE cable of 4 mm<sup>2</sup> c.s.a. adequately protected by a C60N circuit-breaker?

Figure G53 shows that the  $I^2t$  value for the cable is  $0.3272 \times 10^6$ , while the maximum “let-through” value by the circuit-breaker, as given in the manufacturer’s catalogue, is considerably less ( $< 0.1 \cdot 10^6 \text{ A}^2\text{s}$ ).

The cable is therefore adequately protected by the circuit-breaker up to its full rated breaking capability.

### Electrodynamic constraints

For all type of circuit (conductors or bus-trunking), it is necessary to take electrodynamic effects into account.

To withstand the electrodynamic constraints, the conductors must be solidly fixed and the connection must be strongly tightened.

For bus-trunking, rails, etc. it is also necessary to verify that the electrodynamic withstand performance is satisfactory when carrying short-circuit currents. The peak value of current, limited by the circuit-breaker or fuse, must be less than the busbar system rating. Tables of coordination ensuring adequate protection of their products are generally published by the manufacturers and provide a major advantage of such systems.

**G36**

## 6 Protective earthing conductor (PE)

### 6.1 Connection and choice

Protective (PE) conductors provide the bonding connection between all exposed and extraneous conductive parts of an installation, to create the main equipotential bonding system. These conductors conduct fault current due to insulation failure (between a phase conductor and an exposed conductive part) to the earthed neutral of the source. PE conductors are connected to the main earthing terminal of the installation.

The main earthing terminal is connected to the earthing electrode (see Chapter E) by the earthing conductor (grounding electrode conductor in the USA).

PE conductors must be:

- Insulated and coloured yellow and green (stripes)
- Protected against mechanical and chemical damage

In IT and TN-earthed schemes it is strongly recommended that PE conductors should be installed in close proximity (i.e. in the same conduits, on the same cable tray, etc.) as the live cables of the related circuit. This arrangement ensures the minimum possible inductive reactance in the earth-fault current carrying circuits. It should be noted that this arrangement is originally provided by bus-trunking.

#### Connection

PE conductors must:

- Not include any means of breaking the continuity of the circuit (such as a switch, removable links, etc.)
- Connect exposed conductive parts individually to the main PE conductor, i.e. in parallel, not in series, as shown in **Figure G54**
- Have an individual terminal on common earthing bars in distribution boards.

#### TT scheme

The PE conductor need not necessarily be installed in close proximity to the live conductors of the corresponding circuit, since high values of earth-fault current are not needed to operate the RCD-type of protection used in TT installations.

#### IT and TN schemes

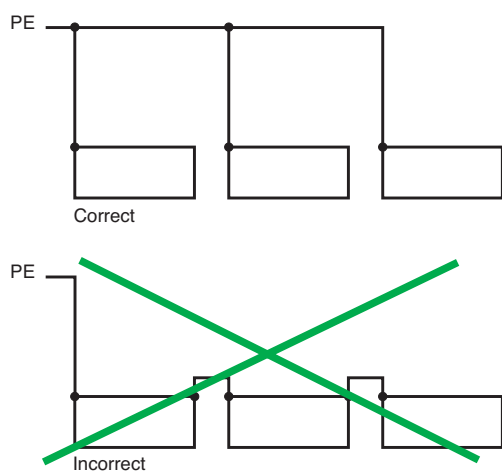
The PE or PEN conductor, as previously noted, must be installed as close as possible to the corresponding live conductors of the circuit and no ferro-magnetic material must be interposed between them. A PEN conductor must always be connected directly to the earth terminal of an appliance, with a looped connection from the earth terminal to the neutral terminal of the appliance (see **Fig. G55**).

- TN-C scheme (the neutral and PE conductor are one and the same, referred to as a PEN conductor)

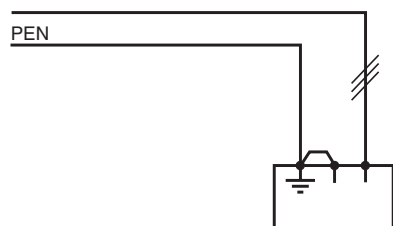
The protective function of a PEN conductor has priority, so that all rules governing PE conductors apply strictly to PEN conductors

- TN-C to TN-S transition

The PE conductor for the installation is connected to the PEN terminal or bar (see **Fig. G56**) generally at the origin of the installation. Downstream of the point of separation, no PE conductor can be connected to the neutral conductor.



**Fig. G54** : A poor connection in a series arrangement will leave all downstream appliances unprotected



**Fig. G55** : Direct connection of the PEN conductor to the earth terminal of an appliance



**Fig. G56** : The TN-C-S scheme

G37

## 6 Protective earthing conductor (PE)

### Types of materials

Materials of the kinds mentioned below in **Figure G57** can be used for PE conductors, provided that the conditions mentioned in the last column are satisfied.

Type of protective earthing conductor (PE)		IT scheme	TN scheme	TT scheme	Conditions to be respected
Supplementary conductor	In the same cable as the phases, or in the same cable run	Strongly recommended	Strongly recommended	Correct	The PE conductor must be insulated to the same level as the phases
	Independent of the phase conductors	Possible <sup>(1)</sup>	Possible <sup>(1) (2)</sup>	Correct	■ The PE conductor may be bare or insulated <sup>(2)</sup>
Metallic housing of bus-trunking or of other prefabricated prewired ducting <sup>(5)</sup>		Possible <sup>(3)</sup>	PE possible <sup>(3)</sup> PEN possible <sup>(8)</sup>	Correct	■ The electrical continuity must be assured by protection against deterioration by mechanical, chemical and electrochemical hazards
External sheath of extruded, mineral- insulated conductors (e.g. «pyrotenax» type systems)		Possible <sup>(3)</sup>	PE possible <sup>(3)</sup> PEN not recommended <sup>(2)(3)</sup>	Possible	■ Their conductance must be adequate
Certain extraneous conductive elements <sup>(6)</sup> such as:		Possible <sup>(4)</sup>	PE possible <sup>(4)</sup> PEN forbidden	Possible	
■ Steel building structures ■ Machine frames ■ Water pipes <sup>(7)</sup>					
Metallic cable ways, such as, conduits <sup>(9)</sup> , ducts, trunking, trays, ladders, and so on...		Possible <sup>(4)</sup>	PE possible <sup>(4)</sup> PEN not recommended <sup>(2)(4)</sup>	Possible	

Forbidden for use as PE conductors, are: metal conduits <sup>(9)</sup>, gas pipes, hot-water pipes, cable-armouring tapes <sup>(9)</sup> or wires <sup>(9)</sup>

(1) In TN and IT schemes, fault clearance is generally achieved by overcurrent devices (fuses or circuit-breakers) so that the impedance of the fault-current loop must be sufficiently low to assure positive protective device operation. The surest means of achieving a low loop impedance is to use a supplementary core in the same cable as the circuit conductors (or taking the same route as the circuit conductors). This solution minimizes the inductive reactance and therefore the impedance of the loop.

(2) The PEN conductor is a neutral conductor that is also used as a protective earth conductor. This means that a current may be flowing through it at any time (in the absence of an earth fault). For this reason an insulated conductor is recommended for PEN operation.

(3) The manufacturer provides the necessary values of R and X components of the impedances (phase/PE, phase/PEN) to include in the calculation of the earth-fault loop impedance.

(4) Possible, but not recommended, since the impedance of the earth-fault loop cannot be known at the design stage. Measurements on the completed installation are the only practical means of assuring adequate protection for persons.

(5) It must allow the connection of other PE conductors. **Note:** these elements must carry an individual green/yellow striped visual indication, 15 to 100 mm long (or the letters PE at less than 15 cm from each extremity).

(6) These elements must be demountable only if other means have been provided to ensure uninterrupted continuity of protection.

(7) With the agreement of the appropriate water authorities.

(8) In the prefabricated pre-wired trunking and similar elements, the metallic housing may be used as a PEN conductor, in parallel with the corresponding bar, or other PE conductor in the housing.

(9) Forbidden in some countries only. Universally allowed to be used for supplementary equipotential conductors.

Fig. G57 : Choice of protective conductors (PE)

### 6.2 Conductor sizing

**Figure G58** below is based on IEC 60364-5-54. This table provides two methods of determining the appropriate c.s.a. for both PE or PEN conductors.

	c.s.a. of phase conductors $S_{ph}$ (mm <sup>2</sup> )	Minimum c.s.a. of PE conductor (mm <sup>2</sup> )	Minimum c.s.a. of PEN conductor (mm <sup>2</sup> )	
			Cu	Al
Simplified method <sup>(1)</sup>	$S_{ph} \leq 16$	$S_{ph}^{(2)}$	$S_{ph}^{(3)}$	$S_{ph}^{(3)}$
	$16 < S_{ph} \leq 25$	16	16	
	$25 < S_{ph} \leq 35$			25
	$35 < S_{ph} \leq 50$	$S_{ph}/2$	$S_{ph}/2$	
	$S_{ph} > 50$			$S_{ph}/2$
Adiabatic method	Any size	$S_{PE/PEN} = \frac{\sqrt{I^2 \cdot t}}{k}^{(3) (4)}$		

(1) Data valid if the prospective conductor is of the same material as the line conductor. Otherwise, a correction factor must be applied.

(2) When the PE conductor is separated from the circuit phase conductors, the following minimum values must be respected:

■ 2.5 mm<sup>2</sup> if the PE is mechanically protected

■ 4 mm<sup>2</sup> if the PE is not mechanically protected

(3) For mechanical reasons, a PEN conductor, shall have a cross-sectional area not less than 10 mm<sup>2</sup> in copper or 16 mm<sup>2</sup> in aluminium.

(4) Refer to table G53 for the application of this formula.

Fig. G58 : Minimum cross section area of protective conductors

## 6 Protective earthing conductor (PE)

The two methods are:

■ **Adiabatic** (which corresponds with that described in IEC 60724)

This method, while being economical and assuring protection of the conductor against overheating, leads to small c.s.a.'s compared to those of the corresponding circuit phase conductors. The result is sometimes incompatible with the necessity in IT and TN schemes to minimize the impedance of the circuit earth-fault loop, to ensure positive operation by instantaneous overcurrent tripping devices. This method is used in practice, therefore, for TT installations, and for dimensioning an earthing conductor <sup>(1)</sup>.

■ **Simplified**

This method is based on PE conductor sizes being related to those of the corresponding circuit phase conductors, assuming that the same conductor material is used in each case.

Thus, in Figure G58 for:

$$S_{ph} \leq 16 \text{ mm}^2 \quad S_{PE} = S_{ph}$$

$$16 < S_{ph} \leq 35 \text{ mm}^2 \quad S_{PE} = 16 \text{ mm}^2$$

$$S_{ph} > 35 \text{ mm}^2 \quad S_{PE} = \frac{S_{ph}}{2}$$

**Note:** when, in a TT scheme, the installation earth electrode is beyond the zone of influence of the source earthing electrode, the c.s.a. of the PE conductor can be limited to 25 mm<sup>2</sup> (for copper) or 35 mm<sup>2</sup> (for aluminium).

The neutral cannot be used as a PEN conductor unless its c.s.a. is equal to or larger than 10 mm<sup>2</sup> (copper) or 16 mm<sup>2</sup> (aluminium).

Moreover, a PEN conductor is not allowed in a flexible cable. Since a PEN conductor functions also as a neutral conductor, its c.s.a. cannot, in any case, be less than that necessary for the neutral, as discussed in Subclause 7.1 of this Chapter.

This c.s.a. cannot be less than that of the phase conductors unless:

■ The kVA rating of single-phase loads is less than 10% of the total kVA load, and

■ I<sub>max</sub> likely to pass through the neutral in normal circumstances, is less than the current permitted for the selected cable size.

Furthermore, protection of the neutral conductor must be assured by the protective devices provided for phase-conductor protection (described in Sub-clause 7.2 of this Chapter).

### Values of factor k to be used in the formulae

These values are identical in several national standards, and the temperature rise ranges, together with factor k values and the upper temperature limits for the different classes of insulation, correspond with those published in IEC 60724 (1984).

The data presented in **Figure G59** are those most commonly needed for LV installation design.

k values		Nature of insulation	
		Polyvinylchloride (PVC)	Cross-linked-polyethylene (XLPE) Ethylene-propylene-rubber (EPR)
Final temperature (°C)		160	250
Initial temperature (°C)		30	30
Insulated conductors not incorporated in cables or bare conductors in contact with cable jackets	Copper	143	176
	Aluminium	95	116
	Steel	52	64
Conductors of a multi-core-cable	Copper	115	143
	Aluminium	76	94

**Fig. G59** : k factor values for LV PE conductors, commonly used in national standards and complying with IEC 60724

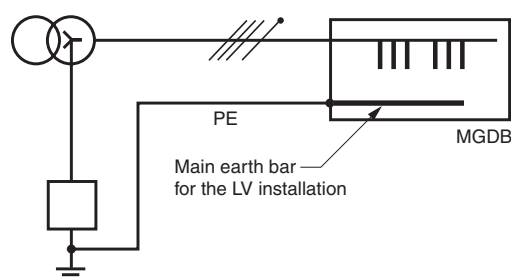
(1) Grounding electrode conductor

*These conductors must be sized according to national practices*

## 6.3 Protective conductor between MV/LV transformer and the main general distribution board (MGDB)

All phase and neutral conductors upstream of the main incoming circuit-breaker controlling and protecting the MGDB are protected by devices at the MV side of the transformer. The conductors in question, together with the PE conductor, must be dimensioned accordingly. Dimensioning of the phase and neutral conductors from the transformer is exemplified in Sub-clause 7.5 of this chapter (for circuit C1 of the system illustrated in Fig. G65).

Recommended conductor sizes for bare and insulated PE conductors from the transformer neutral point, shown in **Figure G60**, are indicated below in **Figure G61**. The kVA rating to consider is the sum of all (if more than one) transformers connected to the MGDB.



**Fig. G60** : PE conductor to the main earth bar in the MGDB

The table indicates the c.s.a. of the conductors in mm<sup>2</sup> according to:

- The nominal rating of the MV/LV transformer(s) in kVA
- The fault-current clearance time by the MV protective devices, in seconds
- The kinds of insulation and conductor materials

If the MV protection is by fuses, then use the 0.2 seconds columns.

In IT schemes, if an overvoltage protection device is installed (between the transformer neutral point and earth) the conductors for connection of the device should also be dimensioned in the same way as that described above for PE conductors.

Transformer rating in kVA (230/400 V output)	Conductor material	Bare conductors			PVC-insulated conductors			XLPE-insulated conductors		
		Copper t(s)			0.2 0.5 -			0.2 0.5 -		
		Aluminium t(s)			- 0.2 0.5			- 0.2 0.5		
≤100	c.s.a. of PE	25	25	25	25	25	25	25	25	25
160	conductors	25	25	35	25	25	50	25	25	35
200	SPE (mm <sup>2</sup> )	25	35	50	25	35	50	25	25	50
250		25	35	70	35	50	70	25	35	50
315		35	50	70	35	50	95	35	50	70
400		50	70	95	50	70	95	35	50	95
500		50	70	120	70	95	120	50	70	95
630		70	95	150	70	95	150	70	95	120
800		70	120	150	95	120	185	70	95	150
1,000		95	120	185	95	120	185	70	120	150
1,250		95	150	185	120	150	240	95	120	185

**Fig. G61** : Recommended c.s.a. of PE conductor between the MV/LV transformer and the MGDB, as a function of transformer ratings and fault-clearance times.

## 6.4 Equipotential conductor

### The main equipotential conductor

This conductor must, in general, have a c.s.a. at least equal to half of that of the largest PE conductor, but in no case need exceed 25 mm<sup>2</sup> (copper) or 35 mm<sup>2</sup> (aluminium) while its minimum c.s.a. is 6 mm<sup>2</sup> (copper) or 10 mm<sup>2</sup> (aluminium).

### Supplementary equipotential conductor

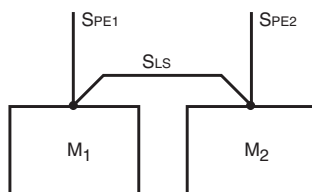
This conductor allows an exposed conductive part which is remote from the nearest main equipotential conductor (PE conductor) to be connected to a local protective conductor. Its c.s.a. must be at least half of that of the protective conductor to which it is connected.

If it connects two exposed conductive parts (M1 and M2 in **Figure G62**) its c.s.a. must be at least equal to that of the smaller of the two PE conductors (for M1 and M2). Equipotential conductors which are not incorporated in a cable, should be protected mechanically by conduits, ducting, etc. wherever possible.

Other important uses for supplementary equipotential conductors concern the reduction of the earth-fault loop impedance, particularly for indirect-contact protection schemes in TN- or IT-earthed installations, and in special locations with increased electrical risk (refer to IEC 60364-4-41).

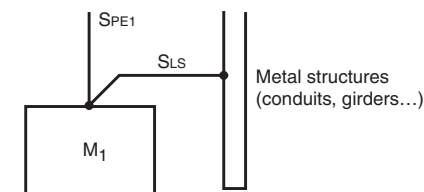
G41

Between two exposed conductive parts  
if  $S_{PE1} \leq S_{PE2}$   
then  $S_{LS} = S_{PE1}$



Between an exposed conductive part  
and a metallic structure

$$S_{LS} = \frac{S_{PE}}{2}$$



**Fig. G62** : Supplementary equipotential conductors

The c.s.a. and the protection of the neutral conductor, apart from its current-carrying requirement, depend on several factors, namely:

- The type of earthing system, TT, TN, etc.
- The harmonic currents
- The method of protection against indirect contact hazards according to the methods described below

The color of the neutral conductor is statutorily blue. PEN conductor, when insulated, shall be marked by one of the following methods :

- Green-and-yellow throughout its length with, in addition, light blue markings at the terminations, or
- Light blue throughout its length with, in addition, green-and-yellow markings at the terminations

## 7.1 Sizing the neutral conductor

### Influence of the type of earthing system

#### TT and TN-S schemes

- Single-phase circuits or those of c.s.a.  $\leq 16 \text{ mm}^2$  (copper)  $25 \text{ mm}^2$  (aluminium): the c.s.a. of the neutral conductor must be equal to that of the phases
- Three-phase circuits of c.s.a.  $> 16 \text{ mm}^2$  copper or  $25 \text{ mm}^2$  aluminium: the c.s.a. of the neutral may be chosen to be:
  - Equal to that of the phase conductors, or
  - Smaller, on condition that:
    - The current likely to flow through the neutral in normal conditions is less than the permitted value  $I_z$ . The influence of triplen<sup>(1)</sup> harmonics must be given particular consideration or
    - The neutral conductor is protected against short-circuit, in accordance with the following Sub-clause G-7.2
    - The size of the neutral conductor is at least equal to  $16 \text{ mm}^2$  in copper or  $25 \text{ mm}^2$  in aluminium

#### TN-C scheme

The same conditions apply in theory as those mentioned above, but in practice, the neutral conductor must not be open-circuited under any circumstances since it constitutes a PE as well as a neutral conductor (see Figure G58 "c.s.a. of PEN conductor" column).

#### IT scheme

In general, it is not recommended to distribute the neutral conductor, i.e. a 3-phase 3-wire scheme is preferred. When a 3-phase 4-wire installation is necessary, however, the conditions described above for TT and TN-S schemes are applicable.

### Influence of harmonic currents

#### Effects of triplen harmonics

Harmonics are generated by the non-linear loads of the installation (computers, fluorescent lighting, rectifiers, power electronic choppers) and can produce high currents in the Neutral. In particular triplen harmonics of the three Phases have a tendency to cumulate in the Neutral as:

- Fundamental currents are out-of-phase by  $2\pi/3$  so that their sum is zero
- On the other hand, triplen harmonics of the three Phases are always positioned in the same manner with respect to their own fundamental, and are in phase with each other (see Fig. G63a).

(1) Harmonics of order 3 and multiple of 3

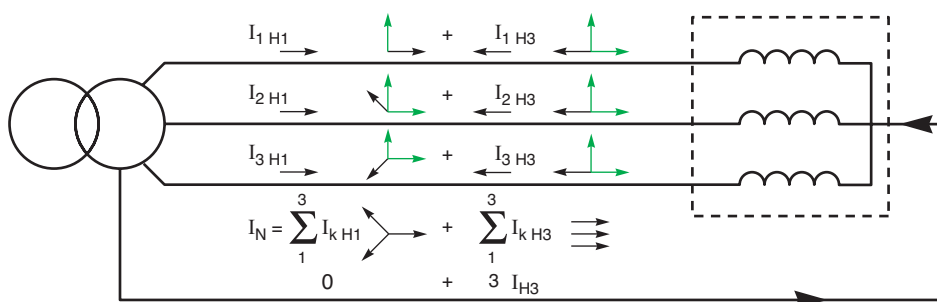
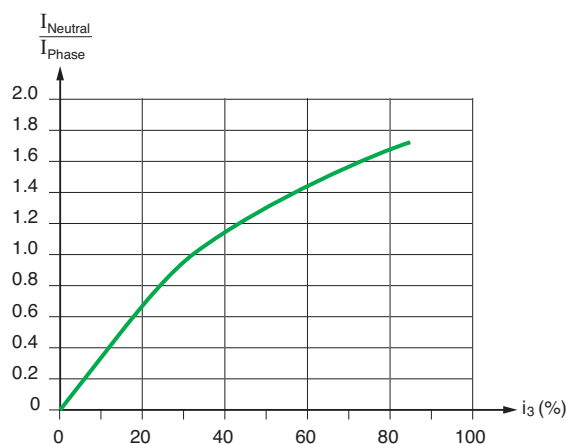


Fig. G63a : Triplen harmonics are in phase and cumulate in the Neutral



**Figure G63b** shows the load factor of the neutral conductor as a function of the percentage of 3<sup>rd</sup> harmonic.

In practice, this maximum load factor cannot exceed  $\sqrt{3}$ .



**Fig. G63b** : Load factor of the neutral conductor vs the percentage of 3<sup>rd</sup> harmonic

#### Reduction factors for harmonic currents in four-core and five-core cables with four cores carrying current

The basic calculation of a cable concerns only cables with three loaded conductors i.e there is no current in the neutral conductor. Because of the third harmonic current, there is a current in the neutral. As a result, this neutral current creates an hot environment for the 3 phase conductors and for this reason, a reduction factor for phase conductors is necessary (see **Fig. G63**).

Reduction factors, applied to the current-carrying capacity of a cable with three loaded conductors, give the current-carrying capacity of a cable with four loaded conductors, where the current in the fourth conductor is due to harmonics. The reduction factors also take the heating effect of the harmonic current in the phase conductors into account.

■ Where the neutral current is expected to be higher than the phase current, then the cable size should be selected on the basis of the neutral current

■ Where the cable size selection is based on a neutral current which is not significantly higher than the phase current, it is necessary to reduce the tabulated current carrying capacity for three loaded conductors

■ If the neutral current is more than 135% of the phase current and the cable size is selected on the basis of the neutral current then the three phase conductors will not be fully loaded. The reduction in heat generated by the phase conductors offsets the heat generated by the neutral conductor to the extent that it is not necessary to apply any reduction factor to the current carrying capacity for three loaded conductors.

■ In order to protect cables, the fuse or circuit-breaker has to be sized taking into account the greatest of the values of the line currents (phase or neutral). However, there are special devices (for example the Compact NSX circuit breaker equipped with the OSN tripping unit), that allow the use of a c.s.a. of the phase conductors smaller than the c.s.a. of the neutral conductor. A big economic gain can thus be made.



Compact NSX100 circuit breaker

Third harmonic content of phase current (%)	Reduction factor	
	Size selection is based on phase current	Size selection is based on neutral current
0 - 15	1.0	-
15 - 33	0.86	-
33 - 45	-	0.86
> 45	-	1.0

**Fig. G63** : Reduction factors for harmonic currents in four-core and five-core cables (according to IEC 60364-5-52)

**Examples**

Consider a three-phase circuit with a design load of 37 A to be installed using four-core PVC insulated cable clipped to a wall, installation method C. From Figure G24, a 6 mm<sup>2</sup> cable with copper conductors has a current-carrying capacity of 40 A and hence is suitable if harmonics are not present in the circuit.

■ If 20 % third harmonic is present, then a reduction factor of 0,86 is applied and the design load becomes:  $37/0.86 = 43$  A.

For this load a 10 mm<sup>2</sup> cable is necessary.

In this case, the use of a special protective device (Compact NSX equipped with the OSN trip unit for instance) would allow the use of a 6 mm<sup>2</sup> cable for the phases and of 10 mm<sup>2</sup> for the neutral.

■ If 40 % third harmonic is present, the cable size selection is based on the neutral current which is:  $37 \times 0,4 \times 3 = 44,4$  A and a reduction factor of 0,86 is applied, leading to a design load of:  $44,4/0.86 = 51,6$  A.

For this load a 10 mm<sup>2</sup> cable is suitable.

■ If 50 % third harmonic is present, the cable size is again selected on the basis of the neutral current, which is:  $37 \times 0,5 \times 3 = 55,5$  A. In this case the rating factor is 1 and a 16 mm<sup>2</sup> cable is required.

In this case, the use of a special protective device (Compact NSX equipped with the OSN trip for instance) would allow the use of a 6 mm<sup>2</sup> cable for the phases and of 10 mm<sup>2</sup> for the neutral.

**7.2 Protection of the neutral conductor**

(see Fig. G64 next page)

**Protection against overload**

If the neutral conductor is correctly sized (including harmonics), no specific protection of the neutral conductor is required because it is protected by the phase protection.

However, in practice, if the c.s.a. of the neutral conductor is lower than the phase c.s.a, a neutral overload protection must be installed.

**Protection against short-circuit**

If the c.s.a. of the neutral conductor is lower than the c.s.a. of the phase conductor, the neutral conductor must be protected against short-circuit.

If the c.s.a. of the neutral conductor is equal or greater than the c.s.a. of the phase conductor, no specific protection of the neutral conductor is required because it is protected by the phase protection.

**7.3 Breaking of the neutral conductor**

(see Fig. G64 next page)

The need to break or not the neutral conductor is related to the protection against indirect contact.

**In TN-C scheme**

The neutral conductor must not be open-circuited under any circumstances since it constitutes a PE as well as a neutral conductor.

**In TT, TN-S and IT schemes**

In the event of a fault, the circuit-breaker will open all poles, including the neutral pole, i.e. the circuit-breaker is omnipolar.

The action can only be achieved with fuses in an indirect way, in which the operation of one or more fuses triggers a mechanical trip-out of all poles of an associated series-connected load-break switch.

**7.4 Isolation of the neutral conductor**

(see Fig. G64 next page)

It is considered to be the good practice that every circuit be provided with the means for its isolation.

	TT	TN-C	TN-S	IT
Single-phase (Phase-Neutral)	 or			 (B)
Single-phase (Phase-Phase)	 (A)		 (A)	
Three-phase four wires $S_n \geq S_{ph}$				 (B)
Three-phase four wires $S_n < S_{ph}$				 (B)

(A) Authorized for TT or TN-S systems if a RCD is installed at the origin of the circuit or upstream of it, and if no artificial neutral is distributed downstream of its location

(B) The neutral overcurrent protection is not necessary:

- If the neutral conductor is protected against short-circuits by a device placed upstream, or,
- If the circuit is protected by a RCD which sensitivity is less than 15% of the neutral admissible current.

Fig. G64 : The various situations in which the neutral conductor may appear

## 8 Worked example of cable calculation

### Worked example of cable calculation (see Fig. G65)

The installation is supplied through a 1,000 kVA transformer. The process requires a high degree of supply continuity and this is provided by the installation of a 500 kVA 400 V standby generator and the adoption of a 3-phase 3-wire IT system at the main general distribution board. The remainder of the installation is isolated by a 400 kVA 400/400 V transformer. The downstream network is a TT-earthed 3-phase 4-wire system. Following the single-line diagram shown in Figure G65 below, a reproduction of the results of a computer study for the circuit C1, the circuit-breaker Q1, the circuit C6 and the circuit-breaker Q6. These studies were carried out with ECODIAL 3.3 software (a Merlin Gerin product).

This is followed by the same calculations carried out by the method described in this guide.

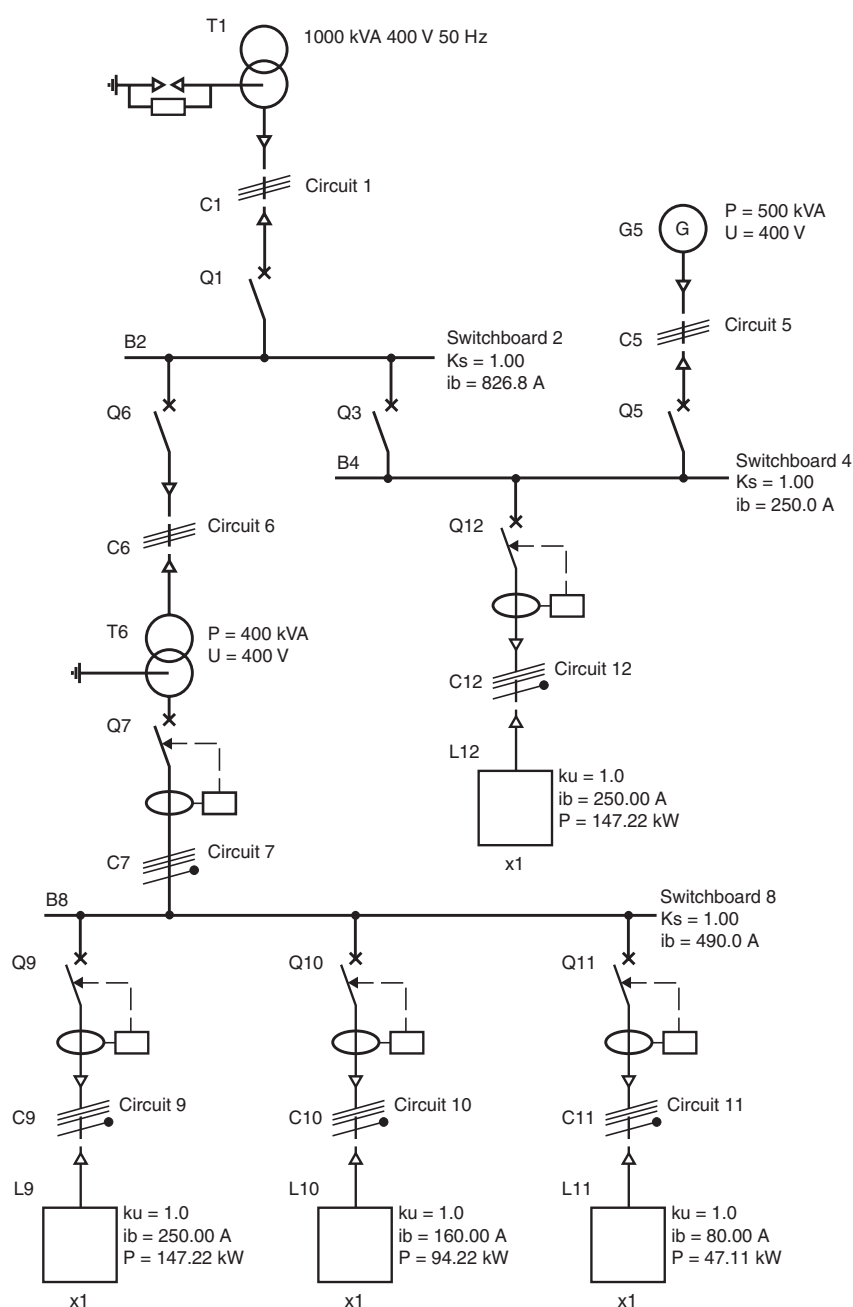


Fig. G65 : Example of single-line diagram

# 8 Worked example of cable calculation

## Calculation using software Ecodial 3.3

General network characteristics	
Earthing system	IT
Neutral distributed	No
Voltage (V)	400
Frequency (Hz)	50
Transformer T1	
Number of transformers	1
Upstream fault level (MVA)	500
Rating (kVA)	1,000
Short-circuit impedance voltage (%)	6
Resistance of MV network (mΩ)	0.0351
Reactance of MV network (mΩ)	0.351
Transformer resistance RT (mΩ)	2.293
Transformer reactance XT (mΩ)	10.333
3-phase short-circuit current Ik3 (kA)	23.3
Cable C1	
Maximum load current (A)	1,374
Type of insulation	PVC
Conductor material	Copper
Ambient temperature (°C)	30
Single-core or multi-core cable	Single
Installation method	F
Number of circuits in close proximity (table G21b)	1
Other coefficient	1
Selected cross-sectional area (mm²)	6 x 95
Protective conductor	1 x 120
Length (m)	5
Voltage drop ΔU (%)	.122
Voltage drop ΔU total (%)	.122
3-phase short-circuit current Ik3 (kA)	23
1-phase-to-earth fault current Id (kA)	17
Circuit-breaker Q1	
3-ph short-circuit current Ik3 upstream of the circuit-breaker (kA)	23
Maximum load current (A)	1,374
Number of poles and protected poles	3P3D
Circuit-breaker	NT 16
Type	H 1 – 42 kA
Tripping unit type	Micrologic 5 A
Rated current (A)	1,600
Busbars B2	
Maximum load current (A)	1,374
Type	Standard on edge
Ambient temperature (°C)	30
Dimensions (m and mm)	1 m 2x5 mm x 63 mm
Material	Copper
3-ph short-circuit current Ik3 (kA)	23
3-ph peak value of short-circuit current Ik (kA)	48
Resistance of busbar R (mΩ)	2.52
Reactance of busbar X (mΩ)	10.8
Circuit-breaker Q6	
3-ph short-circuit current upstream of the circuit-breaker Ik3 (kA)	23
Maximum load current (A)	560
Number of poles and protected poles	3P3D
Circuit-breaker	NS800
Type	N – 50 kA
Tripping unit type	Micrologic 2.0
Rated current (A)	800
Limit of discrimination (kA)	Total
Cable C6	
Maximum load current (A)	560
Type of insulation	PVC
Conductor material	Copper
Ambient temperature (°C)	30
Single-core or multi-core cable	Single
Installation method	F
Number of circuits in close proximity (table G20)	1
Other coefficient	1
Selected cross-sectional area (mm²)	1 x 300
Protective conductor	1 x 150
Length (m)	15
Voltage drop ΔU (%)	.38
Voltage drop ΔU total (%)	.54
3-phase short-circuit current Ik3 (kA)	20
1-phase-to-earth fault current Id (kA)	13.7
Specific sizing constraint	Overloads

G47

Fig. G66 : Partial results of calculation carried out with Ecodial software (Merlin Gerin)

## The same calculation using the simplified method recommended in this guide

### Dimensioning circuit C1

The MV/LV 1,000 kVA transformer has a rated no-load voltage of 420 V. Circuit C1 must be suitable for a current of

$$I_B = \frac{1,000 \times 10^3}{\sqrt{3} \times 420} = 1,374 \text{ A per phase}$$

Six single-core PVC-insulated copper cables in parallel will be used for each phase. These cables will be laid on cable trays according to method F. The “k” correction factors are as follows:

$k_1 = 1$  (see table G12, temperature = 30 °C)

$k_4 = 0.87$  (see table G17, touching cables, 1 tray, ≥ 3 circuits)

Other correction factors are not relevant in this example.

The corrected load current is:

$$I'_{B} = \frac{I_B}{k_1 \cdot k_4} = \frac{1,374}{0.87} = 1,579 \text{ A}$$

Each conductor will therefore carry 263 A. Figure G21a indicates that the c.s.a. is 95 mm².

## 8 Worked example of cable calculation

The resistances and the inductive reactances for the six conductors in parallel are, for a length of 5 metres:

$$R = \frac{22.5 \times 5}{95 \times 6} = 0.20 \text{ m}\Omega \quad (\text{cable resistance: } 22.5 \text{ m}\Omega \cdot \text{mm}^2/\text{m})$$

$$X = 0.08 \times 5 = 0.40 \text{ m}\Omega \quad (\text{cable reactance: } 0.08 \text{ m}\Omega/\text{m})$$

### Dimensioning circuit C6

Circuit C6 supplies a 400 kVA 3-phase 400/400 V isolating transformer

$$\text{Primary current} = \frac{400 \cdot 10^3}{420 \cdot \sqrt{3}} = 550 \text{ A}$$

A single-core cable laid on a cable tray (without any other cable) in an ambient air temperature of 30 °C is proposed. The circuit-breaker is set at 560 A

The method of installation is characterized by the reference letter F, and the "k" correcting factors are all equal to 1.

A c.s.a. of 240 mm<sup>2</sup> is appropriate.

The resistance and inductive reactance are respectively:

$$R = \frac{22.5 \times 15}{240} = 1.4 \text{ m}\Omega$$

$$X = 0.08 \times 15 = 1.2 \text{ m}\Omega$$

### Calculation of short-circuit currents for the selection of circuit-breakers Q 1 and Q 6 (see Fig. G67)

Circuits components parts	R (mΩ)	X (mΩ)	Z (mΩ)	Ikmax (kA)
500 MVA at the MV source network	0.04	0.36		
1 MVA transformer	2.2	9.8	10.0	23
Cable C1	0.20	0.4		
<b>Sub-total for Q1</b>	<b>2.44</b>	<b>10.6</b>	<b>10.9</b>	<b>23</b>
Busbar B2	3.6	7.2		
Cable C6	1.4	1.2		
<b>Sub-total for Q6</b>	<b>4.0</b>	<b>8.4</b>	<b>9.3</b>	<b>20</b>

Fig. G67 : Example of short-circuit current evaluation

### The protective conductor

Thermal requirements: Figures G58 and G59 show that, when using the adiabatic method the c.s.a. for the protective earth (PE) conductor for circuit C1 will be:

$$\frac{34,800 \times \sqrt{0.2}}{143} = 108 \text{ mm}^2$$

A single 120 mm<sup>2</sup> conductor dimensioned for other reasons mentioned later is therefore largely sufficient, provided that it also satisfies the requirements for indirect-contact protection (i.e. that its impedance is sufficiently low).

For the circuit C6, the c.s.a. of its PE conductor should be:

$$\frac{29,300 \times \sqrt{0.2}}{143} = 92 \text{ mm}^2$$

In this case a 95 mm<sup>2</sup> conductor may be adequate if the indirect-contact protection conditions are also satisfied.

## 8 Worked example of cable calculation

### Protection against indirect-contact hazards

For circuit C6 of Figure G65, Figures F45 and F61, or the formula given page F27 may be used for a 3-phase 3-wire circuit.

The maximum permitted length of the circuit is given by :

$$L_{\max} = \frac{0.8 \times 240 \times 230 \sqrt{3} \times 1,000}{2 \times 22.5 \left(1 + \frac{240}{95}\right) \times 630 \times 11} = 70 \text{ m}$$

(The value in the denominator  $630 \times 11 = I_m$  i.e. the current level at which the instantaneous short-circuit magnetic trip of the 630 A circuit-breaker operates). The length of 15 metres is therefore fully protected by "instantaneous" overcurrent devices.

### Voltage drop

From Figure G28 it can be seen that:

■ For the cable C1 (6 x 95mm<sup>2</sup> per phase)

$$\Delta U = \frac{0.42 \text{ (V A}^{-1} \text{ km}^{-1}) \times 1,374 \text{ (A)} \times 0.008}{3} = 1.54 \text{ V}$$

$$\Delta U\% = \frac{100}{400} \times 1.54 = 0.38\%$$

■ For the circuit C6

$$\Delta U = \frac{0.21 \text{ (V A}^{-1} \text{ km}^{-1}) \times 433 \text{ (A)} \times 0.015}{3} = 1.36 \text{ V}$$

$$\Delta U\% = \frac{100}{400} \times 1.36 = 0.34\%$$

At the circuit terminals of the LV/LV transformer the percentage volt-drop  $\Delta U\% = 0.72\%$

# Chapter H

## LV switchgear: functions & selection

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H1



# 1 The basic functions of LV switchgear

The role of switchgear is:

- Electrical protection
- Safe isolation from live parts
- Local or remote switching

National and international standards define the manner in which electric circuits of LV installations must be realized, and the capabilities and limitations of the various switching devices which are collectively referred to as switchgear.

The main functions of switchgear are:

- Electrical protection
- Electrical isolation of sections of an installation
- Local or remote switching

These functions are summarized below in **Figure H1**.

Electrical protection at low voltage is (apart from fuses) normally incorporated in circuit-breakers, in the form of thermal-magnetic devices and/or residual-current-operated tripping devices (less-commonly, residual voltage- operated devices - acceptable to, but not recommended by IEC).

In addition to those functions shown in Figure H1, other functions, namely:

- Over-voltage protection
- Under-voltage protection

are provided by specific devices (lightning and various other types of voltage-surge arrester, relays associated with contactors, remotely controlled circuit-breakers, and with combined circuit-breaker/isolators... and so on)

Electrical protection against	Isolation	Control
<ul style="list-style-type: none"><li>■ Overload currents</li><li>■ Short-circuit currents</li><li>■ Insulation failure</li></ul>	<ul style="list-style-type: none"><li>■ Isolation clearly indicated by an authorized fail-proof mechanical indicator</li><li>■ A gap or interposed insulating barrier between the open contacts, clearly visible</li></ul>	<ul style="list-style-type: none"><li>■ Functional switching</li><li>■ Emergency switching</li><li>■ Emergency stopping</li><li>■ Switching off for mechanical maintenance</li></ul>

Fig. H1 : Basic functions of LV switchgear

## 1.1 Electrical protection

Electrical protection assures:

- Protection of circuit elements against the thermal and mechanical stresses of short-circuit currents
- Protection of persons in the event of insulation failure
- Protection of appliances and apparatus being supplied (e.g. motors, etc.)

The aim is to avoid or to limit the destructive or dangerous consequences of excessive (short-circuit) currents, or those due to overloading and insulation failure, and to separate the defective circuit from the rest of the installation.

A distinction is made between the protection of:

- The elements of the installation (cables, wires, switchgear...)
- Persons and animals
- Equipment and appliances supplied from the installation

### The protection of circuits

- Against overload; a condition of excessive current being drawn from a healthy (unfaulted) installation
- Against short-circuit currents due to complete failure of insulation between conductors of different phases or (in TN systems) between a phase and neutral (or PE) conductor

Protection in these cases is provided either by fuses or circuit-breaker, in the distribution board at the origin of the final circuit (i.e. the circuit to which the load is connected). Certain derogations to this rule are authorized in some national standards, as noted in chapter H1 sub-clause 1.4.

### The protection of persons

- Against insulation failures. According to the system of earthing for the installation (TN, TT or IT) the protection will be provided by fuses or circuit-breakers, residual current devices, and/or permanent monitoring of the insulation resistance of the installation to earth

### The protection of electric motors

- Against overheating, due, for example, to long term overloading, stalled rotor, single-phasing, etc. Thermal relays, specially designed to match the particular characteristics of motors are used. Such relays may, if required, also protect the motor-circuit cable against overload. Short-circuit protection is provided either by type aM fuses or by a circuit-breaker from which the thermal (overload) protective element has been removed, or otherwise made inoperative.

# 1 The basic functions of LV switchgear

*A state of isolation clearly indicated by an approved "fail-proof" indicator, or the visible separation of contacts, are both deemed to satisfy the national standards of many countries*

## 1.2 Isolation

The aim of isolation is to separate a circuit or apparatus (such as a motor, etc.) from the remainder of a system which is energized, in order that personnel may carry out work on the isolated part in perfect safety.

In principle, all circuits of an LV installation shall have means to be isolated. In practice, in order to maintain an optimum continuity of service, it is preferred to provide a means of isolation at the origin of each circuit.

An isolating device must fulfil the following requirements:

- All poles of a circuit, including the neutral (except where the neutral is a PEN conductor) must open<sup>(1)</sup>
- It must be provided with a locking system in open position with a key (e.g. by means of a padlock) in order to avoid an unauthorized reclosure by inadvertence
- It must comply with a recognized national or international standard (e.g. IEC 60947-3) concerning clearance between contacts, creepage distances, overvoltage withstand capability, etc.:

Other requirements apply:

- Verification that the contacts of the isolating device are, in fact, open.

The verification may be:

- Either visual, where the device is suitably designed to allow the contacts to be seen (some national standards impose this condition for an isolating device located at the origin of a LV installation supplied directly from a MV/LV transformer)
- Or mechanical, by means of an indicator solidly welded to the operating shaft of the device. In this case the construction of the device must be such that, in the eventuality that the contacts become welded together in the closed position, the indicator cannot possibly indicate that it is in the open position

- Leakage currents. With the isolating device open, leakage currents between the open contacts of each phase must not exceed:

- 0.5 mA for a new device
- 6.0 mA at the end of its useful life

- Voltage-surge withstand capability, across open contacts. The isolating device, when open must withstand a 1.2/50  $\mu$ s impulse, having a peak value of 6, 8 or 12 kV according to its service voltage, as shown in **Figure H2**. The device must satisfy these conditions for altitudes up to 2,000 metres. Correction factors are given in IEC 60664-1 for altitudes greater than 2,000 metres.

Consequently, if tests are carried out at sea level, the test values must be increased by 23% to take into account the effect of altitude. See standard IEC 60947.

Service (nominal voltage (V))	Impulse withstand peak voltage category (for 2,000 metres) (kV)	
	III	IV
230/400	4	6
400/690	6	8
690/1,000	8	12

**Fig. H2** : Peak value of impulse voltage according to normal service voltage of test specimen. The degrees III and IV are degrees of pollution defined in IEC 60664-1

(1) the concurrent opening of all live conductors, while not always obligatory, is however, strongly recommended (for reasons of greater safety and facility of operation). The neutral contact opens after the phase contacts, and closes before them (IEC 60947-1).

# 1 The basic functions of LV switchgear

*Switchgear-control functions allow system operating personnel to modify a loaded system at any moment, according to requirements, and include:*

- *Functional control (routine switching, etc.)*
- *Emergency switching*
- *Maintenance operations on the power system*

## 1.3 Switchgear control

In broad terms “control” signifies any facility for safely modifying a load-carrying power system at all levels of an installation. The operation of switchgear is an important part of power-system control.

### Functional control

This control relates to all switching operations in normal service conditions for energizing or de-energizing a part of a system or installation, or an individual piece of equipment, item of plant, etc.

Switchgear intended for such duty must be installed at least:

- At the origin of any installation
- At the final load circuit or circuits (one switch may control several loads)

Marking (of the circuits being controlled) must be clear and unambiguous.

In order to provide the maximum flexibility and continuity of operation, particularly where the switching device also constitutes the protection (e.g. a circuit-breaker or switch-fuse) it is preferable to include a switch at each level of distribution, i.e. on each outgoing way of all distribution and subdistribution boards.

The manoeuvre may be:

- Either manual (by means of an operating lever on the switch) or
- Electric, by push-button on the switch or at a remote location (load-shedding and reconnection, for example)

These switches operate instantaneously (i.e. with no deliberate delay), and those that provide protection are invariably omni-polar<sup>(1)</sup>.

The main circuit-breaker for the entire installation, as well as any circuit-breakers used for change-over (from one source to another) must be omni-polar units.

### Emergency switching - emergency stop

An emergency switching is intended to de-energize a live circuit which is, or could become, dangerous (electric shock or fire).

An emergency stop is intended to halt a movement which has become dangerous.

In the two cases:

- The emergency control device or its means of operation (local or at remote location(s)) such as a large red mushroom-headed emergency-stop pushbutton must be recognizable and readily accessible, in proximity to any position at which danger could arise or be seen
- A single action must result in a complete switching-off of all live conductors <sup>(2) (3)</sup>
- A “break glass” emergency switching initiation device is authorized, but in unmanned installations the re-energizing of the circuit can only be achieved by means of a key held by an authorized person

It should be noted that in certain cases, an emergency system of braking, may require that the auxiliary supply to the braking-system circuits be maintained until final stoppage of the machinery.

### Switching-off for mechanical maintenance work

This operation assures the stopping of a machine and its impossibility to be inadvertently restarted while mechanical maintenance work is being carried out on the driven machinery. The shutdown is generally carried out at the functional switching device, with the use of a suitable safety lock and warning notice at the switch mechanism.

(1) One break in each phase and (where appropriate) one break in the neutral.

(2) Taking into account stalled motors.

(3) In a TN schema the PEN conductor must never be opened, since it functions as a protective earthing wire as well as the system neutral conductor.

## 2.1 Elementary switching devices

### Disconnecter (or isolator) (see Fig. H5)

This switch is a manually-operated, lockable, two-position device (open/closed) which provides safe isolation of a circuit when locked in the open position. Its characteristics are defined in IEC 60947-3. A disconnector is not designed to make or to break current<sup>(1)</sup> and no rated values for these functions are given in standards. It must, however, be capable of withstanding the passage of short-circuit currents and is assigned a rated short-time withstand capability, generally for 1 second, unless otherwise agreed between user and manufacturer. This capability is normally more than adequate for longer periods of (lower-valued) operational overcurrents, such as those of motor-starting. Standardized mechanical-endurance, overvoltage, and leakage-current tests, must also be satisfied.

### Load-breaking switch (see Fig. H6)

This control switch is generally operated manually (but is sometimes provided with electrical tripping for operator convenience) and is a non-automatic two-position device (open/closed).

It is used to close and open loaded circuits under normal unfaulted circuit conditions. It does not consequently, provide any protection for the circuit it controls.

IEC standard 60947-3 defines:

- The frequency of switch operation (600 close/open cycles per hour maximum)
- Mechanical and electrical endurance (generally less than that of a contactor)

When closing a switch to energize a circuit there is always the possibility that an unsuspected short-circuit exists on the circuit. For this reason, load-break switches are assigned a fault-current making rating, i.e. successful closure against the electrodynamic forces of short-circuit current is assured. Such switches are commonly referred to as "fault-make load-break" switches. Upstream protective devices are relied upon to clear the short-circuit fault

Category AC-23 includes occasional switching of individual motors. The switching of capacitors or of tungsten filament lamps shall be subject to agreement between manufacturer and user.

The utilization categories referred to in **Figure H7** do not apply to an equipment normally used to start, accelerate and/or stop individual motors.

#### Example

A 100 A load-break switch of category AC-23 (inductive load) must be able:

- To make a current of 10 In (= 1,000 A) at a power factor of 0.35 lagging
- To break a current of 8 In (= 800 A) at a power factor of 0.45 lagging
- To withstand short duration short-circuit currents when closed



Fig. H5 : Symbol for a disconnector (or isolator)



Fig. H6 : Symbol for a load-break switch

Utilization category		Typical applications	Cos φ	Making current x In	Breaking current x In
Frequent operations	Infrequent operations				
AC-20A	AC-20B	Connecting and disconnecting under no-load conditions	-	-	-
AC-21A	AC-21B	Switching of resistive loads including moderate overloads	0.95	1.5	1.5
AC-22A	AC-22B	Switching of mixed resistive and inductive loads, including moderate overloads	0.65	3	3
AC-23A	AC-23B	Switching of motor loads or other highly inductive loads	0.45 for I ≤ 100 A 0.35 for I > 100 A	10	8

Fig. H7 : Utilization categories of LV AC switches according to IEC 60947-3

(1) i.e. a LV disconnector is essentially a dead system switching device to be operated with no voltage on either side of it, particularly when closing, because of the possibility of an unsuspected short-circuit on the downstream side. Interlocking with an upstream switch or circuit-breaker is frequently used.

H6

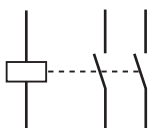


Fig. H8 : Symbol for a bistable remote control switch

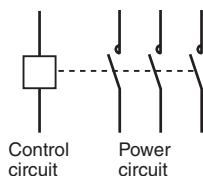


Fig. H9 : Symbol for a contactor

Two classes of LV cartridge fuse are very widely used:

- For domestic and similar installations type gG
- For industrial installations type gG, gM or aM



Fig. H10 : Symbol for fuses

### Remote control switch (see Fig. H8)

This device is extensively used in the control of lighting circuits where the depression of a pushbutton (at a remote control position) will open an already-closed switch or close an opened switch in a bistable sequence.

Typical applications are:

- Two-way switching on stairways of large buildings
- Stage-lighting schemes
- Factory illumination, etc.

Auxiliary devices are available to provide:

- Remote indication of its state at any instant
- Time-delay functions
- Maintained-contact features

### Contactors (see Fig. H9)

The contactor is a solenoid-operated switching device which is generally held closed by (a reduced) current through the closing solenoid (although various mechanically-latched types exist for specific duties). Contactors are designed to carry out numerous close/open cycles and are commonly controlled remotely by on-off pushbuttons. The large number of repetitive operating cycles is standardized in table VIII of IEC 60947-4-1 by:

- The operating duration: 8 hours; uninterrupted; intermittent; temporary of 3, 10, 30, 60 and 90 minutes
- Utilization category: for example, a contactor of category AC3 can be used for the starting and stopping of a cage motor
- The start-stop cycles (1 to 1,200 cycles per hour)
- Mechanical endurance (number of off-load manoeuvres)
- Electrical endurance (number of on-load manoeuvres)
- A rated current making and breaking performance according to the category of utilization concerned

#### Example:

A 150 A contactor of category AC3 must have a minimum current-breaking capability of 8 In (= 1,200 A) and a minimum current-making rating of 10 In (= 1,500 A) at a power factor (lagging) of 0.35.

### Disconnector<sup>(1)</sup>

A contactor equipped with a thermal-type relay for protection against overloading defines a "disconnector". Disconnectors are used extensively for remote push-button control of lighting circuits, etc., and may also be considered as an essential element in a motor controller, as noted in sub-clause 2.2. "combined switchgear elements". The disconnector is not the equivalent of a circuit-breaker, since its short-circuit current breaking capability is limited to 8 or 10 In. For short-circuit protection therefore, it is necessary to include either fuses or a circuit-breaker in series with, and upstream of, the disconnector contacts.

### Fuses (see Fig. H10)

The first letter indicates the breaking range:

- "g" fuse-links (full-range breaking-capacity fuse-link)
- "a" fuse-links (partial-range breaking-capacity fuse-link)

The second letter indicates the utilization category; this letter defines with accuracy the time-current characteristics, conventional times and currents, gates.

For example

- "gG" indicates fuse-links with a full-range breaking capacity for general application
- "gM" indicates fuse-links with a full-range breaking capacity for the protection of motor circuits
- "aM" indicates fuse-links with a partial range breaking capacity for the protection of motor circuits

Fuses exist with and without "fuse-blown" mechanical indicators. Fuses break a circuit by controlled melting of the fuse element when a current exceeds a given value for a corresponding period of time; the current/time relationship being presented in the form of a performance curve for each type of fuse. Standards define two classes of fuse:

- Those intended for domestic installations, manufactured in the form of a cartridge for rated currents up to 100 A and designated type gG in IEC 60269-1 and 3
- Those for industrial use, with cartridge types designated gG (general use); and gM and aM (for motor-circuits) in IEC 60269-1 and 2

(1) This term is not defined in IEC publications but is commonly used in some countries.

*gM fuses require a separate overload relay, as described in the note at the end of sub-clause 2.1.*

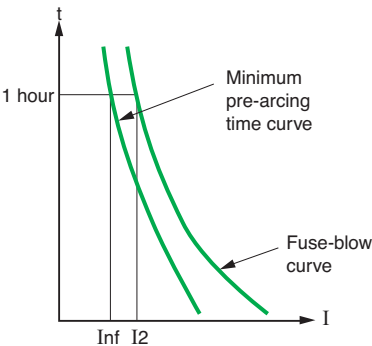


Fig. H12 : Zones of fusing and non-fusing for gG and gM fuses

The main differences between domestic and industrial fuses are the nominal voltage and current levels (which require much larger physical dimensions) and their fault-current breaking capabilities. Type gG fuse-links are often used for the protection of motor circuits, which is possible when their characteristics are capable of withstanding the motor-starting current without deterioration.

A more recent development has been the adoption by the IEC of a fuse-type gM for motor protection, designed to cover starting, and short-circuit conditions. This type of fuse is more popular in some countries than in others, but at the present time the aM fuse in combination with a thermal overload relay is more-widely used. A gM fuse-link, which has a dual rating is characterized by two current values. The first value  $I_n$  denotes both the rated current of the fuse-link and the rated current of the fuseholder; the second value  $I_{ch}$  denotes the time-current characteristic of the fuse-link as defined by the gates in Tables II, III and VI of IEC 60269-1.

These two ratings are separated by a letter which defines the applications. For example:  $I_n M I_{ch}$  denotes a fuse intended to be used for protection of motor circuits and having the characteristic G. The first value  $I_n$  corresponds to the maximum continuous current for the whole fuse and the second value  $I_{ch}$  corresponds to the G characteristic of the fuse link. For further details see note at the end of sub-clause 2.1.

An aM fuse-link is characterized by one current value  $I_n$  and time-current characteristic as shown in Figure H14 next page.

**Important:** Some national standards use a gl (industrial) type fuse, similar in all main essentials to type gG fuses. Type gl fuses should never be used, however, in domestic and similar installations.

Fusing zones - conventional currents

The conditions of fusing (melting) of a fuse are defined by standards, according to their class.

Class gG fuses

These fuses provide protection against overloads and short-circuits. Conventional non-fusing and fusing currents are standardized, as shown in Figure H12 and in Figure H13.

- The conventional non-fusing current  $I_{nf}$  is the value of current that the fusible element can carry for a specified time without melting. Example: A 32 A fuse carrying a current of 1.25  $I_n$  (i.e. 40 A) must not melt in less than one hour (table H13)
  - The conventional fusing current  $I_f$  (=  $I_2$  in Fig. H12) is the value of current which will cause melting of the fusible element before the expiration of the specified time. Example: A 32 A fuse carrying a current of 1.6  $I_n$  (i.e. 52.1 A) must melt in one hour or less
- IEC 60269-1 standardized tests require that a fuse-operating characteristic lies between the two limiting curves (shown in Figure H12) for the particular fuse under test. This means that two fuses which satisfy the test can have significantly different operating times at low levels of overloading.

Rated current <sup>(1)</sup> $I_n$ (A)	Conventional non-fusing current $I_{nf}$	Conventional fusing current $I_2$	Conventional time (h)
$I_n \leq 4$ A	1.5 $I_n$	2.1 $I_n$	1
$4 < I_n \leq 16$ A	1.5 $I_n$	1.9 $I_n$	1
$16 < I_n \leq 63$ A	1.25 $I_n$	1.6 $I_n$	1
$63 < I_n \leq 160$ A	1.25 $I_n$	1.6 $I_n$	2
$160 < I_n \leq 400$ A	1.25 $I_n$	1.6 $I_n$	3
$400 < I_n$	1.25 $I_n$	1.6 $I_n$	4

Fig. H13 : Zones of fusing and non-fusing for LV types gG and gM class fuses (IEC 60269-1 and 60269-2-1)

(1)  $I_{ch}$  for gM fuses



*Class aM fuses protect against short-circuit currents only, and must always be associated with another device which protects against overload*

■ The two examples given above for a 32 A fuse, together with the foregoing notes on standard test requirements, explain why these fuses have a poor performance in the low overload range

■ It is therefore necessary to install a cable larger in ampacity than that normally required for a circuit, in order to avoid the consequences of possible long term overloading (60% overload for up to one hour in the worst case)

By way of comparison, a circuit-breaker of similar current rating:

■ Which passes 1.05  $I_n$  must not trip in less than one hour; and

■ When passing 1.25  $I_n$  it must trip in one hour, or less (25% overload for up to one hour in the worst case)

#### Class aM (motor) fuses

These fuses afford protection against short-circuit currents only and must necessarily be associated with other switchgear (such as discontactors or circuit-breakers) in order to ensure overload protection  $< 4 I_n$ . They are not therefore autonomous. Since aM fuses are not intended to protect against low values of overload current, no levels of conventional non-fusing and fusing currents are fixed. The characteristic curves for testing these fuses are given for values of fault current exceeding approximately  $4 I_n$  (see **Fig. H14**), and fuses tested to IEC 60269 must give operating curves which fall within the shaded area.

**Note:** the small “arrowheads” in the diagram indicate the current/time “gate” values for the different fuses to be tested (IEC 60269).

#### Rated short-circuit breaking currents

A characteristic of modern cartridge fuses is that, owing to the rapidity of fusion in the case of high short-circuit current levels<sup>(1)</sup>, a current cut-off begins before the occurrence of the first major peak, so that the fault current never reaches its prospective peak value (see **Fig. H15**).

This limitation of current reduces significantly the thermal and dynamic stresses which would otherwise occur, thereby minimizing danger and damage at the fault position. The rated short-circuit breaking current of the fuse is therefore based on the rms value of the AC component of the prospective fault current.

No short-circuit current-making rating is assigned to fuses.

#### Reminder

Short-circuit currents initially contain DC components, the magnitude and duration of which depend on the  $XL/R$  ratio of the fault current loop.

Close to the source (MV/LV transformer) the relationship  $I_{peak} / I_{rms}$  (of AC component) immediately following the instant of fault, can be as high as 2.5 (standardized by IEC, and shown in **Figure H16** next page).

At lower levels of distribution in an installation, as previously noted,  $XL$  is small compared with  $R$  and so for final circuits  $I_{peak} / I_{rms} \sim 1.41$ , a condition which corresponds with **Figure H15**.

The peak-current-limitation effect occurs only when the prospective rms AC component of fault current attains a certain level. For example, in the **Figure H16** graph, the 100 A fuse will begin to cut off the peak at a prospective fault current (rms) of 2 kA (a). The same fuse for a condition of 20 kA rms prospective current will limit the peak current to 10 kA (b). Without a current-limiting fuse the peak current could attain 50 kA (c) in this particular case. As already mentioned, at lower distribution levels in an installation,  $R$  greatly predominates  $XL$ , and fault levels are generally low. This means that the level of fault current may not attain values high enough to cause peak current limitation. On the other hand, the DC transients (in this case) have an insignificant effect on the magnitude of the current peak, as previously mentioned.

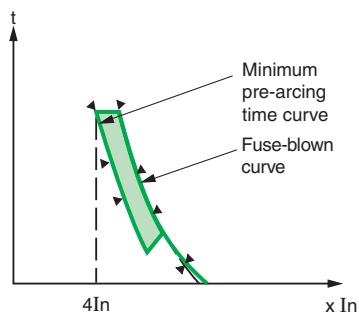
#### Note: On gM fuse ratings

A gM type fuse is essentially a gG fuse, the fusible element of which corresponds to the current value  $I_{ch}$  (ch = characteristic) which may be, for example, 63 A. This is the IEC testing value, so that its time/ current characteristic is identical to that of a 63 A gG fuse.

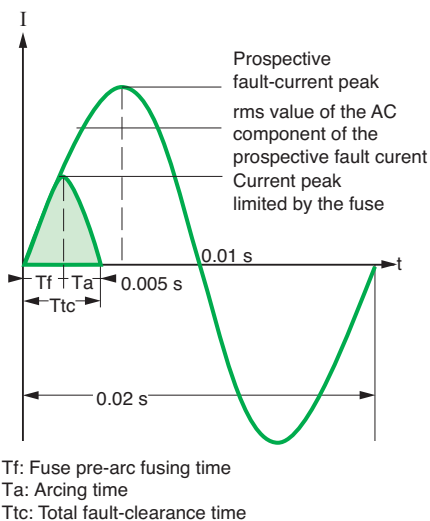
This value (63 A) is selected to withstand the high starting currents of a motor, the steady state operating current ( $I_n$ ) of which may be in the 10-20 A range.

This means that a physically smaller fuse barrel and metallic parts can be used, since the heat dissipation required in normal service is related to the lower figures (10-20 A). A standard gM fuse, suitable for this situation would be designated 32M63 (i.e.  $I_n M I_{ch}$ ).

The first current rating  $I_n$  concerns the steady-load thermal performance of the fuselink, while the second current rating ( $I_{ch}$ ) relates to its (short-time) starting-current performance. It is evident that, although suitable for short-circuit protection,



**Fig. H14 :** Standardized zones of fusing for type aM fuses (all current ratings)



**Fig. H15 :** Current limitation by a fuse

(1) For currents exceeding a certain level, depending on the fuse nominal current rating, as shown below in **Figure H16**.

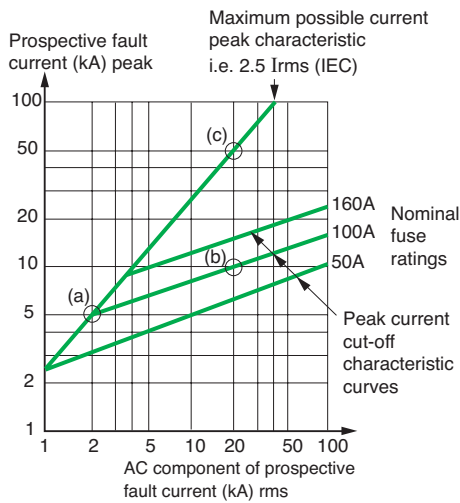


Fig. H16 : Limited peak current versus prospective rms values of the AC component of fault current for LV fuses

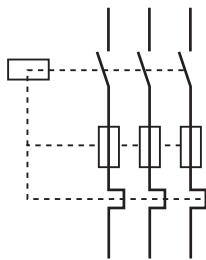


Fig. H17 : Symbol for an automatic tripping switch-fuse

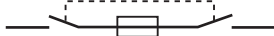


Fig. H18 : Symbol for a non-automatic fuse-switch

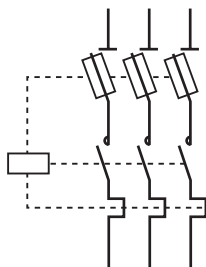


Fig. H20 : Symbol for a fuse disconnect + disconnector

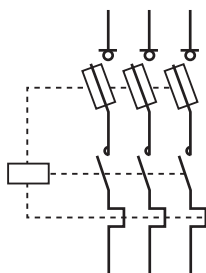


Fig. H21 : Symbol for a fuse-switch disconnect + disconnector

overload protection for the motor is not provided by the fuse, and so a separate thermal-type relay is always necessary when using gM fuses. The only advantage offered by gM fuses, therefore, when compared with aM fuses, are reduced physical dimensions and slightly lower cost.

## 2.2 Combined switchgear elements

Single units of switchgear do not, in general, fulfil all the requirements of the three basic functions, viz: Protection, control and isolation.

Where the installation of a circuit-breaker is not appropriate (notably where the switching rate is high, over extended periods) combinations of units specifically designed for such a performance are employed. The most commonly-used combinations are described below.

### Switch and fuse combinations

Two cases are distinguished:

- The type in which the operation of one (or more) fuse(s) causes the switch to open. This is achieved by the use of fuses fitted with striker pins, and a system of switch tripping springs and toggle mechanisms (see Fig. H17)
- The type in which a non-automatic switch is associated with a set of fuses in a common enclosure.

In some countries, and in IEC 60947-3, the terms “switch-fuse” and “fuse-switch” have specific meanings, viz:

- A switch-fuse comprises a switch (generally 2 breaks per pole) on the upstream side of three fixed fuse-bases, into which the fuse carriers are inserted (see Fig. H18)
- A fuse-switch consists of three switch blades each constituting a double-break per phase.

These blades are not continuous throughout their length, but each has a gap in the centre which is bridged by the fuse cartridge. Some designs have only a single break per phase, as shown in Figure H19.

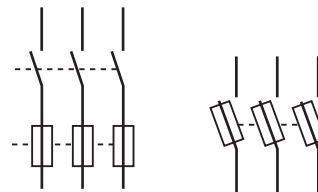


Fig. H19 : Symbol for a non-automatic switch-fuse

The current range for these devices is limited to 100 A maximum at 400 V 3-phase, while their principal use is in domestic and similar installations. To avoid confusion between the first group (i.e. automatic tripping) and the second group, the term “switch-fuse” should be qualified by the adjectives “automatic” or “non-automatic”.

### Fuse – disconnect + disconnector

#### Fuse - switch-disconnector + disconnector

As previously mentioned, a disconnector does not provide protection against short-circuit faults. It is necessary, therefore, to add fuses (generally of type aM) to perform this function. The combination is used mainly for motor control circuits, where the disconnector or switch-disconnector allows safe operations such as:

- The changing of fuse links (with the circuit isolated)
- Work on the circuit downstream of the disconnector (risk of remote closure of the disconnector)

The fuse-disconnector must be interlocked with the disconnector such that no opening or closing manoeuvre of the fuse disconnector is possible unless the disconnector is open (Figure H20), since the fuse disconnector has no load-switching capability.

A fuse-switch-disconnector (evidently) requires no interlocking (Figure H21).

The switch must be of class AC22 or AC23 if the circuit supplies a motor.

### Circuit-breaker + contactor

#### Circuit-breaker + disconnector

These combinations are used in remotely controlled distribution systems in which the rate of switching is high, or for control and protection of a circuit supplying motors.



## 3.1 Tabulated functional capabilities

After having studied the basic functions of LV switchgear (clause 1, Figure H1) and the different components of switchgear (clause 2), **Figure H22** summarizes the capabilities of the various components to perform the basic functions.

Switchgear item	Isolation	Control				Electrical protection		
		Functional	Emergency switching	Emergency stop (mechanical)	Switching for mechanical maintenance	Overload	Short-circuit	Electric shock
Isolator (or disconnector) <sup>(4)</sup>	■							
Switch <sup>(5)</sup>	■	■	■ (1)	■ (1) (2)	■			
Residual device (RCCB) <sup>(5)</sup>	■	■	■ (1)	■ (1) (2)	■			■
Switch-disconnector	■	■	■ (1)	■ (1) (2)	■			
Contactor		■	■ (1)	■ (1) (2)	■	■ (3)		
Remote control switch		■	■ (1)		■			
Fuse	■					■	■	
Circuit breaker		■	■ (1)	■ (1) (2)	■	■	■	
Circuit-breaker disconnector <sup>(5)</sup>	■	■	■ (1)	■ (1) (2)	■	■	■	
Residual and overcurrent circuit-breaker (RCBO) <sup>(5)</sup>	■	■	■ (1)	■ (1) (2)	■	■	■	■
Point of installation (general principle)	Origin of each circuit	All points where, for operational reasons it may be necessary to stop the process	In general at the incoming circuit to every distribution board	At the supply point to each machine and/or on the machine concerned	At the supply point to each machine	Origin of each circuit	Origin of each circuit	Origin of circuits where the earthing system is appropriate TN-S, IT, TT

(1) Where cut-off of all active conductors is provided

(2) It may be necessary to maintain supply to a braking system

(3) If it is associated with a thermal relay (the combination is commonly referred to as a “discontactor”)

(4) In certain countries a disconnector with visible contacts is mandatory at the origin of a LV installation supplied directly from a MV/LV transformer

(5) Certain items of switchgear are suitable for isolation duties (e.g. RCCBs according to IEC 61008) without being explicitly marked as such

**Fig. H22** : Functions fulfilled by different items of switchgear

## 3.2 Switchgear selection

Software is being used more and more in the field of optimal selection of switchgear. Each circuit is considered one at a time, and a list is drawn up of the required protection functions and exploitation of the installation, among those mentioned in Figure H22 and summarized in Figure H1.

A number of switchgear combinations are studied and compared with each other against relevant criteria, with the aim of achieving:

- Satisfactory performance
- Compatibility among the individual items; from the rated current  $I_n$  to the fault-level rating  $I_{cu}$
- Compatibility with upstream switchgear or taking into account its contribution
- Conformity with all regulations and specifications concerning safe and reliable circuit performance

In order to determine the number of poles for an item of switchgear, reference is made to chapter G, clause 7 Fig. G64. Multifunction switchgear, initially more costly, reduces installation costs and problems of installation or exploitation. It is often found that such switchgear provides the best solution.

H10

*The circuit-breaker/disconnector fulfills all of the basic switchgear functions, while, by means of accessories, numerous other possibilities exist*

As shown in **Figure H23** the circuit-breaker/ disconnector is the only item of switchgear capable of simultaneously satisfying all the basic functions necessary in an electrical installation.

Moreover, it can, by means of auxiliary units, provide a wide range of other functions, for example: indication (on-off - tripped on fault); undervoltage tripping; remote control... etc. These features make a circuit-breaker/ disconnector the basic unit of switchgear for any electrical installation.

Functions		Possible conditions
Isolation		■
Control	Functional	■
	Emergency switching	■ (With the possibility of a tripping coil for remote control)
	Switching-off for mechanical maintenance	■
Protection	Overload	■
	Short-circuit	■
	Insulation fault	■ (With differential-current relay)
	Undervoltage	■ (With undervoltage-trip coil)
Remote control		■ Added or incorporated
Indication and measurement		■ (Generally optional with an electronic tripping device)

**Fig. H23** : Functions performed by a circuit-breaker/disconnector

*Industrial circuit-breakers must comply with IEC 60947-1 and 60947-2 or other equivalent standards.*

*Domestic-type circuit-breakers must comply with IEC standard 60898, or an equivalent national standard*

## 4.1 Standards and description

### Standards

For industrial LV installations the relevant IEC standards are, or are due to be:

- 60947-1: general rules
- 60947-2: part 2: circuit-breakers
- 60947-3: part 3: switches, disconnectors, switch-disconnectors and fuse combination units
- 60947-4: part 4: contactors and motor starters
- 60947-5: part 5: control-circuit devices and switching elements
- 60947-6: part 6: multiple function switching devices
- 60947-7: part 7: ancillary equipment

For domestic and similar LV installations, the appropriate standard is IEC 60898, or an equivalent national standard.

### Description

**Figure H24** shows schematically the main parts of a LV circuit-breaker and its four essential functions:

- The circuit-breaking components, comprising the fixed and moving contacts and the arc-dividing chamber

- The latching mechanism which becomes unlatched by the tripping device on detection of abnormal current conditions

This mechanism is also linked to the operation handle of the breaker.

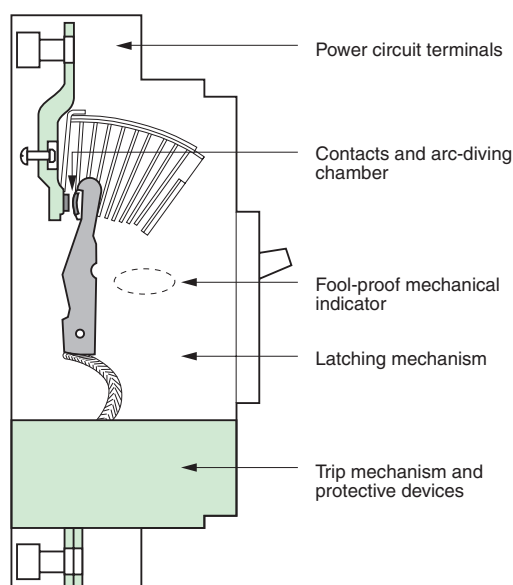
- A trip-mechanism actuating device:

- Either: a thermal-magnetic device, in which a thermally-operated bi-metal strip detects an overload condition, while an electromagnetic striker pin operates at current levels reached in short-circuit conditions, or
- An electronic relay operated from current transformers, one of which is installed on each phase

- A space allocated to the several types of terminal currently used for the main power circuit conductors

Domestic circuit-breakers (see **Fig. H25** next page) complying with IEC 60898 and similar national standards perform the basic functions of:

- Isolation
- Protection against overcurrent



**Fig. H24** : Main parts of a circuit-breaker



**Fig. H25** : Domestic-type circuit-breaker providing overcurrent protection and circuit isolation features

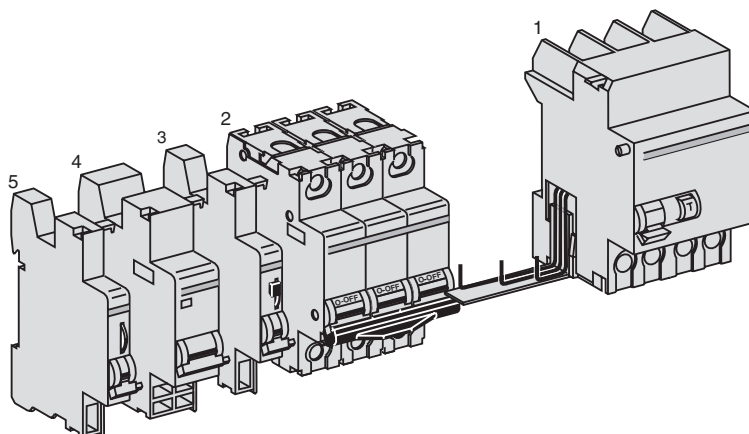
H12



**Fig. H26** : Domestic-type circuit-breaker as above (Fig. H25) with incorporated protection against electric shocks

Some models can be adapted to provide sensitive detection (30 mA) of earth-leakage current with CB tripping, by the addition of a modular block, while other models (RCBOs, complying with IEC 61009 and CBRs complying with IEC 60947-2 Annex B) have this residual current feature incorporated as shown in **Figure H26**.

Apart from the above-mentioned functions further features can be associated with the basic circuit-breaker by means of additional modules, as shown in **Figure H27**; notably remote control and indication (on-off-fault).



**Fig. H27** : "Multi 9" system of LV modular switchgear components

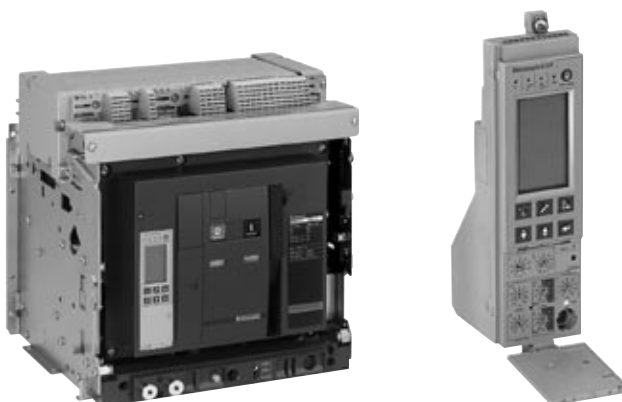
Moulded-case circuit-breakers complying with IEC 60947-2 are available from 100 to 630 A and provide a similar range of auxiliary functions to those described above (see **Figure H28**).

Air circuit-breakers of large current ratings, complying with IEC 60947-2, are generally used in the main switch board and provide protector for currents from 630 A to 6300 A, typically. (see **Figure H29**).

In addition to the protection functions, the Micrologic unit provides optimized functions such as measurement (including power quality functions), diagnosis, communication, control and monitoring.



**Fig. H28** : Example of a Compact NSX industrial type of circuit-breaker capable of numerous auxiliary functions



**Fig. H29** : Example of air circuit-breakers. Masterpact provides many control features in its "Micrologic" tripping unit

## 4.2 Fundamental characteristics of a circuit-breaker

The fundamental characteristics of a circuit-breaker are:

- Its rated voltage  $U_e$
- Its rated current  $I_n$
- Its tripping-current-level adjustment ranges for overload protection ( $I_r^{(1)}$  or  $I_{rth}^{(1)}$ ) and for short-circuit protection ( $I_m^{(1)}$ )
- Its short-circuit current breaking rating ( $I_{cu}$  for industrial CBs;  $I_{cn}$  for domestic-type CBs).

### Rated operational voltage ( $U_e$ )

This is the voltage at which the circuit-breaker has been designed to operate, in normal (undisturbed) conditions.

Other values of voltage are also assigned to the circuit-breaker, corresponding to disturbed conditions, as noted in sub-clause 4.3.

### Rated current ( $I_n$ )

This is the maximum value of current that a circuit-breaker, fitted with a specified overcurrent tripping relay, can carry indefinitely at an ambient temperature stated by the manufacturer, without exceeding the specified temperature limits of the current carrying parts.

#### Example

A circuit-breaker rated at  $I_n = 125$  A for an ambient temperature of  $40^\circ\text{C}$  will be equipped with a suitably calibrated overcurrent tripping relay (set at 125 A). The same circuit-breaker can be used at higher values of ambient temperature however, if suitably "derated". Thus, the circuit-breaker in an ambient temperature of  $50^\circ\text{C}$  could carry only 117 A indefinitely, or again, only 109 A at  $60^\circ\text{C}$ , while complying with the specified temperature limit.

Derating a circuit-breaker is achieved therefore, by reducing the trip-current setting of its overload relay, and marking the CB accordingly. The use of an electronic-type of tripping unit, designed to withstand high temperatures, allows circuit-breakers (derated as described) to operate at  $60^\circ\text{C}$  (or even at  $70^\circ\text{C}$ ) ambient.

**Note:**  $I_n$  for circuit-breakers (in IEC 60947-2) is equal to  $I_u$  for switchgear generally,  $I_u$  being the rated uninterrupted current.

### Frame-size rating

A circuit-breaker which can be fitted with overcurrent tripping units of different current level-setting ranges, is assigned a rating which corresponds to the highest current-level-setting tripping unit that can be fitted.

#### Example

A Compact NSX630N circuit-breaker can be equipped with 11 electronic trip units from 150 A to 630 A. The size of the circuit-breaker is 630 A.

### Overload relay trip-current setting ( $I_{rth}$ or $I_r$ )

Apart from small circuit-breakers which are very easily replaced, industrial circuit-breakers are equipped with removable, i.e. exchangeable, overcurrent-trip relays. Moreover, in order to adapt a circuit-breaker to the requirements of the circuit it controls, and to avoid the need to install over-sized cables, the trip relays are generally adjustable. The trip-current setting  $I_r$  or  $I_{rth}$  (both designations are in common use) is the current above which the circuit-breaker will trip. It also represents the maximum current that the circuit-breaker can carry without tripping. That value must be greater than the maximum load current  $I_B$ , but less than the maximum current permitted in the circuit  $I_z$  (see chapter G, sub-clause 1.3).

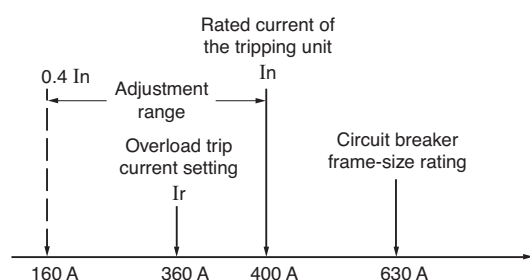
The thermal-trip relays are generally adjustable from 0.7 to 1.0 times  $I_n$ , but when electronic devices are used for this duty, the adjustment range is greater; typically 0.4 to 1 times  $I_n$ .

#### Example (see Fig. H30)

A NSX630N circuit-breaker equipped with a 400 A Micrologic 6.3E overcurrent trip relay, set at 0.9, will have a trip-current setting:

$$I_r = 400 \times 0.9 = 360 \text{ A}$$

**Note:** For circuit-breakers equipped with non-adjustable overcurrent-trip relays,  $I_r = I_n$ . Example: for C60N 20 A circuit-breaker,  $I_r = I_n = 20$  A.



**Fig. H30** : Example of a NSX630N circuit-breaker equipped with a Micrologic 6.3E trip unit adjusted to 0.9, to give  $I_r = 360$  A

(1) Current-level setting values which refer to the current-operated thermal and "instantaneous" magnetic tripping devices for over-load and short-circuit protection.

### Short-circuit relay trip-current setting ( $I_m$ )

Short-circuit tripping relays (instantaneous or slightly time-delayed) are intended to trip the circuit-breaker rapidly on the occurrence of high values of fault current. Their tripping threshold  $I_m$  is:

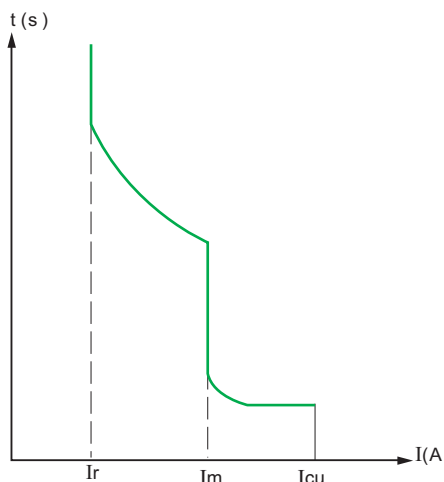
- Either fixed by standards for domestic type CBs, e.g. IEC 60898, or,
- Indicated by the manufacturer for industrial type CBs according to related standards, notably IEC 60947-2.

For the latter circuit-breakers there exists a wide variety of tripping devices which allow a user to adapt the protective performance of the circuit-breaker to the particular requirements of a load (see **Fig. H31**, **Fig. H32** and **Fig. H33**).

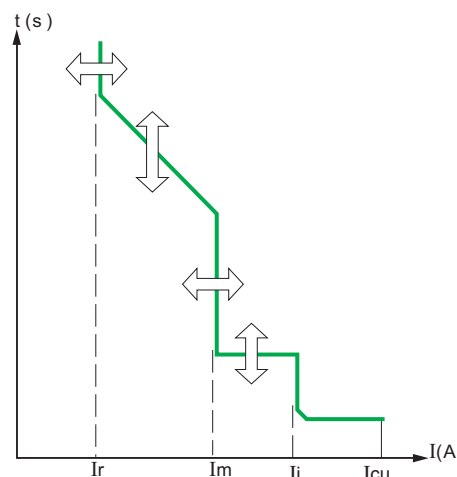
	Type of protective relay	Overload protection	Short-circuit protection		
Domestic breakers IEC 60898	Thermal-magnetic	$I_r = I_n$	Low setting type B $3 I_n \leq I_m \leq 5 I_n$	Standard setting type C $5 I_n \leq I_m \leq 10 I_n$	High setting circuit type D $10 I_n \leq I_m \leq 20 I_n^{(1)}$
Modular industrial <sup>(2)</sup> circuit-breakers	Thermal-magnetic	$I_r = I_n$ fixed	Low setting type B or Z $3.2 I_n \leq \text{fixed} \leq 4.8 I_n$	Standard setting type C $7 I_n \leq \text{fixed} \leq 10 I_n$	High setting type D or K $10 I_n \leq \text{fixed} \leq 14 I_n$
Industrial <sup>(2)</sup> circuit-breakers IEC 60947-2	Thermal-magnetic	$I_r = I_n$ fixed Adjustable: $0.7 I_n \leq I_r \leq I_n$	Fixed: $I_m = 7$ to $10 I_n$ Adjustable: - Low setting : 2 to $5 I_n$ - Standard setting: 5 to $10 I_n$		
	Electronic	Long delay $0.4 I_n \leq I_r \leq I_n$	Short-delay, adjustable $1.5 I_r \leq I_m \leq 10 I_r$ Instantaneous (I) fixed $I = 12$ to $15 I_n$		

- (1)  $50 I_n$  in IEC 60898, which is considered to be unrealistically high by most European manufacturers (Merlin Gerin = 10 to 14  $I_n$ ).  
 (2) For industrial use, IEC standards do not specify values. The above values are given only as being those in common use.

**Fig. H31** : Tripping-current ranges of overload and short-circuit protective devices for LV circuit-breakers



**Fig. H32** : Performance curve of a circuit-breaker thermal-magnetic protective scheme




$I_r$ : Overload (thermal or long-delay) relay trip-current setting  
 $I_m$ : Short-circuit (magnetic or short-delay) relay trip-current setting  
 $I_i$ : Short-circuit instantaneous relay trip-current setting.  
 $I_{cu}$ : Breaking capacity

**Fig. H33** : Performance curve of a circuit-breaker electronic protective scheme

*The short-circuit current-breaking performance of a LV circuit-breaker is related (approximately) to the  $\cos \varphi$  of the fault-current loop. Standard values for this relationship have been established in some standards*

### Isolating feature

A circuit-breaker is suitable for isolating a circuit if it fulfills all the conditions prescribed for a disconnector (at its rated voltage) in the relevant standard (see sub-clause 1.2). In such a case it is referred to as a circuit-breaker-disconnector and marked on its front face with the symbol 

All Multi 9, Compact NSX and Masterpact LV switchgear of Schneider Electric ranges are in this category.

### Rated short-circuit breaking capacity ( $I_{cu}$ or $I_{cn}$ )

The short-circuit current-breaking rating of a CB is the highest (prospective) value of current that the CB is capable of breaking without being damaged. The value of current quoted in the standards is the rms value of the AC component of the fault current, i.e. the DC transient component (which is always present in the worst possible case of short-circuit) is assumed to be zero for calculating the standardized value. This rated value ( $I_{cu}$ ) for industrial CBs and ( $I_{cn}$ ) for domestic-type CBs is normally given in kA rms.

$I_{cu}$  (rated ultimate s.c. breaking capacity) and  $I_{cs}$  (rated service s.c. breaking capacity) are defined in IEC 60947-2 together with a table relating  $I_{cs}$  with  $I_{cu}$  for different categories of utilization A (instantaneous tripping) and B (time-delayed tripping) as discussed in subclause 4.3.

Tests for proving the rated s.c. breaking capacities of CBs are governed by standards, and include:

- Operating sequences, comprising a succession of operations, i.e. closing and opening on short-circuit
- Current and voltage phase displacement. When the current is in phase with the supply voltage ( $\cos \varphi$  for the circuit = 1), interruption of the current is easier than that at any other power factor. Breaking a current at low lagging values of  $\cos \varphi$  is considerably more difficult to achieve; a zero power-factor circuit being (theoretically) the most onerous case.

In practice, all power-system short-circuit fault currents are (more or less) at lagging power factors, and standards are based on values commonly considered to be representative of the majority of power systems. In general, the greater the level of fault current (at a given voltage), the lower the power factor of the fault-current loop, for example, close to generators or large transformers.

**Figure H34** below extracted from IEC 60947-2 relates standardized values of  $\cos \varphi$  to industrial circuit-breakers according to their rated  $I_{cu}$ .

- Following an open - time delay - close/open sequence to test the  $I_{cu}$  capacity of a CB, further tests are made to ensure that:

- The dielectric withstand capability
  - The disconnection (isolation) performance and
  - The correct operation of the overload protection
- have not been impaired by the test.

$I_{cu}$	$\cos \varphi$
$6 \text{ kA} < I_{cu} \leq 10 \text{ kA}$	0.5
$10 \text{ kA} < I_{cu} \leq 20 \text{ kA}$	0.3
$20 \text{ kA} < I_{cu} \leq 50 \text{ kA}$	0.25
$50 \text{ kA} < I_{cu}$	0.2

**Fig. H34** :  $I_{cu}$  related to power factor ( $\cos \varphi$ ) of fault-current circuit (IEC 60947-2)

*Familiarity with the following characteristics of LV circuit-breakers is often necessary when making a final choice.*

## 4.3 Other characteristics of a circuit-breaker

### Rated insulation voltage ( $U_i$ )

This is the value of voltage to which the dielectric tests voltage (generally greater than  $2 U_i$ ) and creepage distances are referred to.

The maximum value of rated operational voltage must never exceed that of the rated insulation voltage, i.e.  $U_e \leq U_i$ .



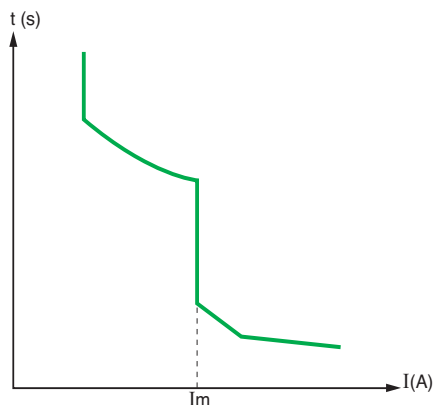


Fig. H35 : Category A circuit-breaker

H16

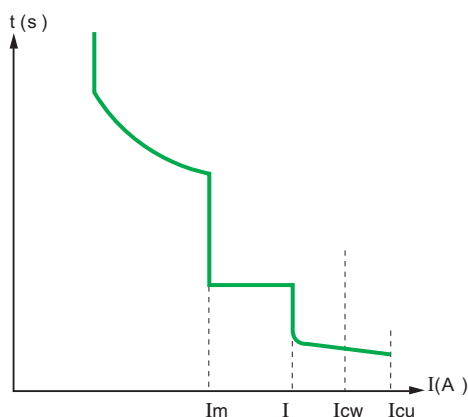


Fig. H36 : Category B circuit-breaker

*In a correctly designed installation, a circuit-breaker is never required to operate at its maximum breaking current  $I_{cu}$ . For this reason a new characteristic  $I_{cs}$  has been introduced. It is expressed in IEC 60947-2 as a percentage of  $I_{cu}$  (25, 50, 75, 100%)*

### Rated impulse-withstand voltage ( $U_{imp}$ )

This characteristic expresses, in kV peak (of a prescribed form and polarity) the value of voltage which the equipment is capable of withstanding without failure, under test conditions.

Generally, for industrial circuit-breakers,  $U_{imp} = 8$  kV and for domestic types,  $U_{imp} = 6$  kV.

### Category (A or B) and rated short-time withstand current ( $I_{cw}$ )

As already briefly mentioned (sub-clause 4.2) there are two categories of LV industrial switchgear, A and B, according to IEC 60947-2:

■ Those of category A, for which there is no deliberate delay in the operation of the “instantaneous” short-circuit magnetic tripping device (see Fig. H35), are generally moulded-case type circuit-breakers, and

■ Those of category B for which, in order to discriminate with other circuit-breakers on a time basis, it is possible to delay the tripping of the CB, where the fault-current level is lower than that of the short-time withstand current rating ( $I_{cw}$ ) of the CB (see Fig. H36). This is generally applied to large open-type circuit-breakers and to certain heavy-duty moulded-case types.  $I_{cw}$  is the maximum current that the B category CB can withstand, thermally and electro-dynamically, without sustaining damage, for a period of time given by the manufacturer.

### Rated making capacity ( $I_{cm}$ )

$I_{cm}$  is the highest instantaneous value of current that the circuit-breaker can establish at rated voltage in specified conditions. In AC systems this instantaneous peak value is related to  $I_{cu}$  (i.e. to the rated breaking current) by the factor  $k$ , which depends on the power factor ( $\cos \phi$ ) of the short-circuit current loop (as shown in Figure H37).

$I_{cu}$	$\cos \phi$	$I_{cm} = k I_{cu}$
$6 \text{ kA} < I_{cu} \leq 10 \text{ kA}$	0.5	$1.7 \times I_{cu}$
$10 \text{ kA} < I_{cu} \leq 20 \text{ kA}$	0.3	$2 \times I_{cu}$
$20 \text{ kA} < I_{cu} \leq 50 \text{ kA}$	0.25	$2.1 \times I_{cu}$
$50 \text{ kA} \leq I_{cu}$	0.2	$2.2 \times I_{cu}$

Fig. H37 : Relation between rated breaking capacity  $I_{cu}$  and rated making capacity  $I_{cm}$  at different power-factor values of short-circuit current, as standardized in IEC 60947-2

**Example:** A Masterpact NW08H2 circuit-breaker has a rated breaking capacity  $I_{cu}$  of 100 kA. The peak value of its rated making capacity  $I_{cm}$  will be  $100 \times 2.2 = 220$  kA.

### Rated service short-circuit breaking capacity ( $I_{cs}$ )

The rated breaking capacity ( $I_{cu}$ ) or ( $I_{cn}$ ) is the maximum fault-current a circuit-breaker can successfully interrupt without being damaged. The probability of such a current occurring is extremely low, and in normal circumstances the fault-currents are considerably less than the rated breaking capacity ( $I_{cu}$ ) of the CB. On the other hand it is important that high currents (of low probability) be interrupted under good conditions, so that the CB is immediately available for reclosure, after the faulty circuit has been repaired. It is for these reasons that a new characteristic ( $I_{cs}$ ) has been created, expressed as a percentage of  $I_{cu}$ , viz: 25, 50, 75, 100% for industrial circuit-breakers. The standard test sequence is as follows:

■ O - CO - CO<sup>(1)</sup> (at  $I_{cs}$ )

■ Tests carried out following this sequence are intended to verify that the CB is in a good state and available for normal service

For domestic CBs,  $I_{cs} = k I_{cn}$ . The factor  $k$  values are given in IEC 60898 table XIV. In Europe it is the industrial practice to use a  $k$  factor of 100% so that  $I_{cs} = I_{cu}$ .

(1) O represents an opening operation.  
CO represents a closing operation followed by an opening operation.

Many designs of LV circuit-breakers feature a short-circuit current limitation capability, whereby the current is reduced and prevented from reaching its (otherwise) maximum peak value (see Fig. H38). The current-limitation performance of these CBs is presented in the form of graphs, typified by that shown in Figure H39, diagram (a)

### Fault-current limitation

The fault-current limitation capacity of a CB concerns its ability, more or less effective, in preventing the passage of the maximum prospective fault-current, permitting only a limited amount of current to flow, as shown in **Figure H38**. The current-limitation performance is given by the CB manufacturer in the form of curves (see **Fig. H39**).

■ Diagram (a) shows the limited peak value of current plotted against the rms value of the AC component of the prospective fault current ("prospective" fault-current refers to the fault-current which would flow if the CB had no current-limiting capability)

■ Limitation of the current greatly reduces the thermal stresses (proportional  $I^2t$ ) and this is shown by the curve of diagram (b) of Figure H39, again, versus the rms value of the AC component of the prospective fault current.

LV circuit-breakers for domestic and similar installations are classified in certain standards (notably European Standard EN 60 898). CBs belonging to one class (of current limiters) have standardized limiting  $I^2t$  let-through characteristics defined by that class.

In these cases, manufacturers do not normally provide characteristic performance curves.

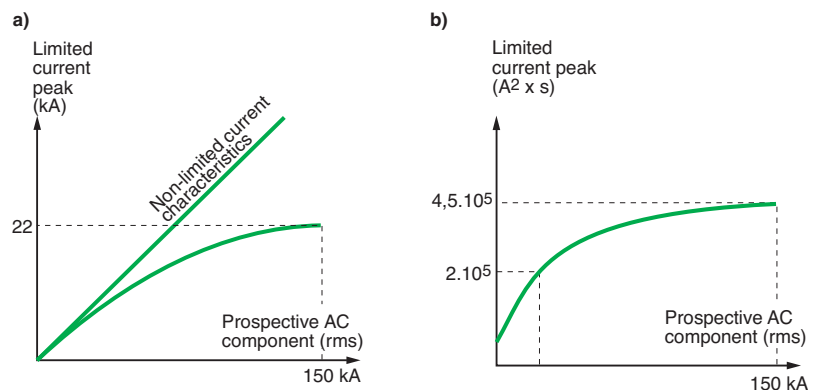


Fig. H39 : Performance curves of a typical LV current-limiting circuit-breaker

Current limitation reduces both thermal and electrodynamic stresses on all circuit elements through which the current passes, thereby prolonging the useful life of these elements. Furthermore, the limitation feature allows "cascading" techniques to be used (see 4.5) thereby significantly reducing design and installation costs

### The advantages of current limitation

The use of current-limiting CBs affords numerous advantages:

- Better conservation of installation networks: current-limiting CBs strongly attenuate all harmful effects associated with short-circuit currents
- Reduction of thermal effects: Conductors (and therefore insulation) heating is significantly reduced, so that the life of cables is correspondingly increased
- Reduction of mechanical effects: forces due to electromagnetic repulsion are lower, with less risk of deformation and possible rupture, excessive burning of contacts, etc.
- Reduction of electromagnetic-interference effects:
  - Less influence on measuring instruments and associated circuits, telecommunication systems, etc.

These circuit-breakers therefore contribute towards an improved exploitation of:

- Cables and wiring
- Prefabricated cable-trunking systems
- Switchgear, thereby reducing the ageing of the installation

### Example

On a system having a prospective shortcircuit current of 150 kA rms, a Compact L circuit-breaker limits the peak current to less than 10% of the calculated prospective peak value, and the thermal effects to less than 1% of those calculated.

Cascading of the several levels of distribution in an installation, downstream of a limiting CB, will also result in important savings.

The technique of cascading, described in sub-clause 4.5 allows, in fact, substantial savings on switchgear (lower performance permissible downstream of the limiting CB(s)) enclosures, and design studies, of up to 20% (overall).

Discriminative protection schemes and cascading are compatible, in the Compact NSX range, up to the full short-circuit breaking capacity of the switchgear.

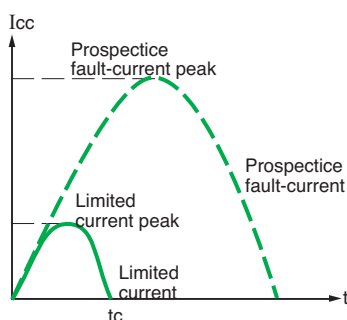


Fig. H38 : Prospective and actual currents



*The choice of a range of circuit-breakers is determined by: the electrical characteristics of the installation, the environment, the loads and a need for remote control, together with the type of telecommunications system envisaged*

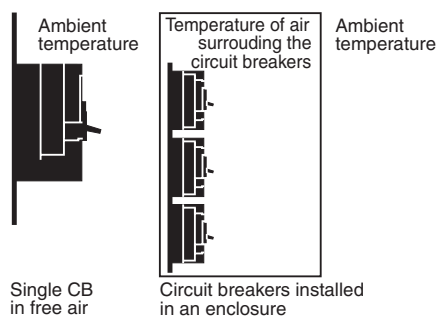


Fig. H40 : Ambient temperature

H18

*Circuit-breakers with uncompensated thermal tripping units have a trip current level that depends on the surrounding temperature*

## 4.4 Selection of a circuit-breaker

### Choice of a circuit-breaker

The choice of a CB is made in terms of:

- Electrical characteristics of the installation for which the CB is intended
- Its eventual environment: ambient temperature, in a kiosk or switchboard enclosure, climatic conditions, etc.
- Short-circuit current breaking and making requirements
- Operational specifications: discriminative tripping, requirements (or not) for remote control and indication and related auxiliary contacts, auxiliary tripping coils, connection
- Installation regulations; in particular: protection of persons
- Load characteristics, such as motors, fluorescent lighting, LV/LV transformers

The following notes relate to the choice LV circuit-breaker for use in distribution systems.

### Choice of rated current in terms of ambient temperature

The rated current of a circuit-breaker is defined for operation at a given ambient temperature, in general:

- 30 °C for domestic-type CBs
- 40 °C for industrial-type CBs

Performance of these CBs in a different ambient temperature depends mainly on the technology of their tripping units (see Fig. H40).

### Uncompensated thermal magnetic tripping units

Circuit-breakers with uncompensated thermal tripping elements have a tripping-current level that depends on the surrounding temperature. If the CB is installed in an enclosure, or in a hot location (boiler room, etc.), the current required to trip the CB on overload will be sensibly reduced. When the temperature in which the CB is located exceeds its reference temperature, it will therefore be “derated”. For this reason, CB manufacturers provide tables which indicate factors to apply at temperatures different to the CB reference temperature. It may be noted from typical examples of such tables (see Fig. H41) that a lower temperature than the reference value produces an up-rating of the CB. Moreover, small modular-type CBs mounted in juxtaposition, as shown typically in Figure H27, are usually mounted in a small closed metal case. In this situation, mutual heating, when passing normal load currents, generally requires them to be derated by a factor of 0.8.

#### Example

What rating ( $I_n$ ) should be selected for a C60 N?

- Protecting a circuit, the maximum load current of which is estimated to be 34 A
- Installed side-by-side with other CBs in a closed distribution box
- In an ambient temperature of 50 °C

A C60N circuit-breaker rated at 40 A would be derated to 35.6 A in ambient air at 50 °C (see Fig. H41). To allow for mutual heating in the enclosed space, however, the 0.8 factor noted above must be employed, so that,  $35.6 \times 0.8 = 28.5$  A, which is not suitable for the 34 A load.

A 50 A circuit-breaker would therefore be selected, giving a (derated) current rating of  $44 \times 0.8 = 35.2$  A.

### Compensated thermal-magnetic tripping units

These tripping units include a bi-metal compensating strip which allows the overload trip-current setting ( $I_r$  or  $I_{rth}$ ) to be adjusted, within a specified range, irrespective of the ambient temperature.

For example:

- In certain countries, the TT system is standard on LV distribution systems, and domestic (and similar) installations are protected at the service position by a circuit-breaker provided by the supply authority. This CB, besides affording protection against indirect-contact hazard, will trip on overload; in this case, if the consumer exceeds the current level stated in his supply contract with the power authority. The circuit-breaker ( $\leq 60$  A) is compensated for a temperature range of - 5 °C to + 40 °C.
- LV circuit-breakers at ratings  $\leq 630$  A are commonly equipped with compensated tripping units for this range (- 5 °C to + 40 °C)

C60a, C60H: curve C. C60N: curves B and C (reference temperature: 30 °C)

Rating (A)	20 °C	25 °C	30 °C	35 °C	40 °C	45 °C	50 °C	55 °C	60 °C
1	1.05	1.02	1.00	0.98	0.95	0.93	0.90	0.88	0.85
2	2.08	2.04	2.00	1.96	1.92	1.88	1.84	1.80	1.74
3	3.18	3.09	3.00	2.91	2.82	2.70	2.61	2.49	2.37
4	4.24	4.12	4.00	3.88	3.76	3.64	3.52	3.36	3.24
6	6.24	6.12	6.00	5.88	5.76	5.64	5.52	5.40	5.30
10	10.6	10.3	10.0	9.70	9.30	9.00	8.60	8.20	7.80
16	16.8	16.5	16.0	15.5	15.2	14.7	14.2	13.8	13.5
20	21.0	20.6	20.0	19.4	19.0	18.4	17.8	17.4	16.8
25	26.2	25.7	25.0	24.2	23.7	23.0	22.2	21.5	20.7
32	33.5	32.9	32.0	31.4	30.4	29.8	28.4	28.2	27.5
40	42.0	41.2	40.0	38.8	38.0	36.8	35.6	34.4	33.2
50	52.5	51.5	50.0	48.5	47.4	45.5	44.0	42.5	40.5
63	66.2	64.9	63.0	61.1	58.0	56.7	54.2	51.7	49.2

Compact NSX100-250 N/H/L equipment with TM-D or TM-G trip units

Rating (A)	Temperature (°C)												
	10	15	20	25	30	35	40	45	50	55	60	65	70
16	18.4	18.7	18	18	17	16.6	16	15.6	15.2	14.8	14.5	14	13.8
25	28.8	28	27.5	25	26.3	25.6	25	24.5	24	23.5	23	22	21
32	36.8	36	35.2	34.4	33.6	32.8	32	31.3	30.5	30	29.5	29	28.5
40	46	45	44	43	42	41	40	39	38	37	36	35	34
50	57.5	56	55	54	52.5	51	50	49	48	47	46	45	44
63	72	71	69	68	66	65	63	61.5	60	58	57	55	54
80	92	90	88	86	84	82	80	78	76	74	72	70	68
100	115	113	110	108	105	103	100	97.5	95	92.5	90	87.5	85
125	144	141	138	134	131	128	125	122	119	116	113	109	106
160	184	180	176	172	168	164	160	156	152	148	144	140	136
200	230	225	220	215	210	205	200	195	190	185	180	175	170
250	288	281	277	269	263	256	250	244	238	231	225	219	213

**Fig. H41** : Examples of tables for the determination of derating/uprating factors to apply to CBs with uncompensated thermal tripping units, according to temperature

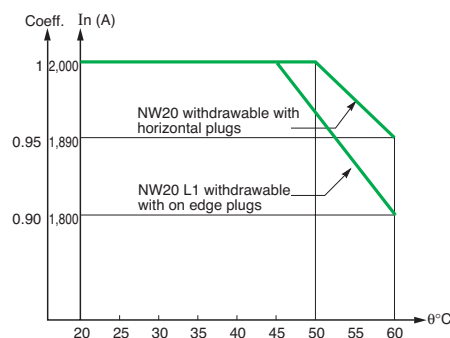
Electronic tripping units are highly stable in changing temperature levels

### Electronic trip units

An important advantage with electronic tripping units is their stable performance in changing temperature conditions. However, the switchgear itself often imposes operational limits in elevated temperatures, so that manufacturers generally provide an operating chart relating the maximum values of permissible trip-current levels to the ambient temperature (see **Fig. H42**).

Moreover, electronic trip units can provide information that can be used for a better management of the electrical distribution, including energy efficiency and power quality.

Masterpact NW20 version			40°C	45°C	50°C	55°C	60°C
H1/H2/H3	Withdrawable with horizontal plugs	In (A)	2,000	2,000	2,000	1,980	1,890
		Maximum adjustment Ir	1	1	1	0.99	0.95
L1	Withdrawable with on-edge plugs	In (A)	2,000	200	1,900	1,850	1,800
		Maximum adjustment Ir	1	1	0.95	0.93	0.90



**Fig. H42** : Derating of Masterpact NW20 circuit-breaker, according to the temperature

### Selection of an instantaneous, or short-time-delay, tripping threshold

Figure H43 below summarizes the main characteristics of the instantaneous or short-time delay trip units.

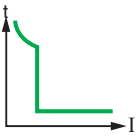
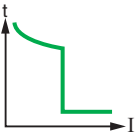
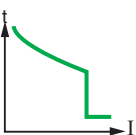
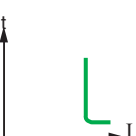
Type	Tripping unit	Applications
	Low setting type B	<ul style="list-style-type: none"> <li>Sources producing low short-circuit-current levels (standby generators)</li> <li>Long lengths of line or cable</li> </ul>
	Standard setting type C	<ul style="list-style-type: none"> <li>Protection of circuits: general case</li> </ul>
	High setting type D or K	<ul style="list-style-type: none"> <li>Protection of circuits having high initial transient current levels (e.g. motors, transformers, resistive loads)</li> </ul>
	12 In type MA	<ul style="list-style-type: none"> <li>Protection of motors in association with discontactors (contactors with overload protection)</li> </ul>

Fig. H43 : Different tripping units, instantaneous or short-time-delayed

The installation of a LV circuit-breaker requires that its short-circuit breaking capacity (or that of the CB together with an associated device) be equal to or exceeds the calculated prospective short-circuit current at its point of installation

### Selection of a circuit-breaker according to the short-circuit breaking capacity requirements

The installation of a circuit-breaker in a LV installation must fulfil one of the two following conditions:

- Either have a rated short-circuit breaking capacity  $I_{cu}$  (or  $I_{cn}$ ) which is equal to or exceeds the prospective short-circuit current calculated for its point of installation, or
- If this is not the case, be associated with another device which is located upstream, and which has the required short-circuit breaking capacity

In the second case, the characteristics of the two devices must be co-ordinated such that the energy permitted to pass through the upstream device must not exceed that which the downstream device and all associated cables, wires and other components can withstand, without being damaged in any way. This technique is profitably employed in:

- Associations of fuses and circuit-breakers
  - Associations of current-limiting circuit-breakers and standard circuit-breakers.
- The technique is known as “cascading” (see sub-clause 4.5 of this chapter)

### The selection of main and principal circuit-breakers

#### A single transformer

If the transformer is located in a consumer's substation, certain national standards require a LV circuit-breaker in which the open contacts are clearly visible such as Compact NSX withdrawable circuit-breaker.

**Example** (see Fig. H44 opposite page)

What type of circuit-breaker is suitable for the main circuit-breaker of an installation supplied through a 250 kVA MV/LV (400 V) 3-phase transformer in a consumer's substation?

In transformer = 360 A

$I_{sc}$  (3-phase) = 8.9 kA

A Compact NSX400N with an adjustable tripping-unit range of 160 A - 400 A and a short-circuit breaking capacity ( $I_{cu}$ ) of 50 kA would be a suitable choice for this duty.

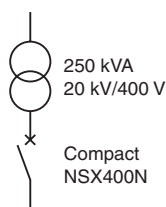


Fig. H44 : Example of a transformer in a consumer's substation

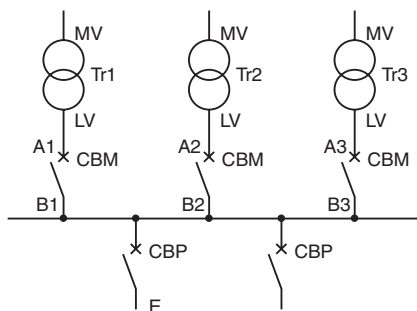


Fig. H45 : Transformers in parallel

**Several transformers in parallel** (see Fig. H45)

- The circuit-breakers CBP outgoing from the LV distribution board must each be capable of breaking the total fault current from all transformers connected to the busbars, viz:  $I_{sc1} + I_{sc2} + I_{sc3}$
  - The circuit-breakers CBM, each controlling the output of a transformer, must be capable of dealing with a maximum short-circuit current of (for example)  $I_{sc2} + I_{sc3}$  only, for a short-circuit located on the upstream side of CBM1.
- From these considerations, it will be seen that the circuit-breaker of the smallest transformer will be subjected to the highest level of fault current in these circumstances, while the circuit-breaker of the largest transformer will pass the lowest level of short-circuit current
- The ratings of CBMs must be chosen according to the kVA ratings of the associated transformers

**Note:** The essential conditions for the successful operation of 3-phase transformers in parallel may be summarized as follows:

1. the phase shift of the voltages, primary to secondary, must be the same in all units to be paralleled.

2. the open-circuit voltage ratios, primary to secondary, must be the same in all units.

3. the short-circuit impedance voltage ( $Z_{sc}\%$ ) must be the same for all units.
- For example, a 750 kVA transformer with a  $Z_{sc} = 6\%$  will share the load correctly with a 1,000 kVA transformer having a  $Z_{sc}$  of 6%, i.e. the transformers will be loaded automatically in proportion to their kVA ratings. For transformers having a ratio of kVA ratings exceeding 2, parallel operation is not recommended.

**Figure H46** indicates, for the most usual arrangement (2 or 3 transformers of equal kVA ratings) the maximum short-circuit currents to which main and principal CBs (CBM and CBP respectively, in Figure H45) are subjected. It is based on the following hypotheses:

- The short-circuit 3-phase power on the MV side of the transformer is 500 MVA
- The transformers are standard 20/0.4 kV distribution-type units rated as listed
- The cables from each transformer to its LV circuit-breaker comprise 5 metres of single core conductors
- Between each incoming-circuit CBM and each outgoing-circuit CBP there is 1 metre of busbar
- The switchgear is installed in a floormounted enclosed switchboard, in an ambient-air temperature of 30 °C

Moreover, this table shows selected circuit-breakers of M-G manufacture recommended for main and principal circuit-breakers in each case.

**Example** (see Fig. H47 next page)

- Circuit-breaker selection for CBM duty:

For a 800 kVA transformer  $I_n = 1.126$  A;  $I_{cu}$  (minimum) = 38 kA (from Figure H46), the CBM indicated in the table is a Compact NS1250N ( $I_{cu} = 50$  kA)

- Circuit-breaker selection for CBP duty:

The s.c. breaking capacity ( $I_{cu}$ ) required for these circuit-breakers is given in the Figure H46 as 56 kA.

A recommended choice for the three outgoing circuits 1, 2 and 3 would be current-limiting circuit-breakers types NSX400 L, NSX250 L and NSX100 L. The  $I_{cu}$  rating in each case = 150 kA.

Number and kVA ratings of 20/0.4 kV transformers	Minimum S.C breaking capacity of main CBs ( $I_{cu}$ ) kA	Main circuit-breakers (CBM) total discrimination with outgoing circuit-breakers (CBP)	Minimum S.C breaking capacity of principal CBs ( $I_{cu}$ ) kA	Rated current $I_n$ of principal circuit-breaker (CPB) 250A
2 x 400	14	NW08N1/NS800N	27	NSX250H
3 x 400	28	NW08N1/NS800N	42	NSX250H
2 x 630	22	NW10N1/NS1000N	42	NSX250H
3 x 630	44	NW10N1/NS1000N	67	NSX250H
2 x 800	19	NW12N1/NS1250N	38	NSX250H
3 x 800	38	NW12N1/NS1250N	56	NSX250H
2 x 1,000	23	NW16N1/NS1600N	47	NSX250H
3 x 1,000	47	NW16N1/NS1600N	70	NSX250H
2 x 1,250	29	NW20N1/NS2000N	59	NSX250H
3 x 1,250	59	NW20N1/NS2000N	88	NSX250L
2 x 1,600	38	NW25N1/NS2500N	75	NSX250L
3 x 1,600	75	NW25N1/NS2500N	113	NSX250L
2 x 2,000	47	NW32N1/NS3200N	94	NSX250L
3 x 2,000	94	NW32N1/NS3200N	141	NSX250L

Fig. H46 : Maximum values of short-circuit current to be interrupted by main and principal circuit-breakers (CBM and CBP respectively), for several transformers in parallel

Short-circuit fault-current levels at any point in an installation may be obtained from tables

These circuit-breakers provide the advantages of:

- Absolute discrimination with the upstream (CBM) breakers
- Exploitation of the “cascading” technique, with its associated savings for all downstream components

### Choice of outgoing-circuit CBs and final-circuit CBs

#### Use of table G40

From this table, the value of 3-phase short-circuit current can be determined rapidly for any point in the installation, knowing:

- The value of short-circuit current at a point upstream of that intended for the CB concerned
- The length, c.s.a., and the composition of the conductors between the two points

A circuit-breaker rated for a short-circuit breaking capacity exceeding the tabulated value may then be selected.

#### Detailed calculation of the short-circuit current level

In order to calculate more precisely the short-circuit current, notably, when the short-circuit current-breaking capacity of a CB is slightly less than that derived from the table, it is necessary to use the method indicated in chapter G clause 4.

#### Two-pole circuit-breakers (for phase and neutral) with one protected pole only

These CBs are generally provided with an overcurrent protective device on the phase pole only, and may be used in TT, TN-S and IT schemes. In an IT scheme, however, the following conditions must be respected:

- Condition (B) of table G67 for the protection of the neutral conductor against overcurrent in the case of a double fault
- Short-circuit current-breaking rating: A 2-pole phase-neutral CB must, by convention, be capable of breaking on one pole (at the phase-to-phase voltage) the current of a double fault equal to 15% of the 3-phase short-circuit current at the point of its installation, if that current is  $\leq 10$  kA; or 25% of the 3-phase short-circuit current if it exceeds 10 kA
- Protection against indirect contact: this protection is provided according to the rules for IT schemes

#### Insufficient short-circuit current breaking rating

In low-voltage distribution systems it sometimes happens, especially in heavy-duty networks, that the  $I_{sc}$  calculated exceeds the  $I_{cu}$  rating of the CBs available for installation, or system changes upstream result in lower level CB ratings being exceeded

- Solution 1: Check whether or not appropriate CBs upstream of the CBs affected are of the current-limiting type, allowing the principle of cascading (described in sub-clause 4.5) to be applied
- Solution 2: Install a range of CBs having a higher rating. This solution is economically interesting only where one or two CBs are affected
- Solution 3: Associate current-limiting fuses (gG or aM) with the CBs concerned, on the upstream side. This arrangement must, however, respect the following rules:
  - The fuse rating must be appropriate
  - No fuse in the neutral conductor, except in certain IT installations where a double fault produces a current in the neutral which exceeds the short-circuit breaking rating of the CB. In this case, the blowing of the neutral fuse must cause the CB to trip on all phases

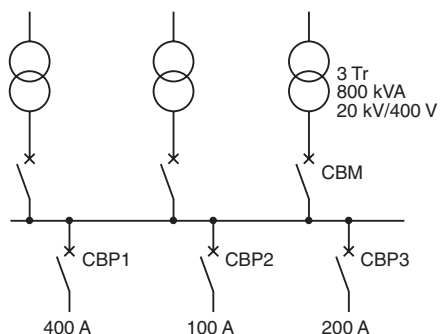


Fig. H47 : Transformers in parallel

The technique of “cascading” uses the properties of current-limiting circuit-breakers to permit the installation of all downstream switchgear, cables and other circuit components of significantly lower performance than would otherwise be necessary, thereby simplifying and reducing the cost of an installation

## 4.5 Coordination between circuit-breakers

### Cascading

#### Definition of the cascading technique

By limiting the peak value of short-circuit current passing through it, a current-limiting CB permits the use, in all circuits downstream of its location, of switchgear and circuit components having much lower short-circuit breaking capacities, and thermal and electromechanical withstand capabilities than would otherwise be necessary. Reduced physical size and lower performance requirements lead to substantial economy and to the simplification of installation work. It may be noted that, while a current-limiting circuit-breaker has the effect on downstream circuits of (apparently) increasing the source impedance during short-circuit conditions, it has no such effect in any other condition; for example, during the starting of a large motor (where a low source impedance is highly desirable). The range of Compact NSX current-limiting circuit-breakers with powerful limiting performances is particularly interesting.

*In general, laboratory tests are necessary to ensure that the conditions of implementation required by national standards are met and compatible switchgear combinations must be provided by the manufacturer*

### Conditions of implementation

Most national standards admit the cascading technique, on condition that the amount of energy "let through" by the limiting CB is less than the energy all downstream CBs and components are able to withstand without damage.

In practice this can only be verified for CBs by tests performed in a laboratory. Such tests are carried out by manufacturers who provide the information in the form of tables, so that users can confidently design a cascading scheme based on the combination of recommended circuit-breaker types. As an example, **Figure H48** indicates the cascading possibilities of circuit-breaker types C60, DT40N, C120 and NG125 when installed downstream of current-limiting CBs Compact NSX 250 N, H or L for a 230/400 V or 240/415 V 3-phase installation.

	kA rms			
Short-circuit breaking capacity of the upstream (limiter) CBs	150			NSX250L
	70		NSX250H	
	50	NSX250N		
		↓	↓	↓
Possible short-circuit breaking capacity of the downstream CBs (benefiting from the cascading technique)	150			NG125L
	70		NG125L	
	36	NG125N	NG125N	
	30	C60N/H<=32A	C60N/H<=32A	C60N/H<=32A
	30	C60L<=25A	C60L<=25A Quick PRD 40/20/8	C60L<=25A
	25	C60H>=40A C120N/H	C60H>=40A C120N/H	C60H>=40A C120N/H
	20	C60N>=40A	C60N>=40A	C60N>=40A

**Fig. H48** : Example of cascading possibilities on a 230/400 V or 240/415 V 3-phase installation

### Advantages of cascading

The current limitation benefits all downstream circuits that are controlled by the current-limiting CB concerned.

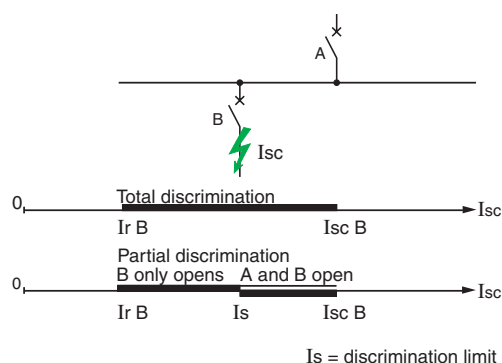
The principle is not restrictive, i.e. current-limiting CBs can be installed at any point in an installation where the downstream circuits would otherwise be inadequately rated.

The result is:

- Simplified short-circuit current calculations
- Simplification, i.e. a wider choice of downstream switchgear and appliances
- The use of lighter-duty switchgear and appliances, with consequently lower cost
- Economy of space requirements, since light-duty equipment have generally a smaller volume

### Principles of discriminative tripping (selectivity)

Discrimination is achieved by automatic protective devices if a fault condition, occurring at any point in the installation, is cleared by the protective device located immediately upstream of the fault, while all other protective devices remain unaffected (see **Fig. H49**).



**Fig. H49** : Total and partial discrimination

*Discrimination may be total or partial, and based on the principles of current levels, or time-delays, or a combination of both. A more recent development is based on the logic techniques.*

*The Schneider Electric system takes advantages of both current-limitation and discrimination*



Discrimination between circuit-breakers A and B is total if the maximum value of short-circuit-current on circuit B ( $I_{sc} B$ ) does not exceed the short-circuit trip setting of circuit-breaker A ( $I_m A$ ). For this condition, B only will trip (see **Fig. H50**).

Discrimination is partial if the maximum possible short-circuit current on circuit B exceeds the short-circuit trip-current setting of circuit-breaker A. For this maximum condition, both A and B will trip (see **Fig. H51**).

**Protection against overload : discrimination based on current levels**  
(see **Fig. H52a**)

This method is realized by setting successive tripping thresholds at stepped levels, from downstream relays (lower settings) towards the source (higher settings). Discrimination is total or partial, depending on particular conditions, as noted above. As a rule of thumb, discrimination is achieved when:

■  $I_r A / I_r B > 2$ :

**Protection against low level short-circuit currents : discrimination based on stepped time delays** (see **Fig. H52b**)

This method is implemented by adjusting the time-delayed tripping units, such that downstream relays have the shortest operating times, with progressively longer delays towards the source.

In the two-level arrangement shown, upstream circuit-breaker A is delayed sufficiently to ensure total discrimination with B (for example: Masterpact with electronic trip unit).

**Discrimination based on a combination of the two previous methods**  
(see **Fig. H52c**)

A time-delay added to a current level scheme can improve the overall discrimination performance.

The upstream CB has two high-speed magnetic tripping thresholds:

- $I_m A$ : delayed magnetic trip or short-delay electronic trip
- $I_i$ : instantaneous strip

Discrimination is total if  $I_{sc} B < I_i$  (instantaneous).

**Protection against high level short-circuit currents: discrimination based on arc-energy levels**

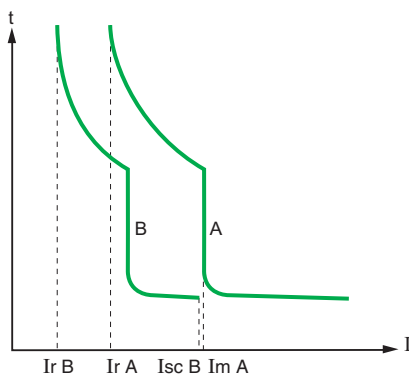
This technology implemented in the Compact NSX range (current limiting circuit-breaker) is extremely effective for achievement of total discrimination.

Principle: When a very high level short-circuit current is detected by the two circuit-breakers A and B, their contacts open simultaneously. As a result, the current is highly limited.

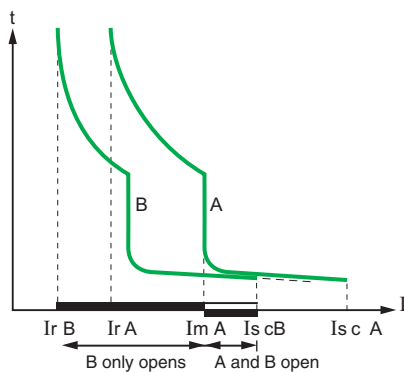
- The very high arc-energy at level B induces the tripping of circuit-breaker B
- Then, the arc-energy is limited at level A and is not sufficient to induce the tripping of A

As a rule of thumb, the discrimination between Compact NSX is total if the size ratio between A and B is greater than 2.5.

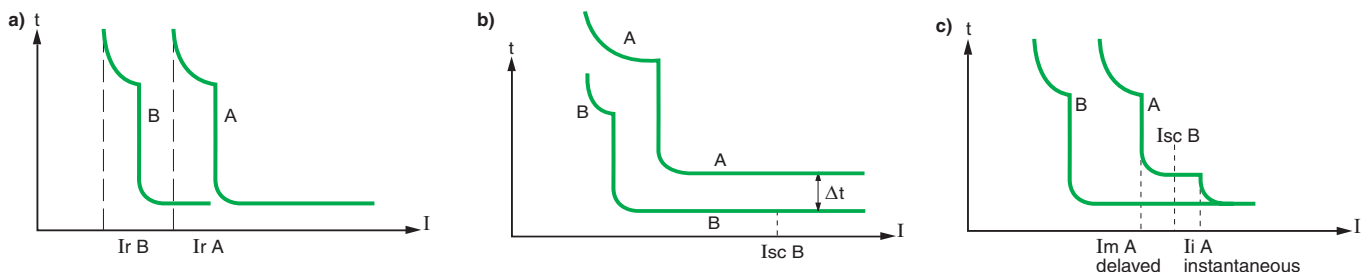
H24



**Fig. H50** : Total discrimination between CBs A and B



**Fig. H51** : Partial discrimination between CBs A and B



**Fig. H52** : Discrimination

### Current-level discrimination

This technique is directly linked to the staging of the Long Time (LT) tripping curves of two serial-connected circuit-breakers.

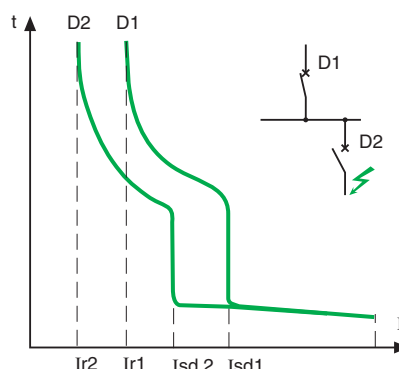


Fig. H53 : Current discrimination

The discrimination limit  $I_s$  is:

- $I_s = I_{sd2}$  if the thresholds  $I_{sd1}$  and  $I_{sd2}$  are too close or merge,
- $I_s = I_{sd1}$  if the thresholds  $I_{sd1}$  and  $I_{sd2}$  are sufficiently far apart.

As a rule, current discrimination is achieved when:

- $I_{r1} / I_{r2} < 2$ ,
- $I_{sd1} / I_{sd2} > 2$ .

The discrimination limit is:

- $I_s = I_{sd1}$ .

#### Discrimination quality

Discrimination is total if  $I_s > I_{sc}(D2)$ , i.e.  $I_{sd1} > I_{sc}(D2)$ .

This normally implies:

- a relatively low level  $I_{sc}(D2)$ ,
- a large difference between the ratings of circuit-breakers D1 and D2.

**Current discrimination is normally used in final distribution.**

*Discrimination based on time-delayed tripping uses CBs referred to as “selective” (in some countries).*

*Implementation of these CBs is relatively simple and consists in delaying the instant of tripping of the several series-connected circuit-breakers in a stepped time sequence*

### Time discrimination

This is the extension of current discrimination and is obtained by staging over time of the tripping curves. This technique consists of giving a time delay of  $t$  to the Short Time (ST) tripping of D1.

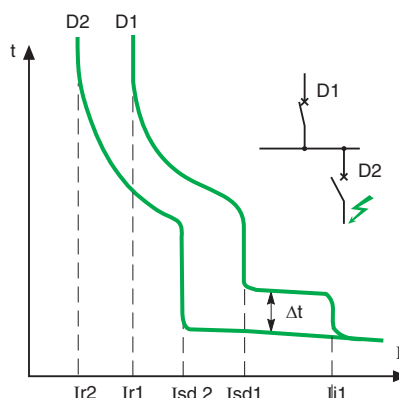


Fig. H54 : Time discrimination



The thresholds ( $I_{r1}$ ,  $I_{sd1}$ ) of D1 and ( $I_{r2}$ ,  $I_{sd2}$ ) comply with the staging rules of current discrimination.

The discrimination limit  $I_s$  of the association is at least equal to  $I_{i1}$ , the instantaneous threshold of D1.

#### Discrimination quality

There are two possible applications:

##### ■ on final and/or intermediate feeders

**A category circuit-breakers** can be used with time-delayed tripping of the upstream circuit-breaker. This allows extension of current discrimination up to the instantaneous threshold  $I_{i1}$  of the upstream circuit-breaker:  $I_s = I_{i1}$ .

**If  $I_{sc}(D2)$  is not too high - case of a final feeder - total discrimination can be obtained.**

##### ■ on the incomers and feeders of the MSB

At this level, as continuity of supply takes priority, the installation characteristics allow use of **B category circuit-breakers** designed for time-delayed tripping. These circuit-breakers have a high thermal withstand ( $I_{cw} \geq 50\% I_{cn}$  for  $t = 1s$ ):  $I_s = I_{cw1}$ .

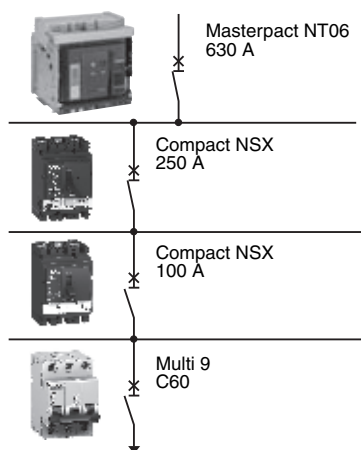
**Even for high  $I_{sc}(D2)$ , time discrimination normally provides total discrimination:  $I_{cw1} > I_{cc}(D2)$ .**

**Note:** Use of B category circuit-breakers means that the installation must withstand high electrodynamic and thermal stresses.

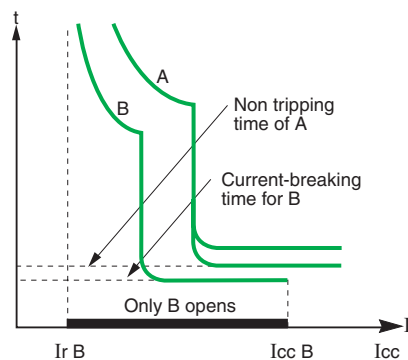
Consequently, these circuit-breakers have a high instantaneous threshold  $I_i$  that can be adjusted and disabled in order to protect the busbars if necessary.

#### Practical example of discrimination at several levels with Schneider Electric circuit-breakers (with electronic trip units)

"Masterpact NT is totally selective with any moulded-case Compact NSX circuit breaker, i.e., the downstream circuit-breaker will trip for any short-circuit value up to its breaking capacity. Further, all Compact NSX CBs are totally selective, as long as the ratio between sizes is greater than 1.6 and the ratio between ratings is greater than 2.5. The same rules apply for the total selectivity with the miniature circuit-breakers Multi9 further downstream (see Fig. H55).



H26



**Fig. H55 :** 4 level discrimination with Schneider Electric circuit breakers : Masterpact NT Compact NSX and Multi 9

### Energy discrimination with current limitation

Cascading between 2 devices is normally achieved by using the tripping of the upstream circuit-breaker A to help the downstream circuit-breaker B to break the current. The discrimination limit  $I_s$  is consequently equal to the ultimate breaking current  $I_{cu}$  B of circuit-breaker B acting alone, as cascading requires the tripping of both devices.

The energy discrimination technology implemented in Compact NSX circuit-breakers allows to improve the discrimination limit to a value higher than the ultimate breaking current  $I_{cu}$  B of the downstream circuit-breaker. The principle is as follows:

- The downstream limiting circuit-breaker B sees a very high short-circuit current. The tripping is very fast ( $<1$  ms) and then, the current is limited
- The upstream circuit-breaker A sees a limited short-circuit current compared to its breaking capability, but this current induces a repulsion of the contacts. As a result, the arcing voltage increases the current limitation. However, the arc energy is not high enough to induce the tripping of the circuit-breaker. So, the circuit-breaker A helps the circuit-breaker B to trip, without tripping itself. The discrimination limit can be higher than  $I_{cu}$  B and the discrimination becomes total with a reduced cost of the devices

### Natural total discrimination with Compact NSX

The major advantage of the Compact NSX range is to provide a natural total discrimination between two series-connected devices if:

- The ratio of the two trip-unit current ratings is  $> 1.6$
- The ratio of rated currents of the two circuit-breakers is  $> 2.5$

### Logic discrimination or “Zone Sequence Interlocking – ZSI”

This type of discrimination can be achieved with circuit-breakers equipped with specially designed electronic trip units (Compact, Masterpact): only the Short Time Protection (STP) and Ground Fault Protection (GFP) functions of the controlled devices are managed by Logic Discrimination. In particular, the Instantaneous Protection function - inherent protection function - is not concerned.

#### Settings of controlled circuit-breakers

- time delay: there are no rules, but staging (if any) of the time delays of time discrimination must be applied ( $\Delta tD1 \geq \Delta tD2 \geq \Delta tD3$ ),
- thresholds: there are no threshold rules to be applied, but natural staging of the protection device ratings must be complied with ( $I_{crD1} \geq I_{crD2} \geq I_{crD3}$ ).

**Note:** This technique ensures discrimination even with circuit-breakers of similar ratings.

### Principles

Activation of the Logic Discrimination function is via transmission of information on the pilot wire:

- ZSI input:
  - low level (no downstream faults): the Protection function is on standby with a reduced time delay ( $\gamma 0,1$  s),
  - high level (presence of downstream faults): the relevant Protection function moves to the time delay status set on the device.
- ZSI output:
  - low level: the trip unit detects no faults and sends no orders,
  - high level: the trip unit detects a fault and sends an order.

### Operation

A pilot wire connects in cascading form the protection devices of an installation (see Fig. H56). **When a fault occurs, each circuit-breaker** upstream of the fault (detecting a fault) sends an order (high level output) and moves the upstream circuit-breaker to its natural time delay (high level input). The circuitbreaker placed just above the fault does not receive any orders (low level input) and thus trips almost instantaneously.

*Discrimination schemes based on logic techniques are possible, using CBs equipped with electronic tripping units designed for the purpose (Compact, Masterpact) and interconnected with pilot wires*

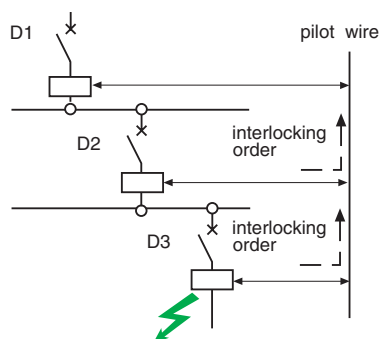


Fig. H56 : Logic discrimination.

**Discrimination quality**

This technique enables:

- easy achievement as standard of discrimination on 3 levels or more,
- elimination of important stresses on the installation, relating to time-delayed tripping of the protection device, in event of a fault directly on the upstream busbars.

**All the protection devices are thus virtually instantaneous,**

- easy achievement of downstream discrimination with non-controlled circuit-breakers.

H28

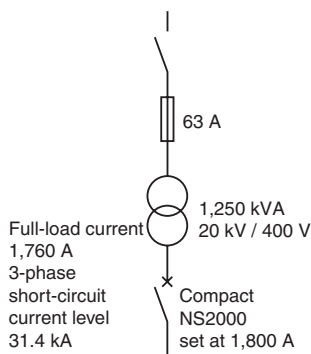


Fig. H57 : Example

## 4.6 Discrimination MV/LV in a consumer's substation

In general the transformer in a consumer's substation is protected by MV fuses, suitably rated to match the transformer, in accordance with the principles laid down in IEC 60787 and IEC 60420, by following the advice of the fuse manufacturer.

The basic requirement is that a MV fuse will not operate for LV faults occurring downstream of the transformer LV circuit-breaker, so that the tripping characteristic curve of the latter must be to the left of that of the MV fuse pre-arcing curve.

This requirement generally fixes the maximum settings for the LV circuit-breaker protection:

- Maximum short-circuit current-level setting of the magnetic tripping element
- Maximum time-delay allowable for the short-circuit tripping element (see Fig. H57)
- Short-circuit level at MV terminals of transformer: 250 MVA
- Transformer MV/LV: 1,250 kVA 20/0.4 kV
- MV fuses: 63 A
- Cabling, transformer - LV circuit-breaker: 10 metres single-core cables
- LV circuit-breaker: Compact NSX 2000 set at 1,800 A ( $I_r$ )

What is the maximum short-circuit trip current setting and its maximum time delay allowable?

The curves of Figure H58 show that discrimination is assured if the short-time delay tripping unit of the CB is set at:

- A level  $\leq 6 I_r = 10.8 \text{ kA}$
- A time-delay setting of step 1 or 2

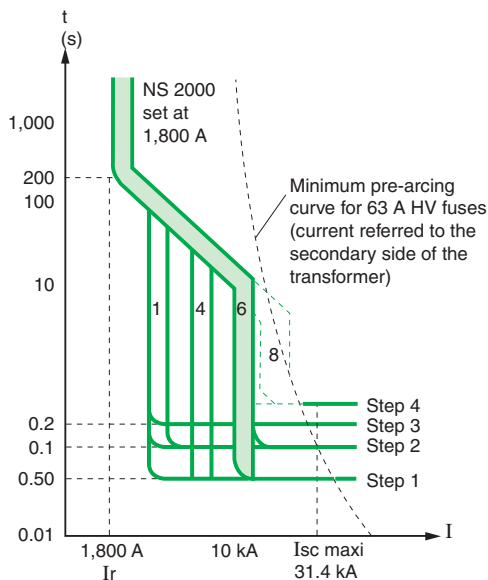


Fig. H58 : Curves of MV fuses and LV circuit-breaker

## Chapter J

# Protection against voltage surges in LV

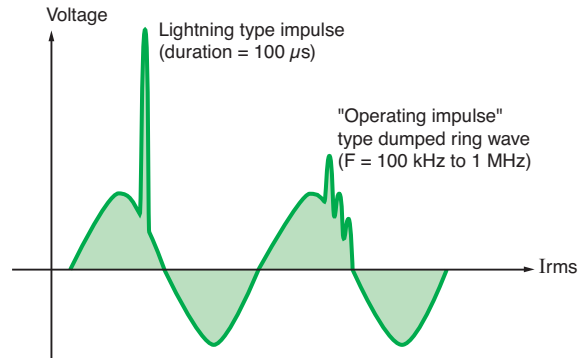
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J1

## 1.1 What is a voltage surge?

A voltage surge is a voltage impulse or wave which is superposed on the rated network voltage (see **Fig. J1**).

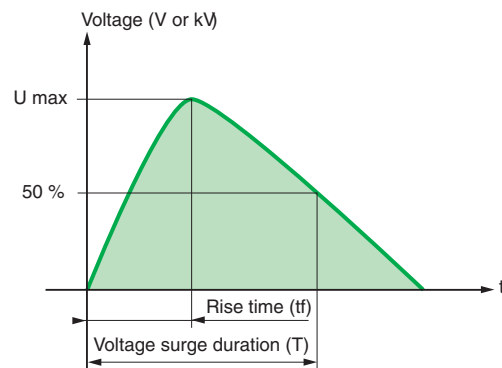


**Fig. J1** : Voltage surge examples

This type of voltage surge is characterised by ( see **Fig. J2**):

- The rise time ( $t_f$ ) measured in  $\mu\text{s}$
- The gradient  $S$  measured in  $\text{kV}/\mu\text{s}$

A voltage surge disturbs equipment and causes electromagnetic radiation. Furthermore, the duration of the voltage surge ( $T$ ) causes a surge of energy in the electrical circuits which is likely to destroy the equipment.



**Fig. J2** : Main overvoltage characteristics

## 1.2 The four voltage surge types

There are four types of voltage surges which may disturb electrical installations and loads:

- Atmospheric voltage surges
- Operating voltage surges
- Transient overvoltage at industrial frequency
- Voltage surges caused by electrostatic discharge

### Atmospheric voltage surges

#### Lightning risk – a few figures

Between 2,000 and 5,000 storms are constantly forming around the earth. These storms are accompanied by lightning which constitutes a serious risk for both people and equipment. Strokes of lightning hit the ground at a rate of 30 to 100 strokes per second. Every year, the earth is struck by about 3 billion strokes of lightning.

- Throughout the world, every year, thousands of people are struck by lightning and countless animals are killed
- Lightning also causes a large number of fires, most of which break out on farms (destroying buildings or putting them out of use)
- Lightning also affects transformers, electricity meters, household appliances, and all electrical and electronic installations in the residential sector and in industry.
- Tall buildings are the ones most often struck by lightning
- The cost of repairing damage caused by lightning is very high
- It is difficult to evaluate the consequences of disturbance caused to computer or telecommunications networks, faults in PLC cycles and faults in regulation systems.

Furthermore, the losses caused by a machine being put out of use can have financial consequences rising above the cost of the equipment destroyed by the lightning.

#### Characteristics of lightning discharge

**Figure J3** shows the values given by the lightning protection committee (Technical Committee 81) of the I.E.C. As can be seen, 50 % of lightning strokes are of a force greater than 33 kA and 5 % are greater than 85 kA. The energy forces involved are thus very high.

Beyond peak probability P%	Current peak I (kA)	Gradient S (kA/μs)	Total duration T (s)	Number of discharges n
95	7	9.1	0.001	1
50	33	24	0.01	2
5	85	65	1.1	6

**Fig. J3** : Lightning discharge values given by the IEC lightning protection committee

J3

It is important to define the probability of adequate protection when protecting a site. Furthermore, a lightning current is a high frequency (HF) impulse current reaching roughly a megahertz.

#### The effects of lightning

A lightning current is therefore a high frequency electrical current. As well as considerable induction and voltage surge effects, it causes the same effects as any other low frequency current on a conductor:

- Thermal effects: fusion at the lightning impact points and joule effect, due to the circulation of the current, causing fires
- Electrodynamics effects: when the lightning currents circulate in parallel conductors, they provoke attraction or repulsion forces between the wires, causing breaks or mechanical deformations (crushed or flattened wires)
- Combustion effects: lightning can cause the air to expand and create overpressure which stretches over a distance of a dozen metres or so. A blast effect breaks windows or partitions and can project animals or people several metres away from their original position. This shock wave is at the same time transformed into a sound wave: thunder
- Voltage surges conducted after an impact on overhead electrical or telephone lines
- Voltage surges induced by the electromagnetic radiation effect of the lightning channel which acts as an antenna over several kilometres and is crossed by a considerable impulse current
- The elevation of the earth potential by the circulation of the lightning current in the ground. This explains indirect strokes of lightning by step voltage and the breakdown of equipment

#### Operating voltage surges

A sudden change in the established operating conditions in an electrical network causes transient phenomena to occur. These are generally high frequency or damped oscillation voltage surge waves (see Fig. J1).

They are said to have a slow gradient: their frequency varies from several ten to several hundred kilohertz.

Operating voltage surges may be created by:

- The opening of protection devices (fuse, circuit-breaker), and the opening or closing of control devices (relays, contactors, etc.)
- Inductive circuits due to motors starting and stopping, or the opening of transformers such as MV/LV substations
- Capacitive circuits due to the connection of capacitor banks to the network
- All devices that contain a coil, a capacitor or a transformer at the power supply inlet: relays, contactors, television sets, printers, computers, electric ovens, filters, etc.

*Lightning comes from the discharge of electrical charges accumulated in the cumulo-nimbus clouds which form a capacitor with the ground. Storm phenomena cause serious damage. Lightning is a high frequency electrical phenomenon which produces voltage surges on all conductive elements, and especially on electrical loads and wires.*

Transient overvoltages at industrial frequency (see Fig. J4)

These overvoltages have the same frequency as the network (50, 60 or 400 Hz); and can be caused by:

- Phase/frame or phase/earth insulating faults on a network with an insulated or impedant neutral, or by the breakdown of the neutral conductor. When this happens, single phase devices will be supplied in 400 V instead of 230 V.
- A cable breakdown. For example, a medium voltage cable which falls on a low voltage line.
- The arcing of a high or medium voltage protective spark-gap causing a rise in earth potential during the action of the protection devices. These protection devices follow automatic switching cycles which will recreate a fault if it persists.

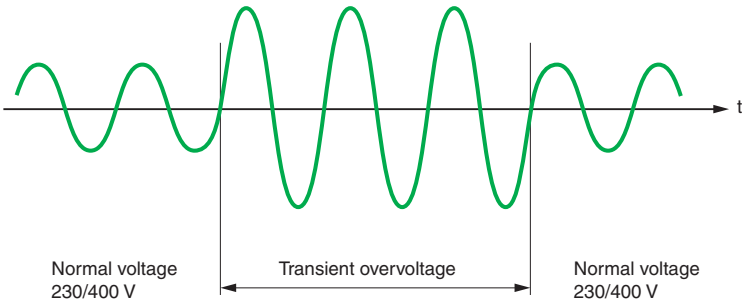


Fig. J4 : Transient overvoltage at industrial frequency

Voltage surges caused by electrical discharge

In a dry environment, electrical charges accumulate and create a very strong electrostatic field. For example, a person walking on carpet with insulating soles will become electrically charged to a voltage of several kilovolts. If the person walks close to a conductive structure, he will give off an electrical discharge of several amperes in a very short rise time of a few nanoseconds. If the structure contains sensitive electronics, a computer for example, its components or circuit boards may be damaged.

1.3 Main characteristics of voltage surges

Figure J5 below sums up the main characteristics of voltage surges.

Type of voltage surge	Voltage surge coefficient	Duration	Front gradient or frequency
Industrial frequency (insulation fault)	≤ 1.7	Long 30 to 1,000 ms	Industrial frequency (50-60-400 Hz)
Operation	2 to 4	Short 1 to 100 ms	Average 1 to 200 kHz
Atmospheric	> 4	Very short 1 to 100 μs	Very high 1 to 1,000 kV/μs

Fig. J5 : Main characteristics of voltage surges

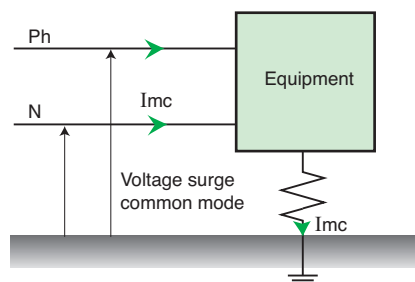
- Three points must be kept in mind:
- A direct or indirect lightning stroke may have destructive consequences on electrical installations several kilometres away from where it falls
  - Industrial or operating voltage surges also cause considerable damage
  - The fact that a site installation is underground in no way protects it although it does limit the risk of a direct strike

## 1.4 Different propagation modes

### Common mode

Common mode voltage surges occur between the live parts and the earth: phase/earth or neutral/earth (see **Fig. J6**).

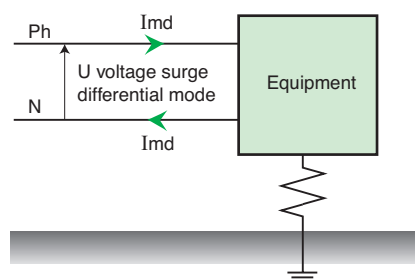
They are especially dangerous for devices whose frame is earthed due to the risk of dielectric breakdown.



**Fig. J6** : Common mode

### Differential mode

Differential mode voltage surges circulate between live conductors: Phase to phase or phase to neutral (see **Fig. J7**). They are especially dangerous for electronic equipment, sensitive computer equipment, etc.



**Fig. J7** : Differential mode



## 2 Overvoltage protection devices

Two major types of protection devices are used to suppress or limit voltage surges: they are referred to as primary protection devices and secondary protection devices.

### 2.1 Primary protection devices (protection of installations against lightning)

The purpose of primary protection devices is to protect installations against direct strokes of lightning. They catch and run the lightning current into the ground. The principle is based on a protection area determined by a structure which is higher than the rest.

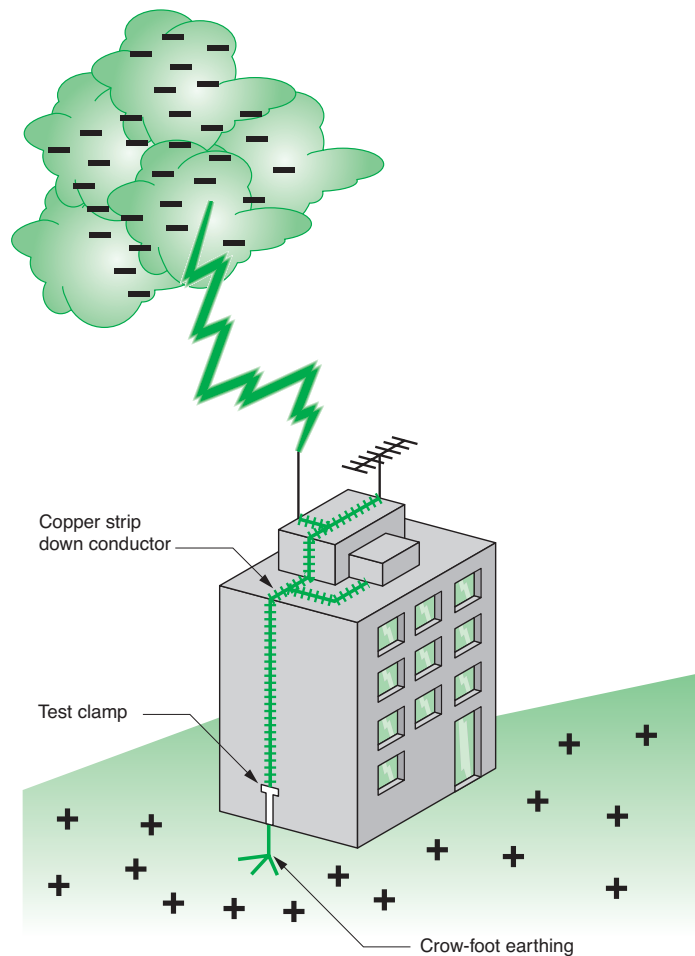
The same applies to any peak effect produced by a pole, building or very high metallic structure.

There are three types of primary protection:

- Lightning conductors, which are the oldest and best known lightning protection device
- Overhead earth wires
- The meshed cage or Faraday cage

#### The lightning conductor

The lightning conductor is a tapered rod placed on top of the building. It is earthed by one or more conductors (often copper strips) (see **Fig. J8**).



**Fig. J8** : Example of protection using a lightning conductor

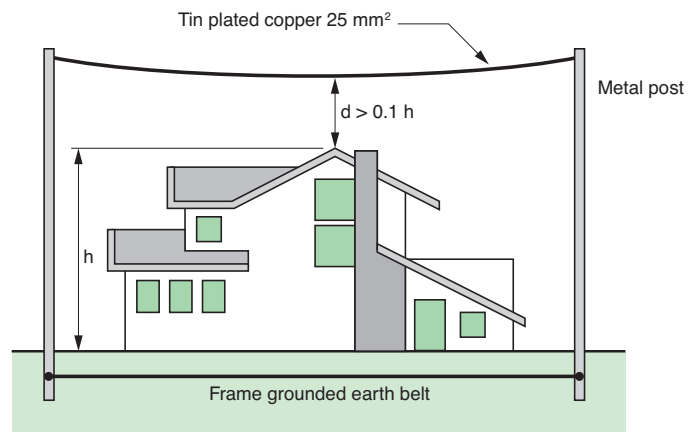
The design and installation of a lightning conductor is the job of a specialist.

Attention must be paid to the copper strip paths, the test clamps, the crow-foot earthing to help high frequency lightning currents run to the ground, and the distances in relation to the wiring system (gas, water, etc.).

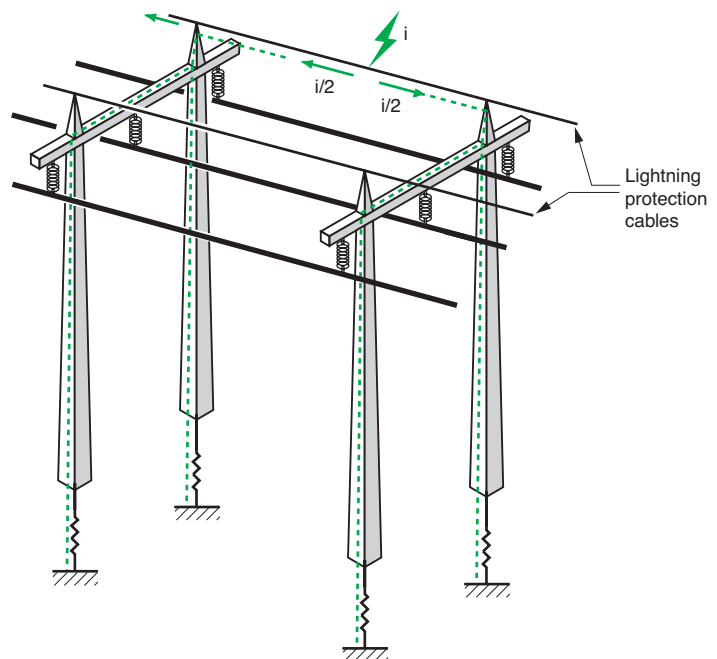
Furthermore, the flow of the lightning current to the ground will induce voltage surges, by electromagnetic radiation, in the electrical circuits and buildings to be protected. These may reach several dozen kilovolts. It is therefore necessary to symmetrically split the down conductor currents in two, four or more, in order to minimise electromagnetic effects.

### Overhead earth wires

These wires are stretched over the structure to be protected (see **Fig. J9**). They are used for special structures: rocket launch pads, military applications and lightning protection cables for overhead high voltage power lines (see **Fig. J10**).



**Fig. J9** : Example of lightning protection using overhead earth wires



**Fig. J10** : Lightning protection wires

Primary lightning conductor protection devices such as a meshed cage or overhead earth wires are used to protect against direct strokes of lightning. These protection devices do not prevent destructive secondary effects on equipment from occurring. For example, rises in earth potential and electromagnetic induction which are due to currents flowing to the earth. To reduce secondary effects, LV surge arresters must be added on telephone and electrical power networks.

### The meshed cage (Faraday cage)

This principle is used for very sensitive buildings housing computer or integrated circuit production equipment. It consists in symmetrically multiplying the number of down strips outside the building. Horizontal links are added if the building is high; for example every two floors (see Fig. J11). The down conductors are earthed by frog's foot earthing connections. The result is a series of interconnected 15 x 15 m or 10 x 10 m meshes. This produces better equipotential bonding of the building and splits lightning currents, thus greatly reducing electromagnetic fields and induction.

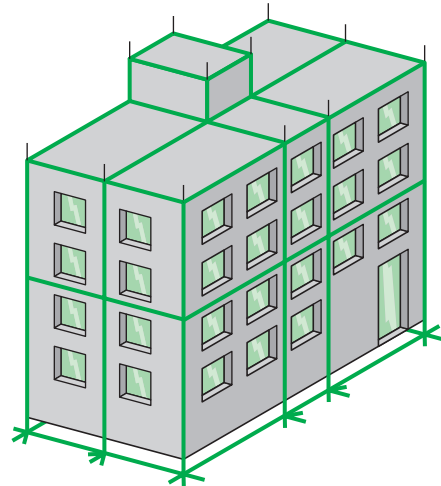


Fig. J11 : Example of protection using the meshed cage (Faraday cage) principle

## 2.2 Secondary protection devices (protection of internal installations against lightning)

These handle the effects of atmospheric, operating or industrial frequency voltage surges. They can be classified according to the way they are connected in an installation: serial or parallel protection.

### Serial protection device

This is connected in series to the power supply wires of the system to be protected (see Fig. J12).

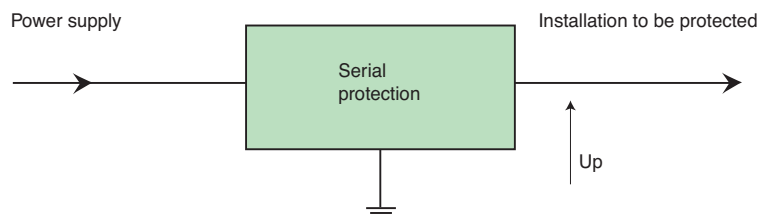


Fig. J12 : Serial protection principle

### Transformers

They reduce voltage surges by inductor effect and make certain harmonics disappear by coupling. This protection is not very effective.

### Filters

Based on components such as resistors, inductance coils and capacitors they are suitable for voltage surges caused by industrial and operation disturbance corresponding to a clearly defined frequency band. This protection device is not suitable for atmospheric disturbance.

**Wave absorbers**

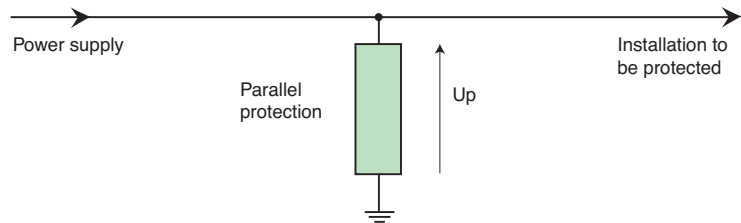
They are essentially made up of air inductance coils which limit the voltage surges, and surge arresters which absorb the currents. They are extremely suitable for protecting sensitive electronic and computing equipment. They only act against voltage surges. They are nonetheless extremely cumbersome and expensive.

**Network conditioners and static uninterrupted power supplies (UPS)**

These devices are essentially used to protect highly sensitive equipment, such as computer equipment, which requires a high quality electrical power supply. They can be used to regulate the voltage and frequency, stop interference and ensure a continuous electrical power supply even in the event of a mains power failure (for the UPS). On the other hand, they are not protected against large, atmospheric type voltage surges against which it is still necessary to use surge arresters.

**Parallel protection device****The principle**

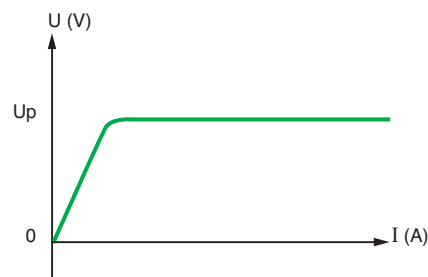
The parallel protection is adapted to any installation power level (see **Fig. J13**). This type of overvoltage protection is the most commonly used.



**Fig. J13** : Parallel protection principle

**Main characteristics**

- The rated voltage of the protection device must correspond to the network voltage at the installation terminals
- When there is no voltage surge, a leakage current should not go through the protection device which is on standby
- When a voltage surge above the allowable voltage threshold of the installation to be protected occurs, the protection device abruptly conducts the voltage surge current to the earth by limiting the voltage to the desired protection level  $U_p$  (see **Fig. J14**).



**Fig. J14** : Typical U/I curve of the ideal protection device

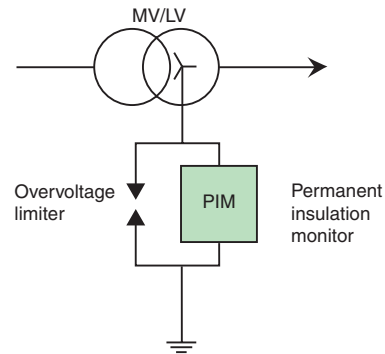
When the voltage surge disappears, the protection device stops conducting and returns to standby without a holding current. This is the ideal U/I characteristic curve:

- The protection device response time ( $t_r$ ) must be as short as possible to protect the installation as quickly as possible
- The protection device must have the capacity to be able to conduct the energy caused by the foreseeable voltage surge on the site to be protected
- The surge arrester protection device must be able to withstand the rated current  $I_n$ .

**The products used**

## ■ Voltage limiters

They are used in MV/LV substations at the transformer output, in IT earthing scheme. They can run voltage surges to the earth, especially industrial frequency surges (see Fig. J15)



**Fig. J15 :** Voltage limiter

## ■ LV surge arresters

This term designates very different devices as far as technology and use are concerned. Low voltage surge arresters come in the form of modules to be installed inside LV switchboard. There are also plug-in types and those that protect power outlets. They ensure secondary protection of nearby elements but have a small flow capacity. Some are even built into loads although they cannot protect against strong voltage surges

## ■ Low current surge arresters or overvoltage protectors

These protect telephone or switching networks against voltage surges from the outside (lightning), as well as from the inside (polluting equipment, switchgear switching, etc.)

Low current voltage surge arresters are also installed in distribution boxes or built into loads.

## 3 Protection against voltage surges in LV

### 3.1 Surge protective device description

A surge protective device (SDP) is a device that limits transient voltage surges and runs current waves to ground to limit the amplitude of the voltage surge to a safe level for electrical installations and equipment.

The surge protective device includes one or several non linear components.

The surge protective device eliminates voltage surges:

- In common mode: Phase to earth or neutral to earth
- In differential mode: Phase to phase or phase to neutral

When a voltage surge exceeds the  $U_c$  threshold, the surge protective device (SDP) conducts the energy to earth in common mode. In differential mode the diverted energy is directed to another active conductor.

The surge protective device has an internal thermal protection device which protects against burnout at its end of life. Gradually, over normal use after withstanding several voltage surges, the Surge Protective Device degrades into a conductive device. An indicator informs the user when end-of-life is close.

Some surge protective devices have a remote indication.

In addition, protection against short-circuits is ensured by an external circuit-breaker.

### 3.2 Surge protective device standards

#### International standard IEC 61643-1 ed. 02/2005

Surge protective devices connected to low-voltage power distribution systems.

Three test classes are defined:

- Class I tests: They are conducted using nominal discharge current ( $I_n$ ), voltage impulse with 1.2/50  $\mu$ s waveshape and impulse current  $I_{imp}$ .

The class I tests is intended to simulate partial conducted lightning current impulses. SPDs subjected to class I test methods are generally recommended for locations at points of high exposure, e.g., line entrances to buildings protected by lightning protection systems.

- Class II tests: They are conducted using nominal discharge current ( $I_n$ ), voltage impulse with 1.2/50  $\mu$ s waveshape

- Class III tests: They are conducted using the combination waveform (1.2/50 and 8/20  $\mu$ s).

SPDs tested to class II or III test methods are subjected to impulses of shorter duration. These SPDs are generally recommended for locations with lesser exposure.

These 3 test classes cannot be compared, since each originates in a country and each has its own specificities. Moreover, each builder can refer to one of the 3 test classes.

#### European standard EN 61643-11 2002

Some requirements as per IEC 61643-1. Moreover SPDs are classified in three categories:

- Type 1: SPD tested to Class I
- Type 2: SPD tested to Class II
- Type 3: SPD tested to Class III

### 3.3 Surge protective device data according to IEC 61643-1 standard

- **Surge protective device (SPD):** A device that is intended to limit transient overvoltages and divert surge currents. It contains at least one nonlinear component.

- **Test classes:** Surge arrester test classification.

- **$I_n$ :** Nominal discharge current; the crest value of the current through the SPD having a current waveshape of 8/20. This is used for the classification of the SPD for the class II test and also for preconditioning of the SPD for class I and II tests.

- **$I_{max}$ :** Maximum discharge current for class II test; crest value of a current through the SPD having an 8/20 waveshape and magnitude according to the test sequence of the class II operating duty test.  $I_{max}$  is greater than  $I_n$ .

- **$I_c$ :** Continuous operating current; current that flows in an SPD when supplied at its permanent full withstand operating voltage ( $U_c$ ) for each mode.  $I_c$  corresponds to the sum of the currents that flow in the SPD's protection component and in all the internal circuits connected in parallel.

### 3 Protection against voltage surges in LV

■ **I<sub>imp</sub>**: Impulse current, it is defined by a current peak value  $I_{peak}$  and the charge  $Q$ . Tested according to the test sequence of the operating duty test. This is used for the classification of the SPD for class I test.

■ **U<sub>n</sub>**: Rated network voltage.

■ **U<sub>c</sub>**: Maximum continuous operating voltage; the maximum r.m.s. or d.c. voltage which may be continuously applied to the SPDs mode of protection. This is equal to the rated voltage.

■ **U<sub>p</sub>**: Voltage protection level; a parameter that characterizes the performance of the SPD in limiting the voltage across its terminals, which is selected from a list of preferred values. This value shall be greater than the highest value of the measured limiting voltages.

The most common values for a **230/400 V** network are:

**1 kV - 1.2 kV - 1.5 kV - 1.8 kV - 2 kV - 2.5 kV.**

■ **U<sub>res</sub>**: Residual voltage, the peak value of the voltage that appears between the terminals of an SPD due to the passage of discharge current.

The SPD is characterised by  $U_c$ ,  $U_p$ ,  $I_n$  and  $I_{max}$  (see **Fig. J16**)

■ To test the surge arrester, standardized voltage and current waves have been defined that are specific to each country:

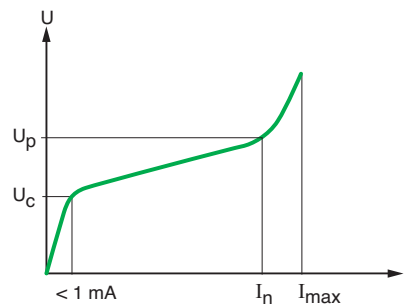
□ Voltage wave

e.g. 1.2/50  $\mu$ s (see **Fig. J17**)

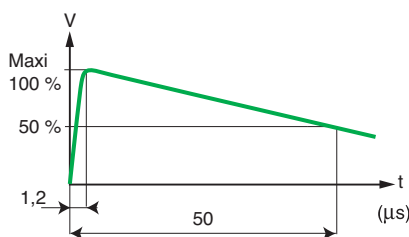
□ Current wave

Example 8/20  $\mu$ s (see **Fig. J18**)

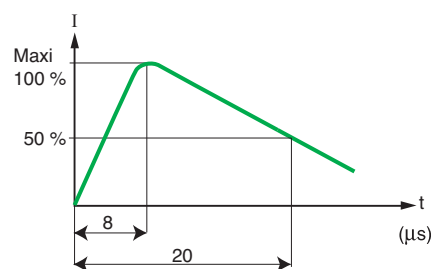
J12



**Fig. J16** : Voltage/current characteristics



**Fig. J17** : 1.2/50  $\mu$ s wave



**Fig. J18** : 8/20  $\mu$ s wave

□ Other possible wave characteristics:

4/10  $\mu$ s, 10/1000  $\mu$ s, 30/60  $\mu$ s, 10/350  $\mu$ s...

Comparison between different surge protective devices must be carried out using the same wave characteristics, in order to get relevant results.

## 3 Protection against voltage surges in LV

### 3.4 Lightning protection standards

The IEC 62305 series (part 1 to 5) restructures and updates the publications of IEC 61024 series, IEC 61312 series and IEC 61663 series.

The need for protection, the economic benefits of installing protection measures and the selection of adequate protection measures should be determined in terms of risk management. Risk management is the subject of IEC 62305-2.

The criteria for design, installation and maintenance of lightning protection measures are considered in three separate groups:

- The first group concerning protection measures to reduce physical damage and life hazard in a structure is given in IEC 62305-3.
- The second group concerning protection measures to reduce failures of electrical and electronic systems in a structure is given in IEC 62305-4.
- The third group concerning protection measures to reduce physical damage and failures of services connected to a structure (mainly electrical and telecommunication lines) is given in IEC 62305-5.

### 3.5 Surge arrester installation standards

■ **International:** IEC 61643-12 selection and application principles

■ **International:** IEC 60364 Electrical installations of buildings

□ IEC 60364-4-443: protection for safety

When an installation is supplied by, or includes, an overhead line, a protection device against atmospheric overvoltages **must be** foreseen if the keraunic level of the site being considered corresponds to the external influences condition AQ 1 (more than 25 days per year with thunderstorms).

□ IEC 60364-4-443-4: selection of equipment in the installation.

This section helps with the choice of the protection level Up for the surge arrester in function of the loads to be protected.

Rated residual voltage of protection devices must not be higher than the value in the voltage impulse withstand category II (see **Fig. J19**):

Nominal voltage of the installation <sup>(1)</sup> V		Required impulse withstand voltage for kV			
Three-phase systems <sup>(2)</sup>	Single-phase systems with middle point	Equipment at the origin of the installation (impulse withstand category IV)	Equipment of distribution and final circuits (impulse withstand category III)	Appliances (impulse withstand category II)	Specially protected equipment (impulse withstand category I)
	120-240	4	2.5	1.5	0.8
230/400 <sup>(2)</sup>	-	6	4	2.5	1.5
277/480 <sup>(2)</sup>	-	8	6	4	2.5
400/690	-	8	6	4	2.5
1,000	-	Values subject to system engineers			

**Fig. J19** : Choosing equipment for the installation according to IEC 60364

(1) According to IEC 60038

(2) In Canada and USA for voltages to earth higher than 300 V, the impulse withstand voltage corresponding to the next higher voltage in column one applies.

Category I is addressed to particular equipment engineering.

Category II is addressed to product committees for equipment for connection to the mains.

Category III is addressed to product committees of installation material and some special product committees.

Category IV is addressed to supply authorities and system engineers (see also 443.2.2).



### 3 Protection against voltage surges in LV

□ IEC 60364-5-534: choosing and implementing electrical equipment  
This section describes surge arrester installation conditions:

- **According to earthing systems:** The maximum continuous operating voltage  $U_c$  of SPDs shall be equal to or higher than shown in **Fig. J20**.

SPDs connected between	System configuration of distribution network				
	TT	TN-C	TN-S	IT with distributed neutral	IT without distributed neutral
Line conductor and neutral conductor	$1.1 U_o$	NA	$1.1 U_o$	$1.1 U_o$	NA
Each line conductor and PE conductor	$1.1 U_o$	NA	$1.1 U_o$	$\sqrt{3} U_o^{(1)}$	Line-to-line voltage <sup>(1)</sup>
Neutral conductor and PE conductor	$U_o^{(1)}$	NA	$U_o^{(1)}$	$U_o^{(1)}$	NA
Each line conductor and PEN conductor	NA	$1.1 U_o$	NA	NA	NA

NA: not applicable  
NOTE 1:  $U_o$  is the line-to-neutral voltage of the low-voltage system.  
NOTE 2: This table is based on IEC 61643-1 amendment 1.

**Fig. J20** : Minimum required  $U_c$  of the SPD dependent on supply system configuration

- **At the origin of the installation:** if the surge arrester is installed at the source of an electrical installation supplied by the utility distribution network, its rated discharge current may be lower than 5 kA.  
If a surge arrester is installed downstream from an earth leakage protection device, an RCD of the s type, with immunity to impulse currents of less than 3 kA (8/20  $\mu$ s), must be used.
- **Protection against overcurrent at 50 Hz** and consequences of a SPD failure: protection against SPDs short-circuits is provided by the overcurrent protective devices F2 which are to be selected according to the maximum recommended rating for the overcurrent protective device given in the manufacturer's SPD instructions.
- **In the presence of lightning conductors:** a surge arrester must be installed, additional specifications for surge arresters must be applied (see IEC 62305 part 4).

(1) These values are related to worst case fault conditions, therefore the tolerance of 10 % is not taken into account

## 4 Choosing a protection device

When installing surge arresters, several elements must be considered, such as:

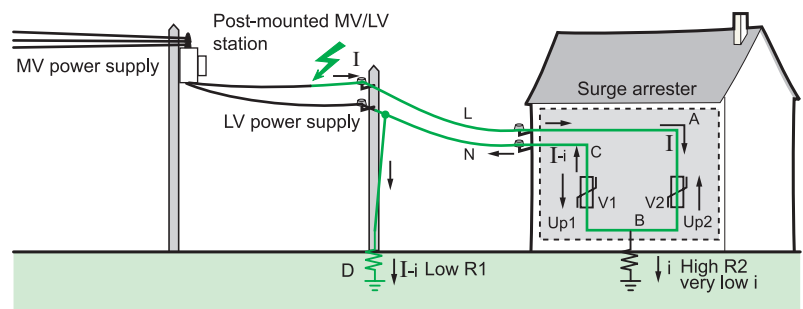
- Cascading
  - Positioning with respect to residual current devices
  - The choice of disconnection circuit breakers
- The earthing system must also be taken into account.

### 4.1 Protection devices according to the earthing system

■ Common mode overvoltage: basic protection involves the installation of a common mode surge arrester between phase and PE or phase and PEN, whatever type of earthing system is used.

■ Differential mode overvoltage: in the TT and TN-S earthing systems, earthing the neutral leads to dissymmetry due to earthing impedances, which causes differential mode voltages to appear, whereas the overvoltage induced by a lightning strike is a common mode voltage.

For example, let us consider a TT earthing system. A two-pole surge arrester is installed in common mode to protect the installation (see **Fig. J21**).



**Fig. J21** : Common mode protection only

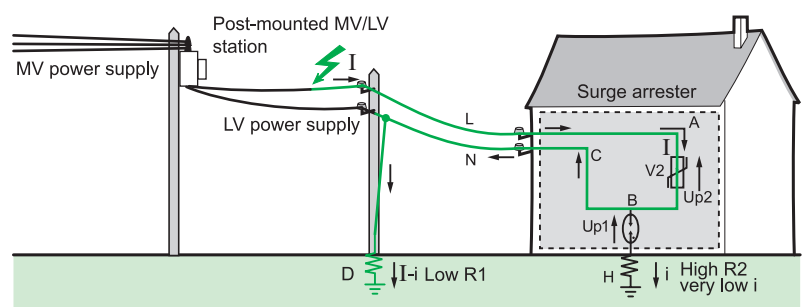
The neutral earthing resistor R1 used for the pylons has a lower resistance than the earthing resistor R2 used for the installation. The lightning current will flow through circuit ABCD to earth via the easiest path. It will pass through varistors V1 and V2 in series, causing a differential voltage equal to twice the residual voltage of the surge arrester ( $Up1 + Up2$ ) to appear at the terminals of A and C at the entrance to the installation in extreme cases.

To protect the loads between Ph and N effectively, the differential mode voltage (between A and C) must be reduced.

Another earthing system is therefore used (see **Fig. J22**).

The lightning current flows through circuit ABH which has a lower impedance than circuit ABCD, as the impedance of the component used between B and H is null (gas filled spark gap).

In this case, the differential voltage is equal to the residual voltage of the surge arrester ( $Up2$ ).



**Fig. J22** : Common + differential mode protection

J15

Mode	Between	TT	TN-S	TN-C	IT
Differential	phase and neutral	yes	yes	-	-
Common	phase and earth	yes	yes	yes	yes
	phase and earth	yes	yes	-	yes (if distributed neutral)

Fig. J23 : Connections to be made according to the earthing systems used, in the case of atmospheric overvoltages

4.2 Internal architecture of surge arresters

- 2P, 3P, 4P surge arresters (see Fig. J24):
  - They provide protection against common-mode overvoltages only
  - They are appropriate for TN-C and IT earthing systems.

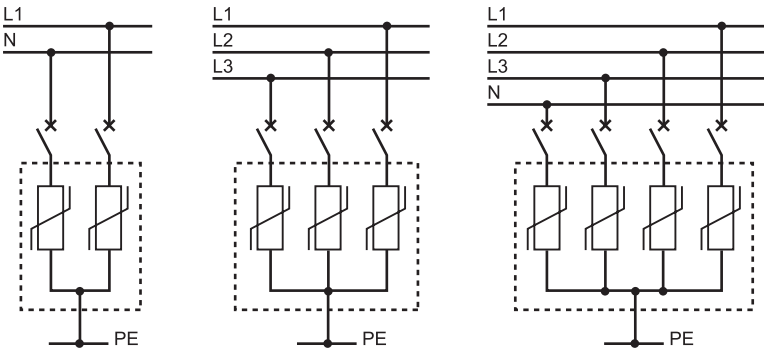


Fig. J24 : 2P, 3P, 4P surge arresters

- 1P+N, 3P+N surge arresters (see Fig. J25):
  - They provide protection against common-mode and differential-mode overvoltages
  - They are appropriate for TT, TN-S, and IT earthing systems.

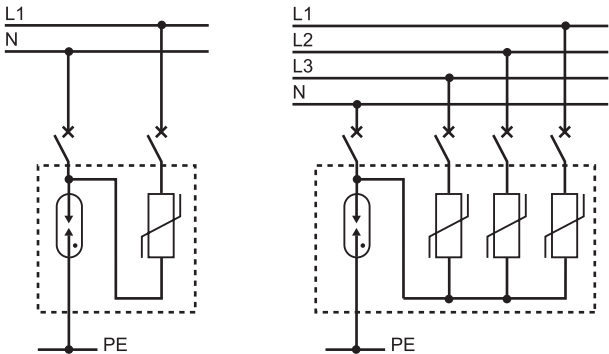


Fig. J25 : 1P+N, 3P+N surge arresters

- Single-pole (1P) surge arresters (see Fig. J26):
  - They are used to satisfy the demand of different assemblies (according to the manufacturer's instructions) by supplying only one product. However, special dimensioning will be required for N - PE protection (for example 1+N and 3P+N)
  - The assembly must be validated by means of the tests specified in EN 61643-11.

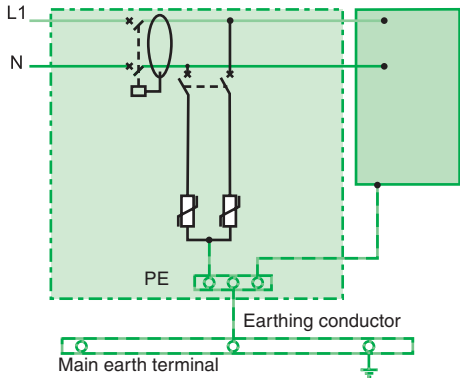


Fig. J26 : Connection example

Cascading protection requires a minimum distance of at least 10 m between the two protection devices.  
This is valid, whatever the field of application: domestic, tertiary or industrial.

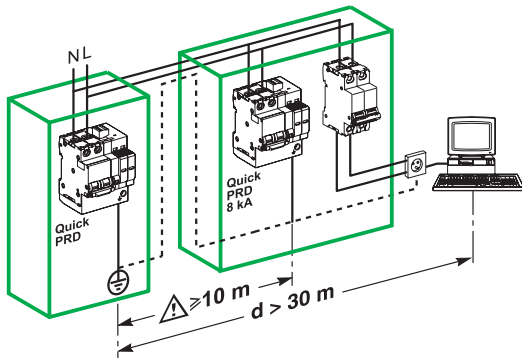


Fig. J27 : Cascading of surge arresters

### 4.3 Coordination of surge arresters

The overvoltage protection study of an installation may show that the site is highly exposed and that the equipment to be protected is sensitive. The surge arrester must be able to discharge high currents and have a low level of protection. This dual constraint cannot always be handled by a single surge arrester. A second one will therefore be required (see Fig. J27).

The first device, P1 (incoming protection) will be placed at the incoming end of the installation.

Its purpose will be to discharge the maximum amount of energy to earth with a level of protection  $\leq 2000$  V that can be withstood by the electrotechnical equipment (contactors, motors, etc.).

The second device (fine protection) will be placed in a distribution enclosure, as close as possible to the sensitive loads. It will have a low discharge capacity and a low level of protection that will limit overvoltages significantly and therefore protect sensitive loads ( $\leq 1500$  V).

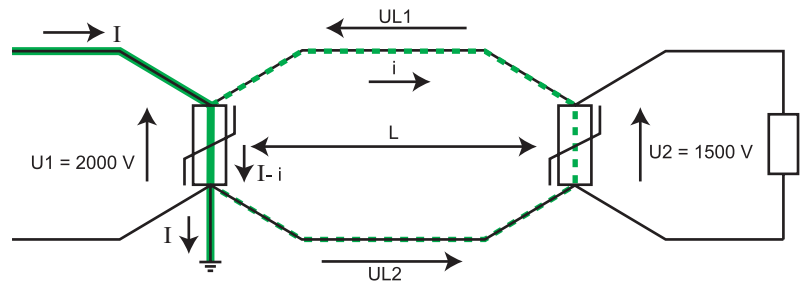


Fig. J28 : Coordination of surge arresters

The fine-protection device P2 is installed in parallel with the incoming protection device P1.

If the distance L is too small, at the incoming overvoltage, P2 with a protection level of  $U_2 = 1500$  V will operate before P1 with a level of  $U_1 = 2000$  V. P2 will not withstand an excessively high current. The protection devices must therefore be coordinated to ensure that P1 activates before P2. To do this, we shall experiment with the length L of the cable, i.e. the value of the self-inductance between the two protection devices. This self-inductance will block the current flow to P2 and cause a certain delay, which will force P1 to operate before P2. A metre of cable gives a self-inductance of approximately  $1 \mu\text{H}$ .

The rule  $\Delta U = \frac{L di}{dt}$  causes a voltage drop of approximately 100 V/m/kA, 8/20  $\mu\text{s}$  wave.

For  $L = 10$  m, we get  $UL_1 = UL_2 \approx 1000$  V.

To ensure that P2 operates with a level of protection of 1500 V requires

$$U_1 = UL_1 + UL_2 + U_2 = 1000 + 1000 + 1500 \text{ V} = 3500 \text{ V}.$$

Consequently, P1 operates before 2000 V and therefore protects P2.

**Note:** if the distance between the surge arrester at the incoming end of the installation and the equipment to be protected exceeds 30 m, cascading the surge arresters is recommended, as the residual voltage of the surge arrester may rise to double the residual voltage at the terminals of the incoming surge arrester; as in the above example, the fine protection surge arrester must be placed as close as possible to the loads to be protected.

**Installation rules (see page Q12).**

## 4.4 Selection guide

1



## Estimate the value of the equipment to be protected

To estimate its value, consider:

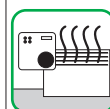
- The cost of the equipment in financial terms
- The economic impact if the equipment goes down.



- Domestic equipment:
  - ☐ audio-video, computers
  - ☐ household appliances
  - ☐ burglar alarm.



- Sensitive equipment:
  - ☐ burglar alarm
  - ☐ fire alarm
  - ☐ access control
  - ☐ video surveillance.



- Building equipment:
  - ☐ automated heating or air-conditioning
  - ☐ lift.



- Professional equipment:
  - ☐ programmable machine
  - ☐ computer server
  - ☐ sound or light control system.



- Heavy equipment:
  - ☐ medical infrastructure
  - ☐ production infrastructure
  - ☐ heavy computer processing.

J18

2



## Determine the electrical architecture of buildings

Lightning protection can be calculated for an entire building or for part of a building that is electrically independent

Depending on the size of the building and the extent of its electrical system, one or more surge arresters must be used in the various switchboards in the installation.

- Detached house.
- Apartment, small semi-detached house.
- Communal part of a building.
- Professional premises.
- Tertiary and industrial buildings:
  - ☐ single switchboard, main switchboard
  - ☐ distribution board
  - ☐ sensitive equipment more than 30 m from the switchboard.

3



## Understand the risk of the impact of lightning on the site

Lightning is attracted by high points that conduct electricity. They can be:

- Natural: tall trees, mountain crest, wet areas, ferrous soil
- Artificial: chimney, aerial, pylon, lightning conductor.

Indirect effects can be incurred within a fifty metre radius around the point of impact.

## Location of the building



In an urban, peri-urban, grouped housing area.



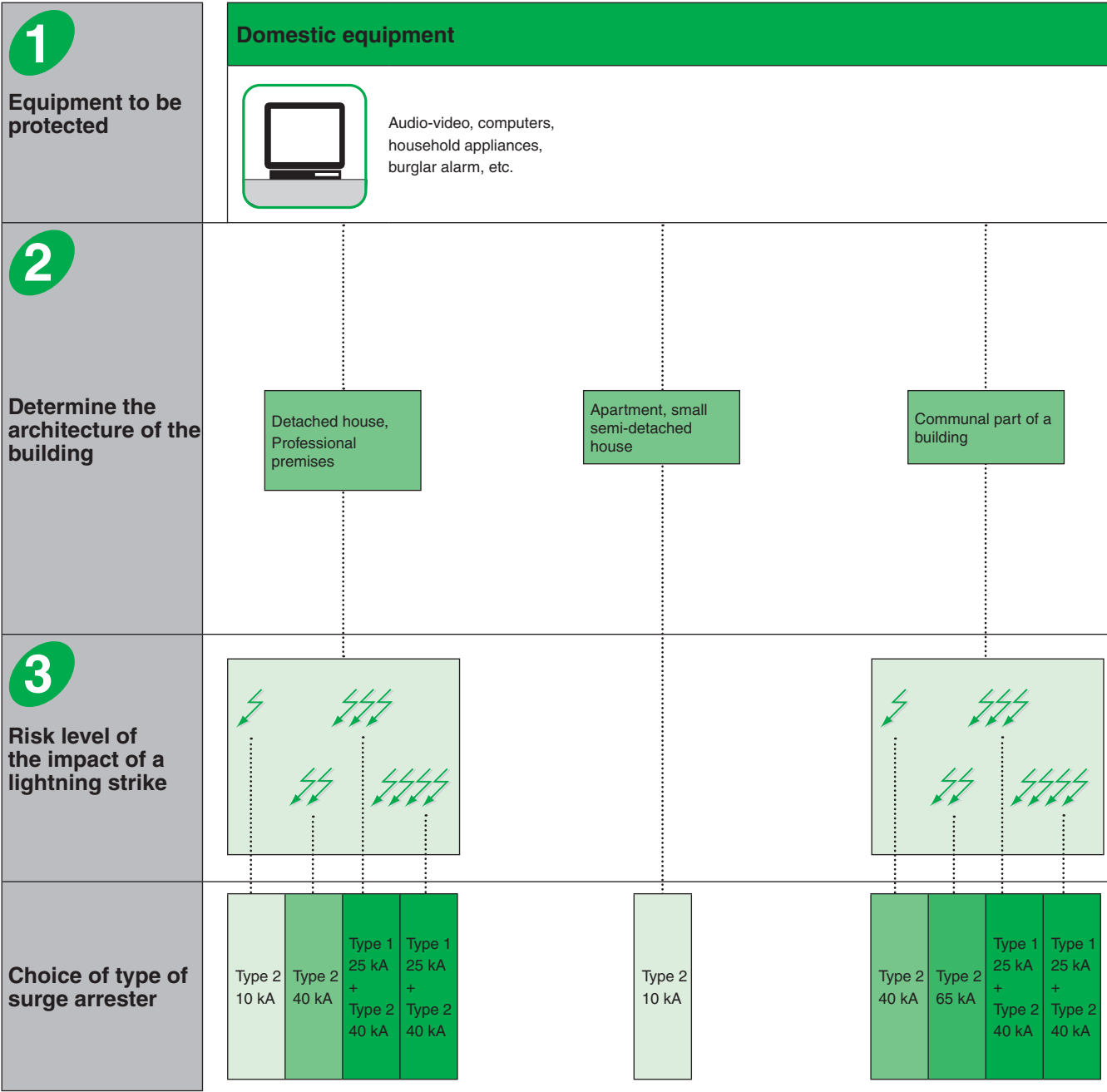
In an area where there is a particular hazard (pylon, tree, mountainous region, mountain crest, wet area or pond).



In flat open country.



In an exceptionally exposed area (lightning conductor on a building less than 50 metres away).







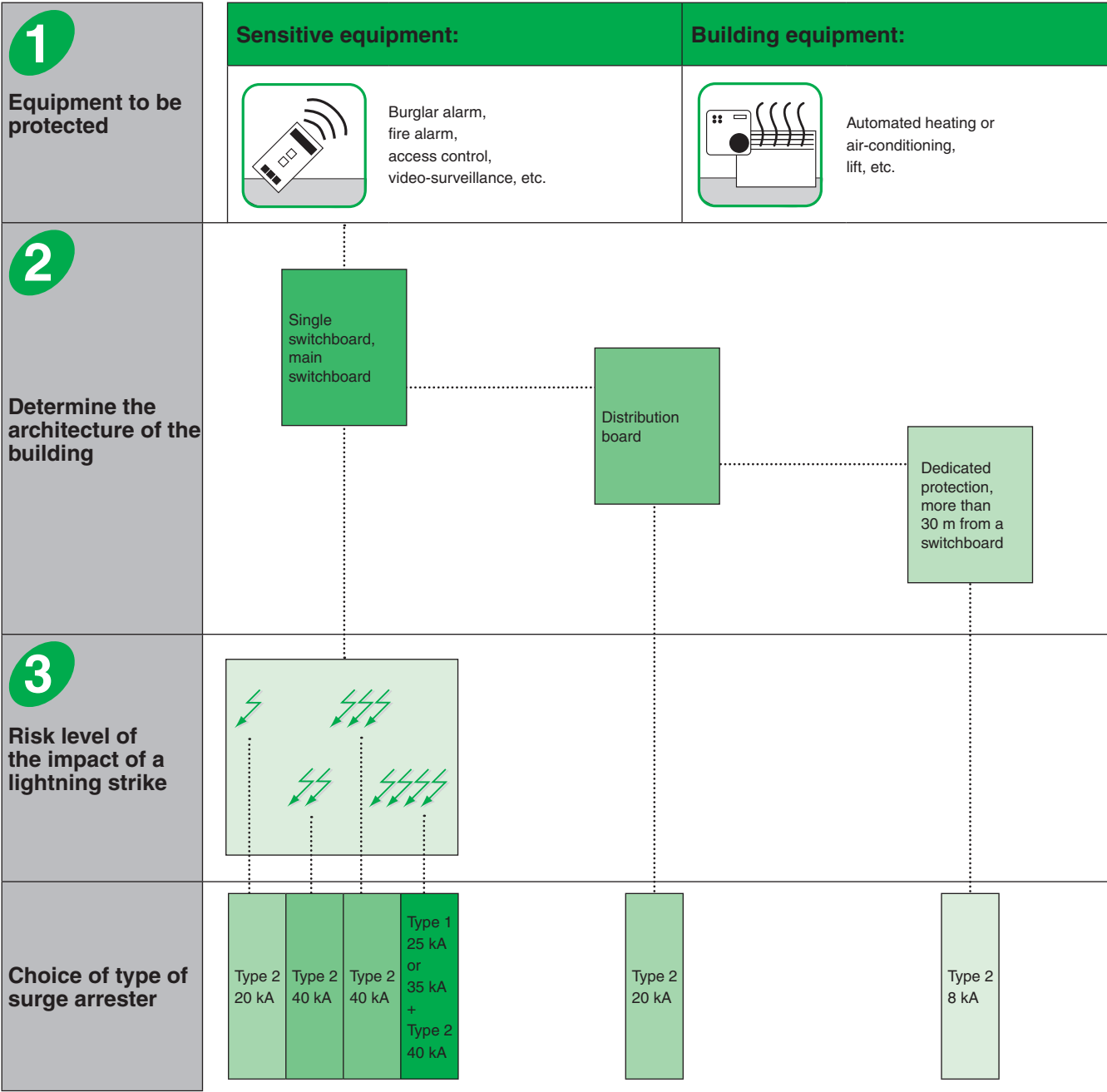
**Note:**  
Type 1: very high discharge capacity surge arrester used with a lightning conductor with an impact level of  and  .  
Type 2: surge arrester used in cascade behind a type 1 surge arrester or alone in zone  and  .

Fig. J32 : Domestic equipment

Lightning also propagates through telecommunications networks. It can damage all the equipment connected to these networks.

Protection of telecommunications equipment

Choice of surge arresters	PRC
Analogue telephone networks < 200 V	<div></div>







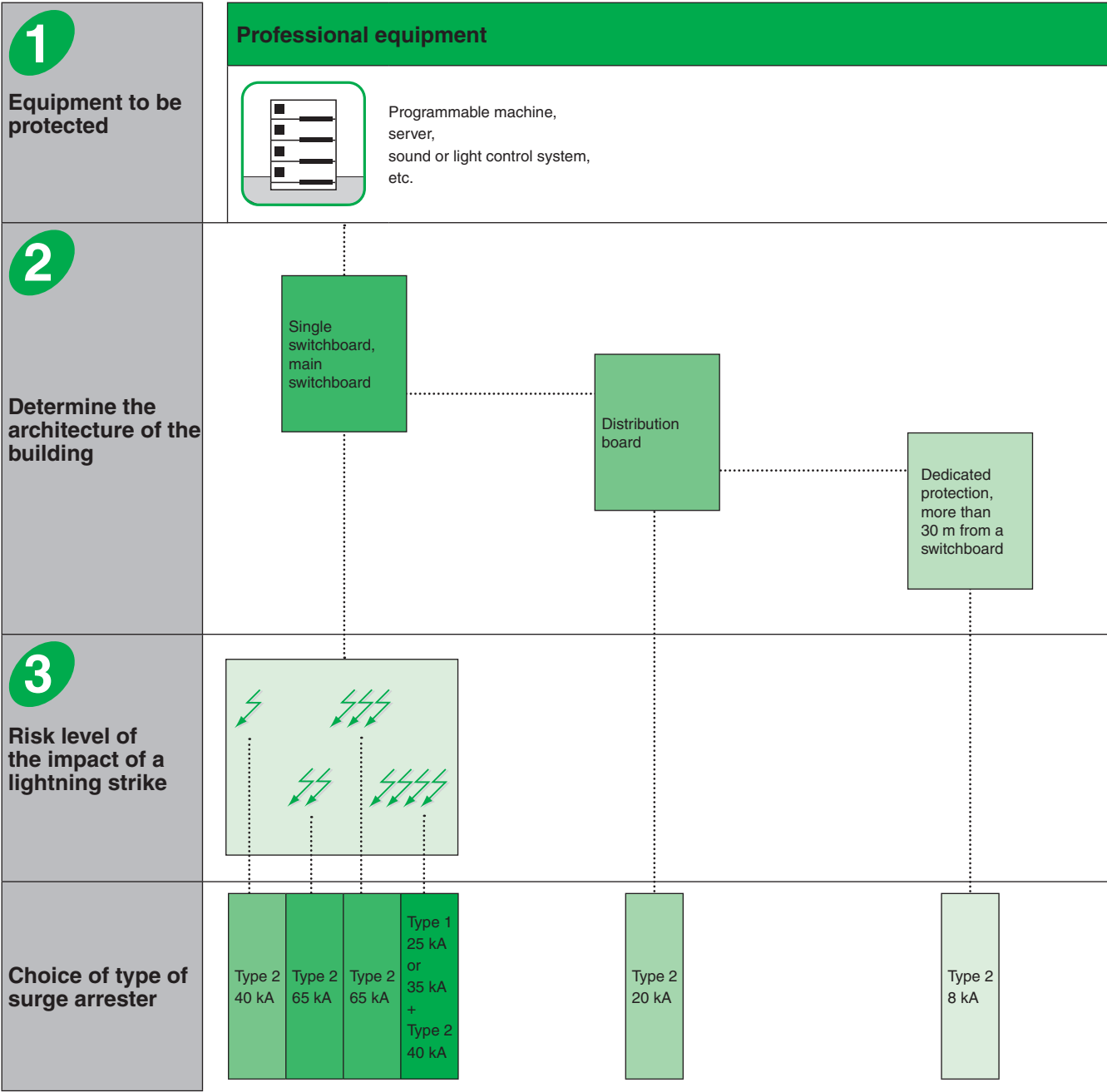
**Note:**  
Type 1: very high discharge capacity surge arrester used with a lightning conductor with an impact level of  and .  
Type 2: surge arrester used in cascade behind a type 1 surge arrester or alone in zone  and .

Fig. J33 : Sensitive equipment, Building equipment







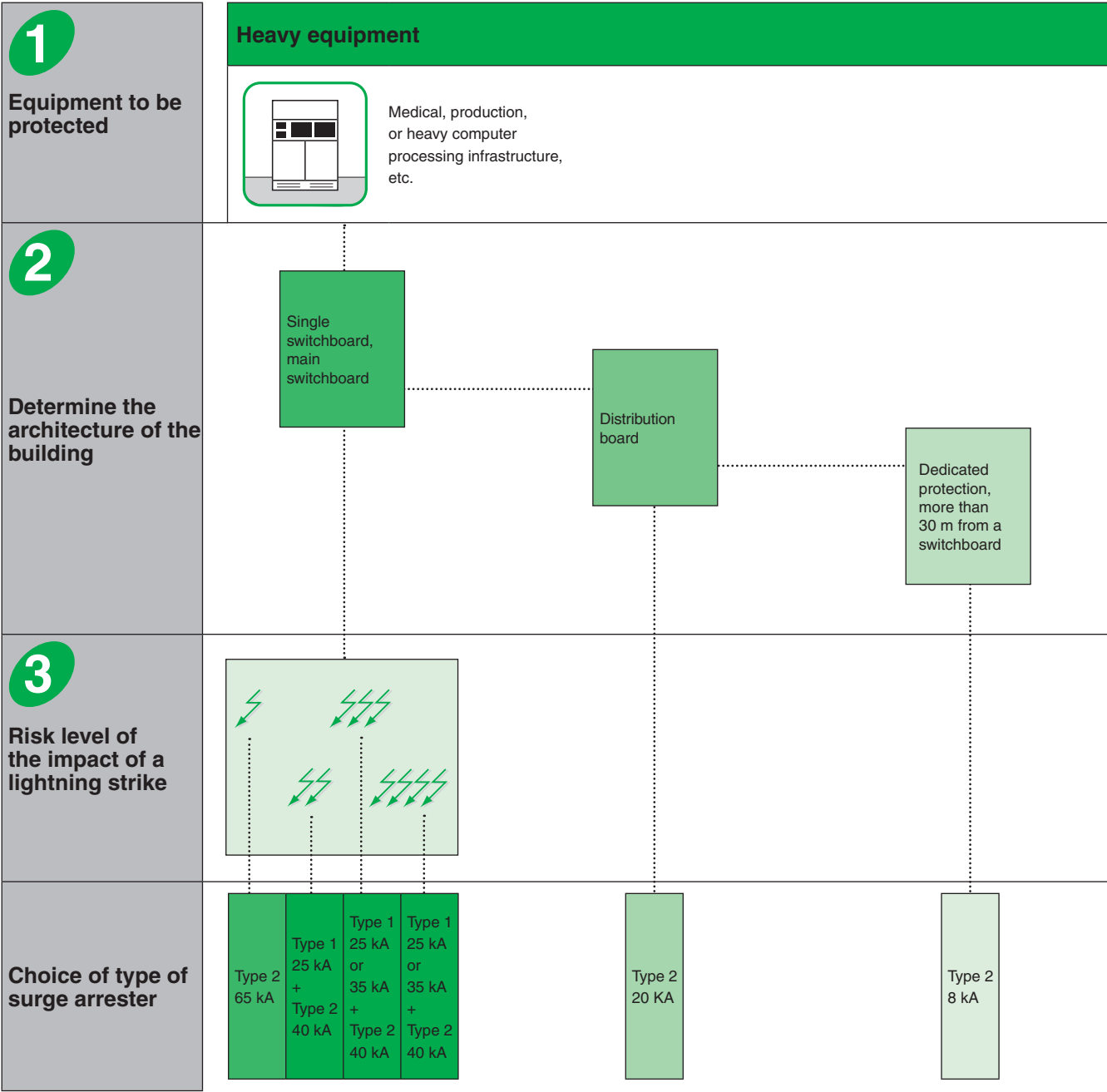
**Note:**  
Type 1: very high discharge capacity surge arrester used with a lightning conductor with an impact level of  and .  
Type 2: surge arrester used in cascade behind a type 1 surge arrester or alone in zone  and .

Fig. J34 : Professional equipment

J21





## 4.5 Choice of disconnecter

**The disconnecter is necessary to ensure the safety of the installation**

■ One of the surge arrester parameters is the maximum current ( $I_{max}$  8/20  $\mu$ s wave) that it can withstand without degradation. If this current is exceeded, the surge arrester will be destroyed; it will be permanently short circuited and it is essential to replace it.

The fault current must therefore be eliminated by an external disconnecter installed upstream.

The disconnecter provides the complete protection required by a surge arrester installation, i.e.:

□ It must be able to withstand standard test waves:

- it must not trip at 20 impulses at  $I_n$

- it can trip at  $I_{max}$  without being destroyed

□ the surge arrester disconnects if it short-circuits.

■ The ready-to-cable surge arresters with an integrated disconnection circuit breaker are:

□ Combi PRF1

□ Quick PF

□ Quick PRD.

**Surge arrester / disconnection circuit breaker correspondence table**

Types	Surge arrester names	Isc I <sub>max</sub> or I <sub>imp</sub>	6 kA	10 kA	15 kA	25 kA	36 kA	50 kA	70 kA	100 kA
Type 1	PRF1 Master	35 kA <sup>(1)</sup>	Compact NSX160B 160A				Compact NSX160F 160A	Compact NSX160N 160A		
	PRD1 Master	25 kA <sup>(1)</sup>	NG 125 N C 80A				NG 125L C 80A			
	PRD1 25r		NG 125 N C 80A				NG 125L C 80A			
	PRF1		D125 D curve							
	Combi PRF1		Integrated							
	PRF1 12,5 r	12,5 kA <sup>(1)</sup>	NG 125 N C 80A				NG 125L C 80A			
Type 2	PF 65/ PRD 65r	65 kA <sup>(2)</sup>	C60N 50A C curve		C60H 50A C curve	NG125L 50A C curve	Fuse NH 50A gL/gG			
	PF 40 / PRD 40r	40 kA <sup>(2)</sup>	C60N 40A C curve		C60H 40A C curve	NG125L 40A C curve	Fuse 22x58 40A gL/gG			
	Quick PRD 40r		Integrated				Contact us			
	PF 20/ PRD 20r	20 kA <sup>(2)</sup>	C60N 25A C curve		C60H 25A C curve	NG125L 25A C curve	Fuse 22x58 25A gL/gG			
	Quick PRD 20r		Integrated				Contact us			
	Quick PF 10	10 kA <sup>(2)</sup>	Integrated							
	PF 8/ PRD 8r	8 kA <sup>(2)</sup>	C60N 20A C curve		C60H 20A C curve	NG125L 20A C curve				
	Quick PRD 8 r		Integrated				Contact us			

*Isc*: prospective short-circuit current at the point of installation.

(1)  $I_{imp}$ .

(2)  $I_{max}$ .

**Fig. J36** : Coordination table between SPD and its disconnecter

J23

## 4.6 End-of-life indication of the surge arrester

Various indication devices are provided to warn the user that the loads are no longer protected against atmospheric overvoltages.

### Type 1 surge arresters (with gas filled spark gap)

#### PRF1 1P 260 V, Combi 1P+N and 3P+N and PRF1 Master

These surge arresters have a light indicating that the module is in good working order. This indicator light requires a minimum operating voltage of 120 V AC.

- The light does not come on:
  - if the operating voltage is  $\leq 120$  V AC
  - if there is no network voltage
  - if the spark-over electronics are defective.

### Type 2 surge arresters (varistor, varistor + gas filled spark gap)

#### PF, PRD

At end of life, the surge arrester or the cartridge are destroyed.

- This can occur in two ways:
  - internal end-of-life disconnection: the accumulated electric shocks cause the varistors to age, resulting in an increase in leakage current. Above 1 mA, a thermal runaway occurs and the surge arrester disconnects.
  - external end-of-life disconnection: this occurs in the event of an excessive overvoltage (direct lightning strike on the line); above the discharge capacity of the surge arrester, the varistor(s) are dead short-circuited to earth (or possibly between phase and neutral). This short-circuit is eliminated when the mandatory associated disconnection circuit breaker opens.

#### Quick PRD and Quick PF

Whatever the hazards of the power supply network, Quick PRD and Quick PF incorporate a perfectly coordinated disconnector.

- In the event of lightning strikes  $< I_{max}$ : like all surge arresters, they have internal anti-ageing protection.
  - In the event of a lightning strike  $> I_{max}$ : Quick PRD and Quick PF are self-protected by their integrated disconnector.
  - In the event of neutral disconnection or phase-neutral reversal occurring on the power supply: Quick PRD and Quick PF are self-protected by their integrated disconnector. To simplify maintenance work, Quick PRD is fitted with local indicators and draw-out cartridges that are mechanically combined with the disconnector.
- Quick PRD has indicator lights on the cartridges and on the integrated disconnector, so that the work to be carried out can quickly be located. For safety reasons, the disconnector opens automatically when a cartridge is removed. It cannot be set until the cartridge is plugged in. When changing the cartridge, a phase/neutral failsafe system ensures that it can be plugged in safely.

#### Operating state continuous display

Quick PRD has an integrated reporting contact to send information about the operating state of the surge arrester from a remote location. Monitoring the surge arresters installed throughout the installation makes it possible to be continuously aware of their operating state and to ensure that the protection devices are always in good working order.

- A reporting contact gives the alert:
  - at end of life of a cartridge
  - if a cartridge is missing, as soon as it has been removed
  - if a fault occurs on the line (short-circuit, neutral disconnection, phase-neutral reversal)
  - in the event of local manual operation (handle down).

Quick PF has an optional indication reporting auxiliary (SR) that sends information about the operating state of the surge arrester from a remote location.

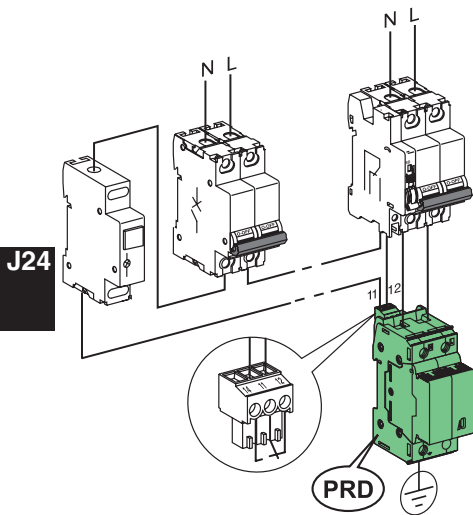


Fig. J37 : Example of indication for PRD

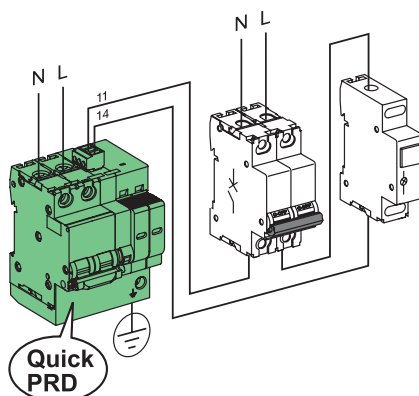


Fig. J39 : Example of indication for Quick PRD

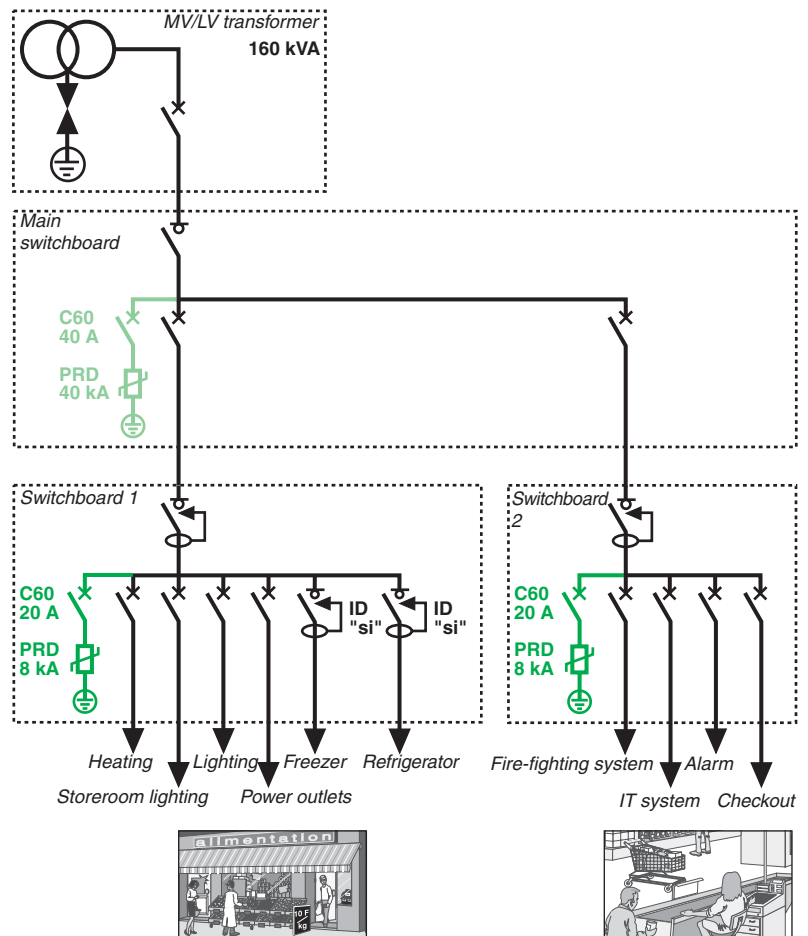


Fig. J39 : Application example : supermarket

J25

## 4.7 Application example: supermarket

### Solutions and schematic diagram

- The surge arrester selection guide has made it possible to determine the precise value of the surge arrester at the incoming end of the installation and that of the associated disconnection circuit breaker.
- As the sensitive devices ( $U_{imp} < 1.5 \text{ kV}$ ) are located more than 30 m from the incoming protection device, the fine protection surge arresters must be installed as close as possible to the loads.
- To ensure better continuity of service for cold room areas:
  - "si" type residual current circuit breakers will be used to avoid nuisance tripping caused by the rise in earth potential as the lightning wave passes through.
- For protection against atmospheric overvoltages:
  - install a surge arrester in the main switchboard
  - install a fine protection surge arrester in each switchboard (1 and 2) supplying the sensitive devices situated more than 30 m from the incoming surge arrester
  - install a surge arrester on the telecommunications network to protect the devices supplied, for example fire alarms, modems, telephones, faxes.

### Cabling recommendations

- Ensure the equipotentiality of the earth terminations of the building.
- Reduce the looped power supply cable areas.

### Installation recommendations

- Install a surge arrester,  $I_{max} = 40 \text{ kA}$  ( $8/20 \mu\text{s}$ ) and a C60 disconnection circuit breaker rated at 20 A.
- Install fine protection surge arresters,  $I_{max} = 8 \text{ kA}$  ( $8/20 \mu\text{s}$ ) and the associated C60 disconnection circuit breakers rated at 20 A.

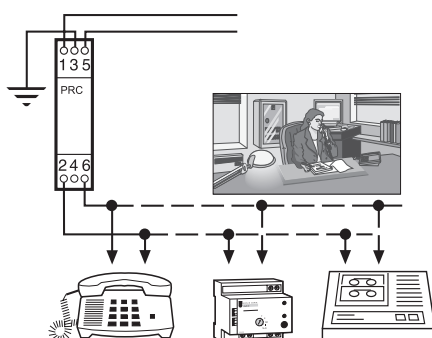


Fig. J40 : Telecommunications network

# Chapter K

## Energy Efficiency in electrical distribution

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K1

While there are a number of factors influencing the attitudes and opinions towards energy efficiency – most notably the increasing cost of energy and a rising social conscience – it is likely to be legislative drivers that have the greatest impact on changing behaviours and practices. Respective governments internationally are introducing energy saving targets and effecting regulations to ensure they are met.

Reducing greenhouse gas emissions is a global target set at the Earth Summit in Kyoto in 1997 and finally ratified by 169 countries in December 2006 enabling the Agreement's enactment in February 2005.

Under the Kyoto Protocol industrialised countries have agreed to reduce their collective emissions of greenhouse gases by 5.2% by 2008-2012 compared to the year 1990 (however, compared to the emissions levels expected by 2012 prior to the Protocol, this limitation represents a 29% cut). The target in Europe is an 8% reduction overall with a target for CO<sub>2</sub> emissions to fall by 20% by 2020.

Of the six greenhouse gases listed by Kyoto, one of the most significant by volume of emissions is carbon dioxide (CO<sub>2</sub>) and it is gas that is mainly emitted as a result of electricity generation and use, as well as direct thermal losses in, for example, heating.

Up to 50% of CO<sub>2</sub> emissions attributable to residential and commercial buildings is from electricity consumption. Moreover, as domestic appliances, computers and entertainment systems proliferate; and other equipment such as air conditioning and ventilation systems increase in use, electricity consumption is rising at a higher rate than other energy usage.

The ability to meet targets by simply persuading people to act differently or deploy new energy saving or energy efficient technology is unlikely to succeed. Just considering construction and the built environment, new construction is far less than 2% of existing stock. If newly constructed buildings perform exactly as existing stock the result by 2020 will be an increase in electricity consumption of 22%. On the other hand, if all new construction has energy consumption of 50% less than existing stock, the result is still an increase of 18%.

In order to reach a fall in consumption of 20% by 2020 the following has to happen:

- All new buildings constructed to consume 50% less energy
- 1 in 10 existing buildings reduce consumption by 30% each year

(see Fig.K1).

Significantly, by 2020 in most countries 80% of all buildings will have already been built. The refurbishment of existing building stock and improving energy management is vital in meeting emission reduction targets. Given that in the west, most buildings have already undergone thermal insulation upgrades such as cavity wall insulation, loft insulation and glazing, the only potential for further savings is by reducing the amount of energy consumed.

Action on existing built environment will almost certainly become compulsory to meet targets fixed for the coming years.

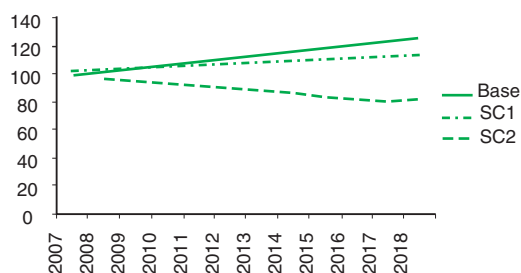
As a result, governments are applying pressures to meet the ambitious targets. It is almost certain that ever more demanding regulations will be enforced to address all energy uses, including existing buildings and, naturally, industry. At the same time energy prices are rising as natural resources become exhausted and the electrical infrastructure in some countries struggles to cope with increasing demand.

Technology exists to help tackle energy efficiency on many levels from reducing electrical consumption to controlling other energy sources more efficiently. Strong regulatory measures may be required to ensure these technologies are adopted quickly enough to impact on the 2020 targets.

The most important ingredient however, lies with the ability of those in control of industry, business and government to concentrate their hearts and minds on making energy efficiency a critical target. Otherwise, it might not be just the Kyoto targets on which the lights go out.

**The message to heed is that if those empowered to save energy don't do so willingly now, they will be compelled under legal threat to do so in the future.**

K2



A minimum **renovation of 10% per year** of existing stock is compulsory to reach less 20%

**Renovation = 70% of the savings**  
**New = 30% of the savings**

**Fig. K1** : How to reach a fall in consumption of 20% by 2020



## 2.1 Regulation is pushing Energy Efficiency worldwide

Kyoto Protocol was the start of fixing quantitative targets and agenda in CO<sub>2</sub> emissions reduction with clear government's commitments.

Beyond Kyoto commitment (which covers only the period up to 2012) many countries have fixed longer time frame and targets in line with the last GIEEC recommendations to UNFCCC to stabilise the CO<sub>2</sub> concentration at a level of 450 ppm (this should require a division by 2 before 2050 of the CO<sub>2</sub> emission level based on 1990).

European Union is a good example and firm commitment with a target of less 20% before 2020 has been taken by heads of EU member states in March 2007 (known as the 3x20: it includes reduction of 20% of CO<sub>2</sub> emission, Improvement of 20% of the Energy Efficiency level and reaching 20% of the energy produced from renewable). This commitment of less 20% in 2020 could be extended to less 30% in 2020 in case of post Kyoto international agreement.

Some European Countries are planning commitment for the 2050 with level of reduction up to 50%. All of this illustrates that Energy Efficiency landscape and policies will be present in a long time frame.

Reaching these targets will require real change and regulations, legislation, standardisation are enablers governments are reinforcing everyday.

**All over the world Régulation/Législation is strengthening stakeholders obligations and putting in place financial & fiscal schemes**

- In US
  - Energy Policy Act of 2005
  - Building Codes
  - Energy Codes (10CFR434)
  - State Energy program (10CFR420)
  - Energy Conservation for Consumer Goods (10CFR430)
- In European Union
  - EU Emission Trading Scheme
  - Energy Performance of Building Directive
  - Energy Using Product Directive
  - End use of energy & energy services directive
- In China
  - China Energy Conservation Law
  - China Architecture law (EE in Building)
  - China Renewable Energy Law
  - Top 1000 Industrial Energy Conservation Program

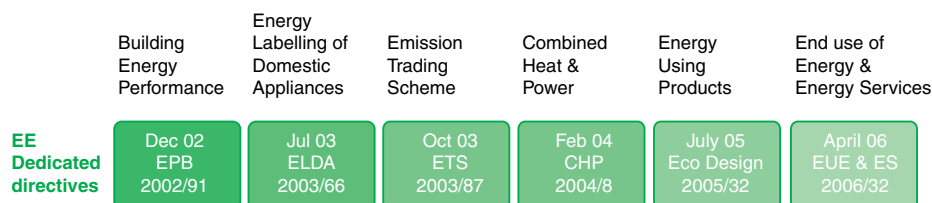


Fig. K2 : EE Dedicated directives

**Various legislative and financial-fiscal incentives schemes are developed at national and regional levels such as:**

- Auditing & assessment schemes
- Performance labelling schemes
- Building Codes
- Energy Performance Certificates
- Obligation to energy sellers to have their clients making energy savings
- Voluntary agreements in Industry
- Financial-market mechanism (tax credit, accelerated depreciation, white certificates,...)
- Taxation and incentive schemes

All sectors are concerned and regulations impact not only new construction and installation but as well the existing buildings in industrial or infrastructure environment.

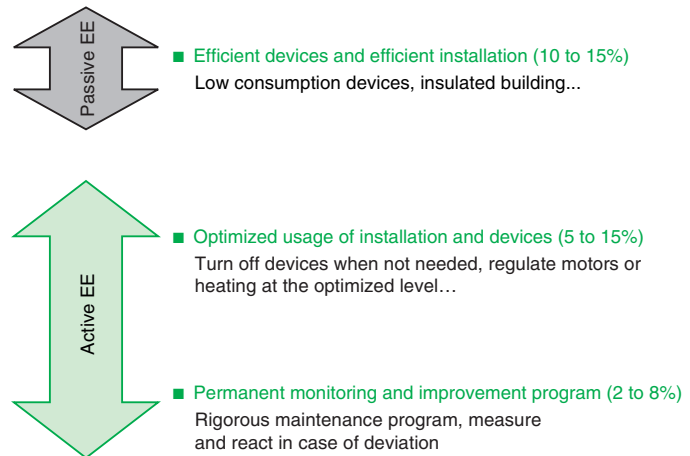
In parallel Standardisation work has started with a lot of new standards being issued or in progress.

In building all energy use are concerned:

- Lighting
- Ventilation
- Heating
- Cooling and AC

For industries as well as commercial companies Energy Management Systems standards ( in line with the well known ISO 9001 for quality and ISO 14001 for environment) are under process in Standardisation Bodies. Energy Efficiency Services standards are as well at work.

## 2.2 How to achieve Energy Efficiency



**Fig. K2** : 30% Savings are available today...

30% savings are available through existing EE solutions, but to really understand where these opportunities are, let's understand first the main differences between **Passive and Active EE**.

Passive EE is regarded as the installation of countermeasures against thermal losses, the use of low consumption equipment and so forth. Active Energy Efficiency is defined as effecting permanent change through measurement, monitoring and control of energy usage. It is vital, but insufficient, to make use of energy saving equipment and devices such as low energy lighting. Without proper control, these measures often merely militate against energy losses rather than make a real reduction in energy consumed and in the way it is used.

Everything that consumes power – from direct electricity consumption through lighting, heating and most significantly electric motors, but also in HVAC control, boiler control and so forth – must be addressed actively if sustained gains are to be made. This includes changing the culture and mindsets of groups of individuals, resulting in behavioural shifts at work and at home, but clearly, this need is reduced by greater use of technical controls.

■ 10 to 15% savings are achievable through passive EE measures such as installing low consumption devices, insulating building, etc.

■ 5 to 15% can be achieved through such as optimizing usage of installation and devices, turn off devices when not needed, regulating motors or heating at the optimized level...

□ Up to 40% of the potential savings for a motor system are realized by the Drive & Automation

□ Up to 30% of the potential for savings in a building lighting system can be realized via the lighting control system



- And a further 2 to 8% can also be achieved through active EE measures such as putting in place a permanent monitoring and improvement program

But savings can be lost quickly if there is:

- Unplanned, unmanaged shutdowns of equipment and processes
- Lack of automation and regulation (motors, heating)
- No continuity of behaviors

#### Energy Efficiency : it's easy, just follow the 4 sustainability steps

##### 1 Measure

- Energy meters
- Power quality meters

##### 2 Fix the basics

- Low consumption devices
- Insulation material
- Power quality
- Power reliability

##### 3 Automate

- Building management systems
- Lighting control systems
- Motor control systems
- Home control systems
- Variable speed drive

##### 4 Monitor and Improve

- Energy management software
- Remote monitoring systems

*Fig. K4 : The 4 sustainability steps*

Energy Efficiency is not different from other disciplines and we take a very rational approach to it, very similar to the 6Sigma DMAIC (Define, Measure, Analyze, Improve and Control) approach.

As always, the first thing that we need to do is to measure in order to understand where are the main consumptions, what is the consumption pattern, etc. This initial measurement, together with some benchmarking information, will allow us to see how good or bad we are doing, to define the main improvement axis and an estimation of what can be expected in terms of gains. We can not improve what we can not measure.

Then, we need to fix the basics or what is called **passive** EE. Change old end-use devices by Low consumption ones (bulbs, motors, etc), Improve the Insulation of your installations, and assure power quality reliability in order to be able to work in a stable environment where the gains are going to sustainable over time.

After that, we are ready to enter into the automation phase or **Active** Energy efficiency. As already highlighted, everything that consumes power must be addressed actively if sustained gains are to be made.

Active Energy Efficiency can be achieved not only when energy saving devices and equipment are installed, but with all kind of end-use devices. It is this aspect of control that is critical to achieving the maximum efficiency. As an example, consider a low consumption bulb that is left on in an empty room. All that is achieved is that less energy is wasted compared to using an ordinary bulb, but energy is still wasted!

Responsible equipment manufacturers are continually developing more efficient products. However, while for the most part the efficiency of the equipment is a fair representation of its energy saving potential - say, in the example of a domestic washing machine or refrigerator - it is not always the case in industrial and commercial equipment. In many cases the overall energy performance of the system is what really counts. Put simply, if an energy saving device is left permanently on stand-by it can be less efficient than a higher consuming device that is always switched off when not in use.

Summarizing, managing energy is the key to maximizing its usefulness and economizing on its waste. While there are increasing numbers of products that are now more energy efficient than their predecessors, controlling switching or reducing settings of variables such as temperature or speed, makes the greatest impact.

### The key to sustainable savings

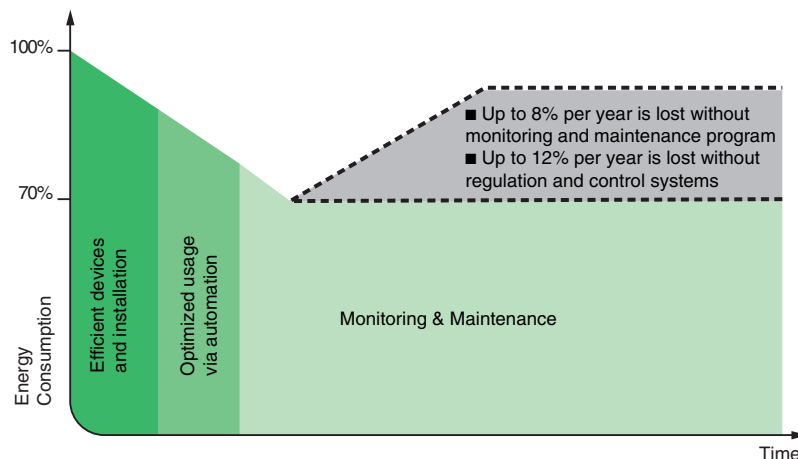


Fig. K5 : Control and monitoring technologies will sustain the savings

As you could see, 30% energy saving are available and quite easily achievable today but up to 8% per year can be lost without proper maintenance and diligent monitoring of your key indicators. Information is key to sustaining the energy savings. You cannot manage what you cannot measure and therefore metering and monitoring devices coupled with proper analysis provide the tools required to take on that challenge successfully.

### Lifecycle approach to Energy Efficiency

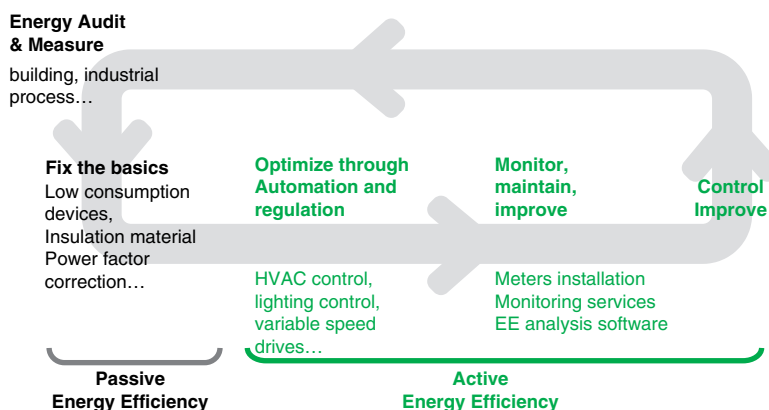


Fig. K6 : Lifecycle solutions for Energy Efficiency

Energy Efficiency needs a structured approach in order to provide significant and sustainable savings. Schneider Electric take a customer lifecycle approach to tackle it. It starts with a diagnosis or audit on buildings and industrial processes... This will provide us an indication of the situation and the main avenues to pursue savings. But is not enough, it is just the beginning, what really counts is getting the results. Only companies having the means to be active in the whole process can be there with their customers up to the real savings and results.

Then, we will fix the basics, automate and finally monitor, maintain and improve. Then we are ready to start again and continue the virtuous cycle.

Energy Efficiency is an issue where a risk sharing and a win-win relation shall be established to reach the goal.

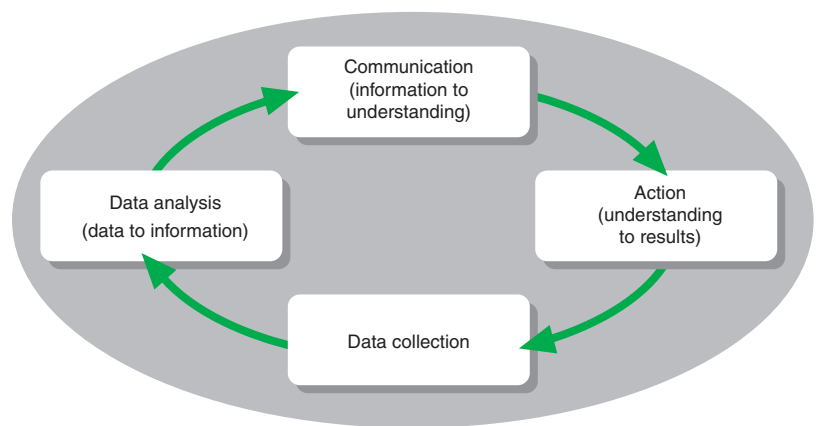
As targets are fixed over long timeframe (less 20% in 2020 , less 50% in 2050), for most of our customers EE programs are not one-shot initiatives and permanent improvement over the time is key. Therefore, frame services contracts is the ideal way to deal with these customer needs.

## 3 Diagnosis through electrical measurement

The energy efficiency performance in terms of electricity can only be expressed in terms of fundamental physical measurements – voltage, current, harmonics, etc. These physical measurements are then reprocessed to become digital data and then information.

In the raw form, data are of little use. Unfortunately, some energy managers become totally immersed in data and see data collection and collation as their primary task. To gain value from data they must be transformed into information (used to support the knowledge development of all those managing energy) and understanding (used to action energy savings).

The operational cycle is based on four processes: data collection; data analysis; communication; and action (see **Fig. K7**). These elements apply to any information system. The cycle works under condition that an adequate communication network has been set up.



**Fig. K7** : The operational cycle

K7

The data processing level results in information that can be understood by the recipient profile: the ability to interpret the data by the user remains a considerable challenge in terms of decision making.

The data is then directly linked to loads that consume electricity – industrial process, lighting, air conditioning, etc. – and the service that these loads provide for the company – quantity of products manufactured, comfort of visitors to a supermarket, ambient temperature in a refrigerated room, etc.

The information system is then ready to be used on a day to day basis by users to achieve energy efficiency objectives set by senior managers in the company.

### 3.1 Physical value acquisition

The quality of data starts with the measurement itself: at the right place, the right time and just the right amount.

Basically, electrical measurement is based on voltage and current going through the conductors. These values lead to all the others: power, energy, power factor, etc.

Firstly we will ensure consistency of the precision class of current transformers, voltage transformers and the precision of the measurement devices themselves. The precision class will be lower for higher voltages: an error in the measurement of high voltage for example represents a very large amount of energy.

The total error is the quadratic sum of each error.

$$\sum \text{of error} = \sqrt{\text{error}^2 + \text{error}^2 + \dots + \text{error}^2}$$

Example:

a device with an error of 2% connected on a CT 's with an error of 2% that means:

$$\sum \text{of error} = \sqrt{(2)^2 + (2)^2} = 2.828\%$$

That could mean a loss of 2,828 kWh for 100,000 kWh of consumption.

A CT is defined by:

- transformation ratio. For example: 50/5A
- precision class Cl. Example: Cl=0.5
- precision power in VA to supply power to the measurement devices on the secondary. Example: 1.25 VA
- limit precision factor indicated as a factor applied to  $I_n$  before saturation. Example: FLP (or  $F_s$ ) = 10 for measurement devices with a precision power that is in conformity.

## Voltage measurement

In low voltage, the voltage measurement is directly made by the measurement device. When the voltage level becomes incompatible with the device capacity, for example in medium voltage, we have to put in voltage transformers.

A VT (Voltage transformer) is defined by:

- its primary voltage and secondary voltage
- its apparent power
- its precision class

## Current measurement

Current measurement is made by split or closed-core CT's placed around the phase and neutral conductors as appropriate.

According to the required precision for measurement, the CT used for the protection relay also allows current measurement under normal conditions.

## Energy measurement

To measure energy, we consider two objectives:

- A contractual billing objective, e.g. between an electricity company and its client or even between an airport manager (sub-billing) and stores renting airport surface areas. In this case IEC 62053-21 for Classes 1 and 2 and IEC 62053-22 for Classes 0.5S and 0.2S become applicable to measure active energy. The full measurement chain – CT, VT and measurement unit – can reach a precision class Cl of 1 in low voltage, Cl 0.5 in medium voltage and 0.2 in high voltage, or even 0.1 in the future.
- An internal cost allocation objective for the company, e.g. to break-down the cost of electricity for each product produced in a specific workshop. In this case of a precision class between 1 and 2 for the whole chain (CT, VT and measurement station) is sufficient.

It is recommended to match the full measurement chain precision with actual measurement requirements: there is no one single universal solution, but a good technical and economic compromise according to the requirement to be satisfied. Note that the measurement precision also has a cost, to be compared with the return on investment that we are expecting.

Generally gains in terms of energy efficiency are even greater when the electrical network has not been equipped in this way until this point. In addition, permanent modifications of the electrical network, according to the company's activity, mainly cause us to search for significant and immediate optimizations straight away.

Example:

A class 1 analogue ammeter, rated 100 A, will display a measurement of  $\pm 1$  A at 100 A. However if it displays 2 A, the measurement is correct to within 1 A and therefore there is uncertainty of 50%.

A class 1 energy measurement station such as PM710 – like all other Power Meter and Circuit Monitor Measurement Units – is accurate to 1% throughout the measurement range as described in IEC standards 62053.

Other physical measurements considerably enhance the data:

- on/off, open/closed operating position of devices, etc.
- energy metering impulse
- transformer, motor temperature
- operation hours, quantity of switching operations
- motor load
- UPS battery load
- event logged equipment failures
- etc.

## 3.2 Electrical data for real objectives

Electrical data is transformed into information that is usually intended to satisfy several objectives:

- It can modify the behaviour of users to manage energy wisely and finally lowers overall energy costs
- It can contribute to field staff efficiency increase
- It can contribute to decrease the cost of Energy
- It can contribute to save energy by understanding how it is used and how assets and process can be optimized to be more energy efficient

K8



PM700 measurement unit



**Fig. K8** : Facility utility costs parallel the visualisation of an iceberg

- It may help in optimizing and increasing the life duration of the assets associated to the electrical network

- And finally it may be a master piece in increasing the productivity of the associated process (industrial process or even office, building management), by preventing, or reducing downtime, or insuring higher quality energy to the loads.

Facility utility costs parallel the visualization of an iceberg (see **Fig. K8**). While an iceberg seems large above the surface, the size is completely overwhelming beneath the surface. Similarly, electrical bills are brought to the surface each month when your power provider sends you a bill. Savings in this area are important and can be considerable enough to be the only justification needed for a power monitoring system. However, there are other less obvious yet more significant savings opportunities to be found below the surface if you have the right tools at your disposal.

### Modify the behaviour of energy users

Using cost allocation reports, you can verify utility billing accuracy, distribute bills internally by department, make effective fact-based energy decisions and drive accountability in every level of your organization. Then providing ownership of electricity costs to the appropriate level in an organization, you modify the behaviour of users to manage energy wisely and finally lowers overall energy costs.

### Increase field staff efficiency

One of the big challenges of field staff in charge of the electrical network is to make the right decision and operate in the minimum time.

The first need of such people is then to better know what happens on the network, and possibly to be informed everywhere on the concerned site.

This site-wise transparency is a key feature that enables a field staff to:

- Understand the electrical energy flows – check that the network is correctly set-up, balanced, what are the main consumers, at what period of the day, or the week...
- Understand the network behaviour – a trip on a feeder is easier to understand when you have access to information from downstream loads.
- Be spontaneously informed on events, even outside the concerned site by using today's mobile communication
- Going straight forward to the right location on the site with the right spare part, and with the understanding of the complete picture
- Initiate a maintenance action taking into account the real usage of a device, not too early and not too late
- Therefore, providing to the electrician a way to monitor the electrical network can appear as a powerful mean to optimize and in certain case drastically reduce the cost of power.

Here are some examples of the main usage of the simplest monitoring systems:

- Benchmark between zones to detect abnormal consumption.
- Track unexpected consumption.
- Ensure that power consumption is not higher than your competitors.
- Choose the right Power delivery contract with the Power Utility.
- Set-up simple load-shedding just focusing on optimizing manageable loads such as lights.
- Be in a position to ask for damage compensation due to non-quality delivery from the Power Utilities – "The process has been stopped because of a sag on the networks".

### Implementing energy efficiency projects

The Power monitoring system will deliver information that support a complete energy audit of a facility. Such audit can be the way to cover not only electricity but also Water, Air, Gas and Steam. Measures, benchmark and normalized energy consumption information will tell how efficient the industrial facilities and process are. Appropriate action plans can then be put in place. Their scope can be as wide as setting up control lighting, Building automation systems, variable speed drive, process automation, etc.

### Optimizing the assets

One increasing fact is that electrical network evolves more and more and then a recurrent question occurs : Will my network support this new evolution?

This is typically where a Monitoring system can help the network owner in making the right decision.

By its logging activity, it can archive the real use of the assets and then evaluate quite accurately the spare capacity of a network, or a switchboard, a transformer... A better use of an asset may increase its life duration.

Monitoring systems can provide accurate information of the exact use of an asset and then the maintenance team can decide the appropriate maintenance operation, not too late, or not too early.

In some cases also, the monitoring of harmonics can be a positive factor for the life duration of some assets (such as motors or transformers).

## Increasing the productivity by reducing the downtime

Downtime is the nightmare of any people in charge of an electrical network. It may cause dramatic loss for the company, and the pressure for powering up again in the minimum time – and the associated stress for the operator – is very high.

A monitoring and control system can help reducing the downtime very efficiently. Without speaking of a remote control system which are the most sophisticated system and which may be necessary for the most demanding application, a simple monitoring system can already provide relevant information that will highly contribute in reducing the downtime:

- Making the operator spontaneously informed, even remote, even out of the concerned site (Using the mobile communication such as DECT network or GSM/SMS)
- Providing a global view of the whole network status
- Helping the identification of the faulty zone
- Having remotely the detailed information attached to each event caught by the field devices (reason for trip for example)

Then remote control of a device is a must but not necessary mandatory. In many cases, a visit of the faulty zone is necessary where local actions are possible.

## Increasing the productivity by improving the Energy Quality

Some loads can be very sensitive to electricity quality, and operators may face unexpected situations if the Energy quality is not under control.

Monitoring the Energy quality is then an appropriate way to prevent such event and / or to fix specific issue.



Compact NSX with Micrologic trip unit

K10



ION 6200 metering unit



TeSys U motor controller

## 3.3 Measurement starts with the “stand alone product” solution

The choice of measurement products in electrical equipment is made according to your energy efficiency priorities and also current technological advances:

- measurement and protection functions of the LV or MV electrical network are integrated in the same device,

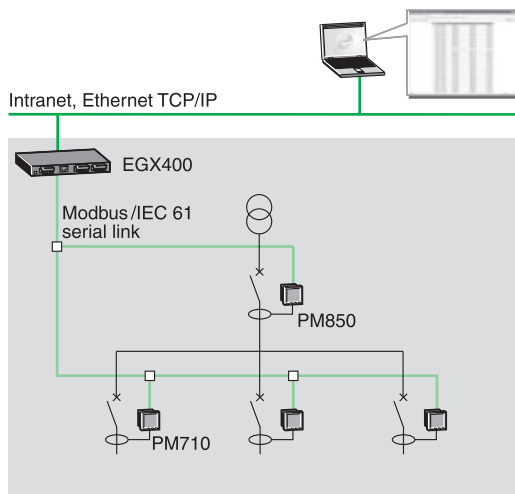
Example: Sepam metering and protection relays, Micrologic tripping unit for Compact NSX and Masterpact, TeSys U motor controller, NRC12 capacitor bank controller, Galaxy UPSs

- the measurement function is in the device, separate from the protection function, e.g. built on board the LV circuit breaker.

Example: PowerLogic ION 6200 metering unit

The progress made in real time industrial electronics and IT are used in a single device:

- to meet requirements for simplification of switchboards
- to reduce acquisition costs and reduce the number of devices
- to facilitate product developments by software upgrade procedures



**Fig. K9 :** Example of electrical network protected and monitored via the Intranet site

## Example of solutions for a medium-sized site:

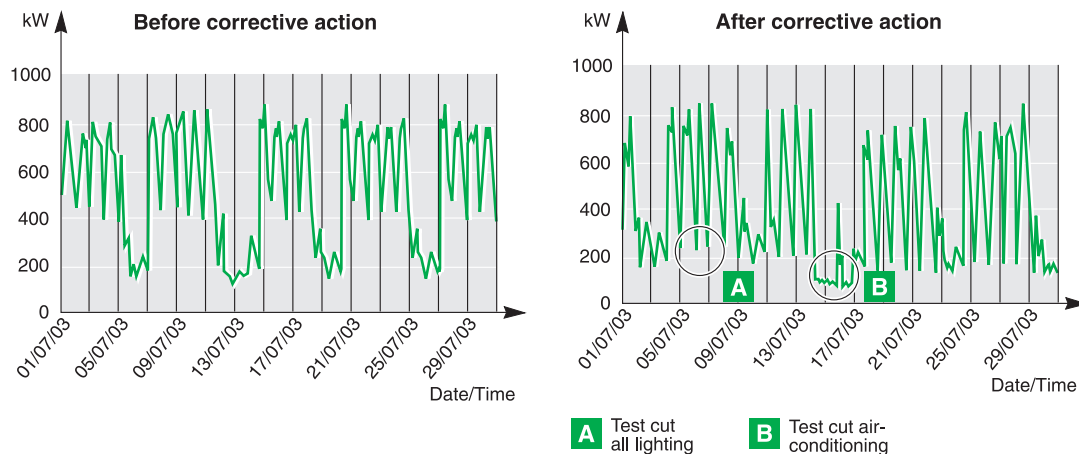
Analysesample Ltd. is a company specialized in analyzing industrial samples from regional factories: metals, plastics, etc., to certify their chemical characteristics. The company wants to carry out better control of its electrical consumption for the existing electrical furnaces, its air conditioning system and to ensure quality of electrical supply for high-precision electronic devices used to analyze the samples.

## Electrical network protected and monitored via the Intranet site

The solution implemented involves recovering power data via metering units that also allows measurement of basic electrical parameters as well as verification of energy power quality. Connected to a web server, an Internet browser allows to use them very simply and export data in a Microsoft Excel™ type spreadsheet. Power curves can be plotted in real time by the spreadsheet (see **Fig. K9**).

Therefore no IT investment, either in software or hardware, is necessary to use the data.

For example to reduce the electricity bill and limit consumption during nighttime and weekends, we have to study trend curves supplied by the measurement units (see **Fig. K10**).



**Fig. K10 :** **A** Test to stop all lighting **B** Test to stop air conditioning  
Here consumption during non-working hours seems excessive, consequently two decisions were taken:  
■ reducing night time lighting  
■ stopping air conditioning during weekends  
The new curve obtained shows a significant drop in consumption.

K11



# 3 Diagnosis through electrical measurement

Below we give examples of measurements available via Modbus, RS485 or Ethernet (see Fig. K11):

	Measurement units	MV protection and measurement relays	LV protection and measurement relays	Capacitor bank regulators	Insulation monitors
Examples	Power Meter, Circuit Monitor	Sepam	Masterpact & Compact Micrologic trip units	Varlogic	Vigilohm System
<b>Keep control over power consumption</b>					
Power, inst., max., min.	■	■	■	■	-
Energy, reset capability	■	■	■	-	-
Power factor, inst.	■	■	■	-	-
Cos φ inst.	-	-	-	■	-
<b>Improve power supply availability</b>					
Current, inst., max., min., unbalance	■	■	■	■	-
Current, wave form capture	■	■	■	-	-
Voltage, inst., max., min., unbalance	■	■	■	■	-
Voltage, wave form capture	■	■	■	-	-
Device status	■	■	■	■	-
Faults history	■	■	■	-	-
Frequency, inst., max., min.	■	■	■	-	-
THDu, THDi	■	■	■	■	-
<b>Manage electrical installation better</b>					
Load temperature, load and device thermal state	■	■	-	■	-
Insulating resistance	-	-	-	-	■
	Motor controllers	LV variable speed drives	LV softstarters	MV softstarters	UPSs
Examples	TeSys U	ATV.1	ATS.8	Motorpact RVSS	Galaxy
<b>Keep control over power consumption</b>					
Power, inst., max., min.	-	■	-	■	■
Energy, reset capability	-	■	■	■	-
Power factor, inst.	-	-	■	■	■
<b>Improve power supply availability</b>					
Current, inst., max., min., unbalance	■	■	■	■	■
Current, wave form capture	-	-	-	■	■
Device status	■	■	■	■	■
Faults history	■	■	■	■	-
THDu, THDi	-	■	-	-	-
<b>Manage electrical installation better</b>					
Load temperature, load and device thermal state	■	■	■	■	■
Motor running hours	-	■	■	■	-
Battery follow up	-	-	-	-	■

Fig. K11 : Examples of measurements available via Modbus, RS485 or Ethernet

K12



Based on the reports collected by the power monitoring system or energy information system, appropriate energy efficiency projects can be selected. There are various strategies for choosing which projects to implement:

- Often organizations like to get started with relatively low-cost, easy projects to generate some quick wins before making larger investments.
- The simple payback period (the length of time the project will take to pay for itself) is a popular method to rank and choose projects. Its advantage is simplicity of the analysis. The disadvantage is that this method may not take into account the full long-term impact of the project.
- Other more complex methods such as net present value or internal rate of return can also be used. Additional effort is required to make the analysis, but a truer indication of the full project benefits is obtained.

Energy savings can be achieved in a number of ways:

- Energy reduction measures that either use less energy to achieve the same results, or reduce energy consumption by ensuring that energy is not over-used beyond the real requirements. An example of the former is using high-efficiency lamps to provide the same illumination at lower energy cost. An example of the latter is reducing the number of lamps in over-illuminated areas to reduce lighting levels to the required level.
- Energy cost saving measures that do not reduce the total energy consumed, but reduce the per-unit cost. An example is scheduling some activities at night to take advantage of time-of-day electricity tariffs. Peak demand avoidance and demand response schemes are other examples.
- Energy reliability measures that not only contribute to operational efficiency by avoiding downtime, but which also avoid the energy losses associated with restarts or reworking spoiled batches.

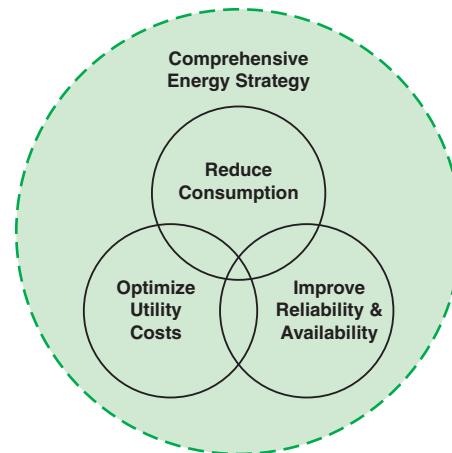


Fig. K12 : Comprehensive Energy strategy

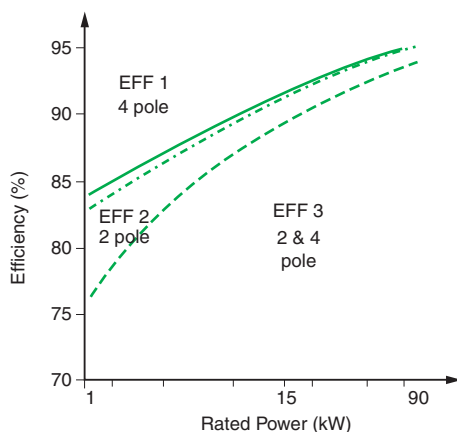


Fig. K13 : Definition of energy efficiency classes for LV motors established by the European Commission and CEMEP (European Committee of Manufacturers of Electrical Machines and Power Electronics)

## 4.1 Motor systems and replacement

Since in industry, 60% of consumed electricity is used to run motors, there is a high likelihood that motor systems will appear strongly among the identified opportunities. Two reasons to consider replacing motors and thereby improve **passive** energy efficiency are:

- to take advantage of new high-efficiency motor designs
- to address oversizing

Depending on horsepower, high efficiency motors operate between 1% and 10% more efficiently than standard motors. Motors that operate for long periods may be good candidates for replacement with high efficiency motors, especially if the existing motor needs rewinding. Note that rewind motors are usually 3% – 4% less efficient than the original motor. However, if the motor receives low to moderate use (e.g. under 3000 hours per year), replacement of standard efficiency motors (particularly those that have not yet been re-wound) with high efficiency motors may not be economical. Also, it is important to ensure the critical performance characteristics (such as speed) of the new motor are equivalent to those of the existing motor.

Motors are most efficient when operated between about 60% and 100% of their full-rated load. Efficiency falls sharply when loading is below 50%. Historically, designers have tended to oversize motors by a significant safety margin in order to eliminate any risk of failure even under extremely unlikely conditions. Facility studies show that about one-third of motors are severely oversized and generally are running below 50% of rated load <sup>(1)</sup>. Average loading of motors is around 60%<sup>(2)</sup>. Oversized motors are not only inefficient but have higher initial purchase cost than correctly-sized units. Larger motors can also contribute to lower power factor, which may lead to reactive power charges on the electricity bill. Replacement considerations should take this into account along with the remaining useful life of the motor. In addition, note that some motors may be oversized but still be so lightly loaded or infrequently used that they do not consume enough electricity to make it cost-effective to install a different motor.

Clearly, wherever appropriate the two approaches should be combined to replace over-sized standard motors with high-efficiency motors sized suitably for the application.

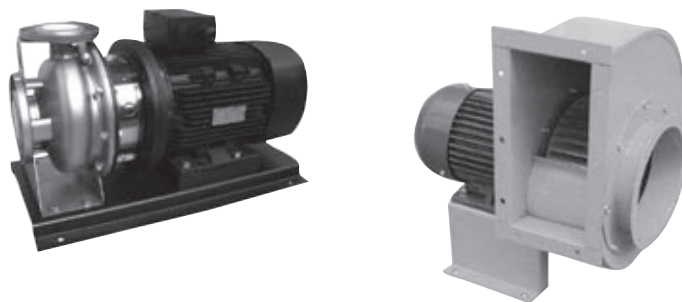
Other tactics which can be applied to motor systems include:

- Improve **active** energy efficiency by simply turn off motors when they are not required. This may require improvements in automatic control, or education, monitoring and perhaps incentives for operators. If the operator of the motor is not accountable for its energy consumption, they are more likely to leave it running even when not in use.
- Check and if necessary correct shaft alignment, starting with the largest motors. Misaligned motor couplings waste energy and eventually lead to coupling failure and downtime. An angular offset of 0.6 mm in a pin coupling can result in a power loss of as much as 8%.

## 4.2 Pumps, fans and variable speed drives

63% of energy used by motors is for fluid applications such as pumps and fans. Many of these applications run the motor at full speed even when lower levels of flow are required. To obtain the level of flow needed, inefficient methods such as valves, dampers and throttles are often used. In a car, these methods would be equivalent to using the brake to control speed while keeping the gas or accelerator pedal fully depressed. These are still some of the most common control methods used in industry. Given that motors are the leading energy-consuming device, and pumps and fans are the largest category of motor-driven equipment, these applications are frequently among the top-ranked energy saving opportunities.

An Altivar variable speed drive is an **active** EE approach that can provide the means to obtain the variable output required from the fan or pump along with significant energy savings and other benefits. Well-chosen projects can result in simple payback periods as short as ten months, with many useful projects in the range of paybacks up to three years. Variable speed drives (VSD) can be useful in many applications, including air compressors, plastic injection moulding machines, and other machines.



**Fig. K14** : Examples of centrifugal pump and fan which can benefit from variable speed control

K14

Most pumps are required either to move fluids between a source and a destination (e.g. filling a reservoir at a higher level) or to circulate liquid in a system (e.g. to transfer heat). Fans are required to move air or other gases, or to maintain a pressure differential. To make the liquid or air flow at the required rate, pressure is required. Many pumping or ventilation systems require the flow or pressure to vary from time to time.

To change the flow or pressure in the system, there are a number of possible methods. The suitability will depend on the design of the fan or pump, e.g. whether a pump is a positive displacement pump or rotodynamic pump, whether a fan is a centrifugal fan or axial fan.

- Multiple pumps or fans: This leads to step increase when additional pumps or fans are switched in, making fine control difficult. Usually there are efficiency losses as the real needs are somewhere between the possible steps.
- Stop/start control: This is only practical where intermittent flow is acceptable.
- Flow control valve: This uses a valve to reduce the flow by increased frictional resistance to the output of the pump. This wastes energy since the pump is producing a flow which is then cut back by the valve. In addition, pumps have a preferred operating range, and increasing the resistance by this method can force the pump to operate in a range where its efficiency is lower (wasting even more energy) and where its reliability is reduced.
- Damper: Similar in effect to a flow control valve in a pumping system, this reduces the flow by obstructing the output of the fan. This wastes energy since the fan is producing a flow which is then cut back by the damper.
- Bypass control: This technique keeps the pump running at full power and routes surplus fluid output from the pump back to the source. It allows a low value of flow to be achieved without risk of increasing the output pressure, but inefficiency is very high since the energy used to pump the surplus fluid is entirely wasted.
- Spillage valve: Similar in effect to a bypass control valve in a pumping system, this technique keeps the fan running at full power and vents surplus flow. Inefficiency is very high since the energy used to move the vented air or gas is entirely wasted.
- Variable pitch: Some fan designs allow the angle of the blades to be adapted to change the output.
- Inlet guide vane: these are structures using fins to improve or disrupt the routing of air or gas into a fan. In this way they increase or decrease the airflow going in and hence increase or decrease the output.

K15

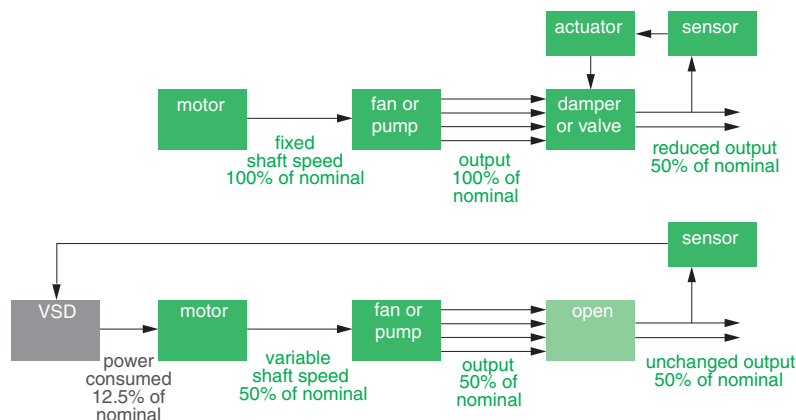


Fig. K15 : Fan and pump control: in theory

Wherever a fan or a pump has been installed for a range of required flow rates or pressure levels, it will have been sized to meet the greatest output demand. It will therefore usually be oversized, and will be operating inefficiently for other duties. Combining this with the inefficiency of the control methods listed above means that there is generally an opportunity to achieve an energy cost saving by using control methods which reduce the power to drive the pump or fan during the periods of reduced demand. However, a fan or pump that is not required to perform variable duties may be running at full speed without any of the above control methods, or with those control methods present but unused (e.g. valves or dampers set to fully open). In this case the device will be operating at or close to its best efficiency and a variable frequency drive will not bring any improvement.

For those fans and pumps which are required to generate varying levels of output, a variable frequency drive reduces the speed of the pump or fan and the power it consumes. Among fans, effectiveness will vary depending on the design. Centrifugal fans offer good potential, both with forward curved and backward curved impellers. Axial fans have a greater intrinsic efficiency and normally do not offer enough economic potential for a VSD application. In pumps, the effectiveness will vary depending on a number of factors, including the 'static head' of the system (the effects of a difference in height between the source and destination of the fluid) and 'friction head' (the effects of the liquid moving in the pipes, valves and equipment). The variable frequency drive should always be matched with the safe operating range of the pump. Generally, variable speed drives bring greater benefits in systems where the friction head is the dominant effect. In some cases, replacing the fan or pump with a more efficient design may bring greater benefits than retrofit of a VSD. A fan or pump that is infrequently used, even if it is inefficient, may not generate enough savings to make replacement or VSD retrofit cost-effective. However note that flow control by speed regulation is always more efficient than by control valve or bypass control.

Fan and pump applications are governed by the affinity laws:

- Flow is proportional to shaft speed
- Half the shaft speed gives you half the flow
- Pressure or head is proportional to the square of shaft speed
- Half the shaft speed gives you quarter the pressure
- Power is proportional to the cube of shaft speed
- Half the shaft speed uses one-eighth of the power
- Hence half the flow uses one-eighth of the power

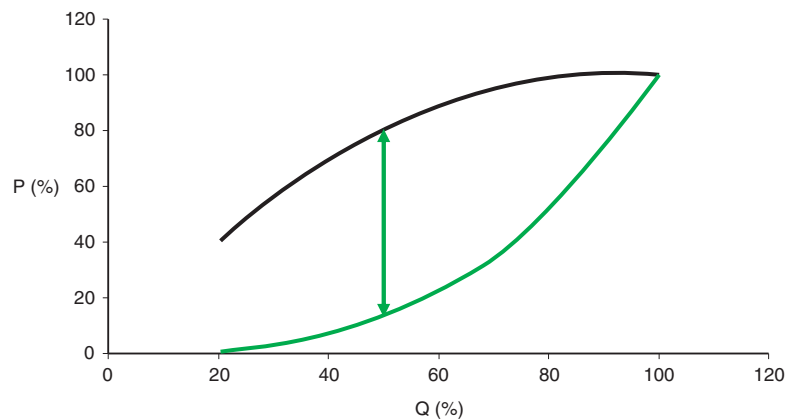


Fig. K16 : Theoretical power saving with a fan running at half speed

Therefore, if you don't need the fan or pump to run at 100% flow or pressure output, you can reduce the power consumed by the fan, and the amount of the reduction can be very substantial for moderate changes in flow. Unfortunately in practice, efficiency losses in the various components render the theoretical values not achievable.

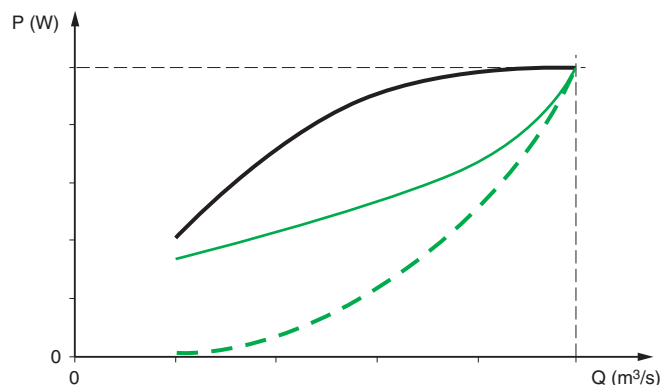


Fig. K17 : Power versus flow rate for the different fan control methods: downstream damper, inlet vanes, and variable speed (top to bottom).

The actual achievable savings depend on the design of the fan or pump, its inherent efficiency profile, the size of the motor, the number of hours used per year, and the local cost of electricity. These savings can be estimated using a tool such as ECO8, or can be accurately forecast by installing temporary metering and analyzing the data obtained in the context of the appropriate curve.

The drive can be integrated into a variety of possible control methods:

- **Control by fixing pressure but varying flow:** This uses a pressure sensor connected to the VSD which in turn varies the speed allowing the fan or pump to increase or decrease the flow required by the system. This is a common method in water supply schemes where constant pressure is required but water is required at different flows dependant on the number of users at any given time. This is also common on centralised cooling and distribution systems and in irrigation where a varying number of spray heads or irrigation sections are involved.

- **Heating system control:** In heating and cooling systems there is a requirement for flow to vary based on temperature. The VSD is controlled by a temperature sensor, which increases or decreases the flow of hot or cold liquid or air based on the actual temperature required by the process. This is similar to pressure control, where the flow also varies, but a constant temperature requirement from a temperature sensor replaces that from a pressure sensor.

- **Control by fixing flow but varying pressure:** Constant flow may be required in irrigation and water supply systems. Since the water levels both upstream and downstream of the pumping station can change, the pressure will be variable. Also many cooling, chiller, spraying and washing applications require a specific volume of water to be supplied even if the suction and delivery conditions vary. Typically suction conditions vary when the height of a suction reservoir or tank drops and delivery pressure can change if filters blind or if system resistance increases occur through blockages etc. A flowmeter is used to keep the flow rate constant, normally installed in the discharge line.

The benefits achieved include:

- Reduced energy consumption and hence cost savings by replacing inefficient control methods or other obsolete components such as two-speed motors
- Better control and accuracy in achieving required flow and pressure
- Reduced noise and vibration, as the inverter allows fine adjustment of the speeds and so prevents the equipment running at a resonant frequency of the pipes or ductwork
- Increased lifecycle and improved reliability, for example, pumps that are operated in a throttled condition usually suffer from reduced useful life
- Simplified pipe or duct systems (elimination of dampers, control valves & by-pass lines)
- Soft start & stop creates less risk of transient effects in the electrical network or mechanical stress on the rotating parts of the pump or fan. This also reduces water hammer in pumps, because the drive provides smooth acceleration and deceleration instead of abrupt speed variations
- Reduced maintenance

	Without VSD	With VSD	Reduction	% savings
<b>Average power use (2 motors per fan)</b>	104 kW per motor	40 kW per motor	64 kW per motor	62%
<b>Electricity cost per fan</b>	£68.66 per tonne output	£26.41 per tonne output	£42.25 per tonne output	
<b>CO<sub>2</sub> rate</b>	459,000 kg / year	175,541 kg / year	283,459 kg / year	
<b>Annual running cost</b>	£34,884	£13,341	£21,542	
<b>Payback period</b>		10 months with local capital allowances claimed 14 months without local capital allowances		

*Fig. K18 : Example of savings for variable speed driven pumps*

Additionally, significant energy savings can often be made simply by changing pulley sizes, to ensure a fan or pump runs at a more appropriate duty point. This doesn't provide the flexibility of variable speed control but costs very little, can probably be done within the maintenance budget and doesn't require capital approval.

### 4.3 Lighting

Lighting can represent over 35% of energy consumption in buildings depending on the business. Lighting control is one of the easiest ways to save energy costs for low investment and is one of the most common energy saving measures.

#### Lamps and ballasts

Lighting design for commercial buildings is governed by standards, regulations and building codes. Lighting not only needs to be functional but must meet occupational health and safety requirements and be fit for purpose. In many instances, office lighting is over-illuminated, and substantial energy savings are possible by **passive EE**: replacing inefficient, old technology lamps with high efficiency, low wattage lamps in conjunction with electronic ballasts.

This is especially appropriate in areas where lighting is required constantly or for long periods, because in such places there is less opportunity to save energy by turning lights off. Simple payback periods vary but many projects have paybacks of around two years.

Depending on the needs, type and age of your lighting installation, more efficient lamps may be available. For example, 40-watt T12 fluorescent lamps may be replaced by newer 32-watt T8 fluorescent lamps. (T designates a tubular lamp. The number is the diameter in eighths of an inch. T12 lamps are therefore 1.5 inches in diameter. Standards vary between countries.) Changing the lamp will also require changing the ballast.

Fluorescent lamps contain gases that emit ultraviolet light when excited by electricity. The phosphor coating of the lamp converts the ultraviolet light into the visible spectrum. If the electricity entering the lamp is not regulated, the light will continue to gain in intensity. A ballast supplies the initial electricity to create the light and then regulates the current thereafter to maintain the correct light level. Ballasts are also used with arc lamps or mercury vapor lamps. New designs of electronic ballasts deliver considerable savings compared with older electromagnetic ballast designs. T8 lamps with electronic ballasts will use from 32% to 40% less electricity than T12 lamps with electromagnetic ballasts.

Electronic ballasts do have a disadvantage compared to magnetic ballasts. Magnetic ballasts operate at line frequency (50 or 60 Hz), but electronic ballasts operate at 20,000 to 60,000 Hz and can introduce harmonic distortion or noise into the electrical network. This can contribute to overheating or reduced life of transformers, motors, neutral lines, overvoltage trips and damage to electronics.

Usually this is not a problem apart from facilities with heavy lighting loads and a large number of electronic ballasts. Most makes of electronic ballasts integrate passive filtering within the ballast to keep the total harmonic distortion to less than 20 percent of fundamental current.

If the facility has strict needs for power quality, (e.g. hospitals, sensitive manufacturing environments, etc) electronic ballasts are available having total harmonic distortion of five percent or less.

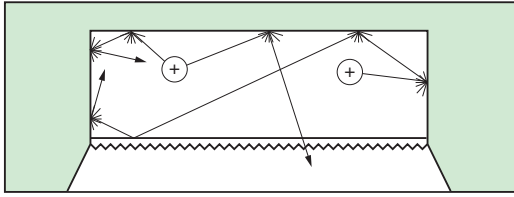
Other types of lighting are also available and may be suitable depending on the requirements of the facility. An assessment of lighting needs will include evaluation of the activities taking place and the required degree of illumination and colour rendering. Many older lighting systems were designed to provide more light than current standards require. Savings can be made by redesigning a system to provide the minimum necessary illumination.

The use of high efficiency lamps in conjunction with electronic ballasts have a number of advantages, firstly energy and cost savings can be easily qualified, modern lamps and electronic ballasts are more reliable leading to reduced maintenance costs, lighting levels are restored to more appropriate levels for office space, whilst complying with relevant building codes, practices and lighting standards, the incidence of "frequency beat" often associated with migraines and eye strain disappears and the color rendering of modern lamps produces a more conducive working environment.

#### Reflectors

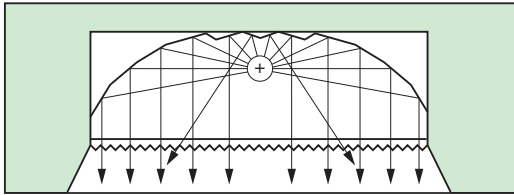
A less common **passive EE** recommendation, but one which should be considered along with changing lamps and ballasts, is to replace reflectors. The reflector in a luminaire (light fixture) directs light from the lamps towards the area where it is intended to fall. Advances in materials and design have resulted in improved reflector designs which can be retrofitted to existing luminaires. This results in increased usable light, and may allow lamps to be removed, this saving energy while maintaining the needed level of lighting.





**Above:** Around 70% of a fluorescent tube's light is directed sideways and upwards to the light fittings surfaces;

**Below:** KW/2's silver surface is shaped to reflect the maximum amount of light downward.



**Fig. K19 :** Overview on KW/2 principle

A KW2 high efficiency reflector has a spectral efficiency of over 90%. This means two lamps may be replaced by a single lamp. In this way it is possible to reduce energy costs attributed to lighting by 50% or more. Existing luminaires may be retrofitted with the space age technology reflector, whilst maintaining spatial distance between luminaires, making retrofitting easy and cost effective, with minimal disruption to the existing ceiling design.

### Lighting control

Improved lighting control is another method of increasing efficiency in lighting. Such recommendations are less common, but the simple payback period is typically shorter, between six and twelve months. By itself, passive EE from lamps, ballasts and reflectors does not maximize savings, since an energy efficient lamp will still waste energy if left on when not required. Although users can be sensitized to switch off lights, in practice lapses are common, and automatic control is much more effective in obtaining and sustaining efficiency. The objective of lighting control schemes is to provide the comfort and flexibility that users require, while simultaneously ensuring **active** EE, minimizing costs by ensuring lights are turned off promptly whenever they are not needed. The sophistication of such schemes can vary considerably.

Some of the simplest methods include:

- Timer switches to turn off lights after a fixed period has passed. Timers are best deployed in areas where occupancy is well defined (e.g. in hotel corridors where the time for a person to pass through is predictable).
- Occupancy sensors / movement detectors to turn off lights when no movement has been detected for a certain period. Occupancy sensors are best deployed in offices, storerooms, stairwells, kitchens and bathrooms where the use of the facilities cannot be predicted with a high degree of accuracy during the day.
- Photoelectric cells / daylight harvesting sensors to control lights near windows. When bright exterior light is available, lamps are turned off or dimmed.
- Programmable timers to switch lights on and off at predetermined times (e.g. shop fronts, ensure office lights are turned off at nights and weekends).
- Dimmable lights to maintain a low level of illumination at off-peak periods (e.g. a car parking lot which needs to be fully illuminated during peak use, perhaps until midnight, but which can have lower ambient illumination from midnight until dawn)
- Voltage regulators to optimize the power consumed. Ballasts perform this function on fluorescent lighting. Voltage regulators are also available for other lighting types such as high pressure sodium lamps.

**K19**



**Fig. K20 :** Examples of lighting control devices: timers, light detectors, movement detectors,...

Methods may be combined, e.g. the ability to dim lights in the parking lot may be combined with movement detectors or override switches with a timer to increase illumination when needed if a user requires access outside normal hours.

More sophisticated and customizable schemes can be implemented with integrated lighting control systems. Aesthetic requirements can be incorporated, such as using programmable lighting panels to record a variety of lighting setups which can be reproduced at the touch of a button (e.g. for boardrooms requiring different light arrangements for meetings, presentations, demonstrations, etc). Wireless technology can make retrofit applications simple and economical.

Lighting control systems such as C-Bus and KNX offer the additional advantage that they can be networked and integrated with the building management system, for greater flexibility of control, central monitoring and control function as well as combination of lighting controls with other building services such as HVAC for even greater energy savings.

Lighting controls have the potential to realize energy savings of 30% but this depends very much on application. A lighting survey and energy audit can help define the best lighting solution for the premises and activities performed as well as identify areas for energy and cost savings. In addition to office space, Schneider offers solutions for exterior, car parking and landscape lighting for optimum lighting and energy savings.

#### 4.4 Load management strategies

Since electricity has to be generated in response to immediate needs, and cannot economically be stored, suppliers are obliged to size their generating capacity according to peak needs, which may occur infrequently. At other times, that capacity is surplus and represents capital tied up in facilities and equipment that are idle and unused. Suppliers are therefore motivated to smooth out peaks in electricity demand.

Load management requires an active EE approach, since even high-efficiency devices will contribute to peak needs.

##### Peak demand avoidance

One way utilities encourage users to avoid peaks is by transferring the cost of maintaining the peak production capacity to those users who contribute most to the peaks. Utilities structure their billing with various components. One is always the actual consumption in the billing period, but another component (the demand charge) is normally based on the peak usage at some point during the preceding period, which could be twelve months or another period such as a season. The demand charge is a premium that large users pay each month for the utility to have the extra generation capacity and infrastructure required to meet their peak demand levels whenever they need it – even if they don't use it very often. If a customer can avoid setting peaks in their energy usage, they can minimize the part of their energy bill driven by the peak consumption, even if their total consumption remains the same. Note that setting a new peak has a continuing economic impact, because it determines the demand charge not only for that month, but for each subsequent month during the period defined by the tariff, which may be as much as a year. This means that a single short event that spikes consumption for as little as a few minutes can have a continuing effect on the electricity bill.

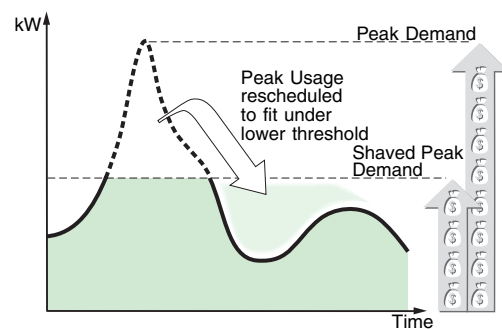
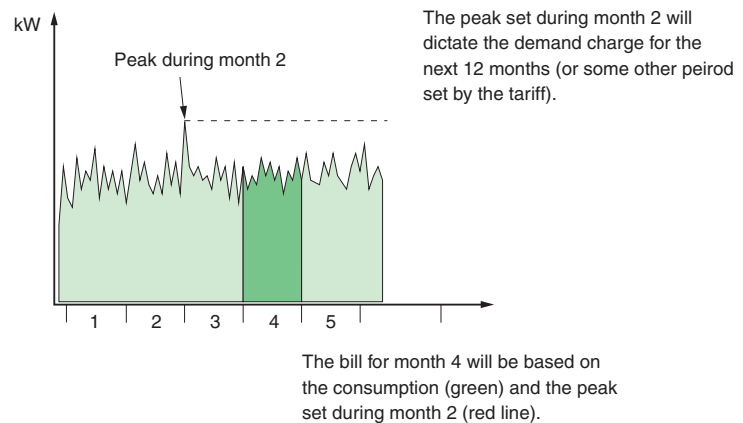


Fig. K21 : Example of load management strategy



Peak demand avoidance applications are PLC controlled automatic electrical distribution control systems. A demand interval is defined as a particular level of consumption in a period of time (e.g. kWh in a 15 minute period). The objective is to keep the total energy consumed in each period below the limit. If the customer is consuming a large amount of power in a given period, the system will detect that a peak is approaching. An alarm is activated, and unless an operator overrides the system, it will begin to shed non-essential loads in a predetermined order, until the alarm condition is cleared, or the demand interval ends. All loads in a facility are defined in one of three categories: critical, essential, and non-essential loads. Usually only non-essential loads are shed, and the order of shedding can be configured.



**Fig. K22 :** Impact of peak demand on electricity bill

Providing the customer has enough non-essential loads to be able to impact their peak consumption, it may be possible to reduce the demand charge by as much as 10% to 30%. Demand charge can be up to 60% of the bill. The application usually pays for itself in one year or less.

### Load scheduling

Utilities often have different rates that apply for different times of the day. During normal daily business hours, the rates are the highest. Many users shift, or reschedule loads to take advantage of lower rates. These are loads that are not time sensitive or critical.

### Demand response (curtailment)

Another tactic is demand response (also known as demand curtailment). Demand response is a means to manage the demand from customers taking supply conditions into account. Utilities may offer financial incentives to customers to reduce load during periods when the utility does not have the distribution capacity to handle the total demand. Typically this will be during the hottest months of the year, when consumer and business needs for cooling and ventilation are high and draw a lot of electricity in addition to normal requirements. In some countries, third-party aggregators may manage schemes that monitor the network capacity and the real-time price of electricity on the network. Participants in the scheme receive incentives to shed load, creating capacity which the aggregator can sell into the network.

In each case, the utility or aggregator offers a contract including an agreement from the customer to reduce the kW consumption at their site down to a predetermined level when notified. These contracts may contain both emergency curtailments (when the participants in the scheme must comply or face penalties) and opt-in curtailments (where participants can evaluate the specific conditions for that particular curtailment and decide whether or not to accept). Usually the contract limits the duration of the curtailment (e.g. 2 to 6 hours) and the number of times per year the curtailment can be activated (3 to 5). Industrial customers tend to have more opportunity to participate, since building managers are less likely to be able to drop substantial loads without impacting the building occupants' comfort.

A curtailment is activated following a notification by phone or via a signal output from the utility revenue meter. Typically there is 30 to 60 minutes advance notice. The customer systematically reduces load until the curtailment level is obtained, either by manually reducing or shutting off loads or by an automated PLC controlled system. The utility or aggregator then signals the start of the curtailment period. After the curtailment period is complete, the utility or aggregator signals the end of the curtailment period. The customer may then re-establish normal facility loading and production.

The return on investment from demand response schemes will vary depending on local tariff rates and electricity market. The incentive generally takes the form of a credit for the demand reduction during the response period. If the customer has enough non-essential loads to be able to impact peak consumption, he may be able to benefit from incentives that in effect reduce the cost per unit by as much as 30%.

Automated demand response control applications usually pay for themselves in one year or less. Without such a scheme, loads have to be turned off manually, with a significant chance of failure, for example, if a human operator does not act quickly enough. Failing to comply with a curtailment brings financial penalties, and so an automated application which can support both peak demand avoidance and demand curtailment can be a very good investment.

Together with the control applications, a demand response portal can make participation in a demand response scheme much more convenient. Such a portal provides a means for a utility or aggregator to notify the participants of emergency or opt-in events. Participants can evaluate the conditions of an opt-in and view their current consumption and what they would have to do in order to comply with the request before accepting or rejecting the event. The portal also supports auditing or completed events to demonstrate compliance with the conditions.

### On-site generation

On-site generation increases the flexibility available to facility operators. Instead of shedding loads, on-site generation can provide the power required to keep running during a period of peak avoidance or demand curtailment. The automated control system can be extended to integrate control of on-site generation facilities into the scheme. If the customer is buying electricity from a supplier at a time-of-use rate, the control system can be configured to continuously monitor the current cost of electricity from the supplier and compare it to the cost of energy generated on site using another fuel source. When the cost of electricity rises above the cost of using the generator (replacing the fuel), the control scheme automatically shifts load to the on-site generation. When the cost falls, load is shifted back to the supply utility.

However, in many places the local authorities only permit diesel generators to be used for a certain maximum number of hours per year, in order to limit emissions. This has to be taken into account as it limits the opportunities to make use of the generator.

## 4.5 Power factor correction

If the electricity supplier charges penalties for reactive power, implementing power factor correction has the potential to bring significant savings on the electricity bill. Power factor correction solutions are typically **passive** EE measures that operate transparently once installed, and don't require any changes to existing procedures or behaviour of staff. Simple payback periods can be less than a year.

Power factor correction is treated in detail in chapter L.

## 4.6 Harmonic filtering

Many solutions to improve efficient use of electricity can have side effects, bring harmonics into the electrical network. High-efficiency motors, variable speed drives, electronic ballasts for fluorescent lights, and computers can all generate electrical pollution which can have significant effects. Harmonics can create transient over-voltage conditions that cause protection relays to trip and result in production downtime. They increase heat and vibration and thereby decrease efficiency and shorten life of neutral conductors, transformers, motors and generators. Power factor correction capacitors may magnify harmonics, and can suffer from overloading and premature aging.

Management of harmonics is treated in detail in chapter M.

### 4.7 Other measures

Outside the scope of the electrical installation, other energy savings measures may be available depending on the activities present on the site. Productivity enhancements in production such as reducing bottlenecks, eliminating defects and reducing materials can generate further savings. Combustion systems (such as furnaces, ovens, boilers) and thermal systems (such as steam systems, heat generation, containment and recovery, cooling towers, chillers, refrigerators, dryers) may also provide opportunities.

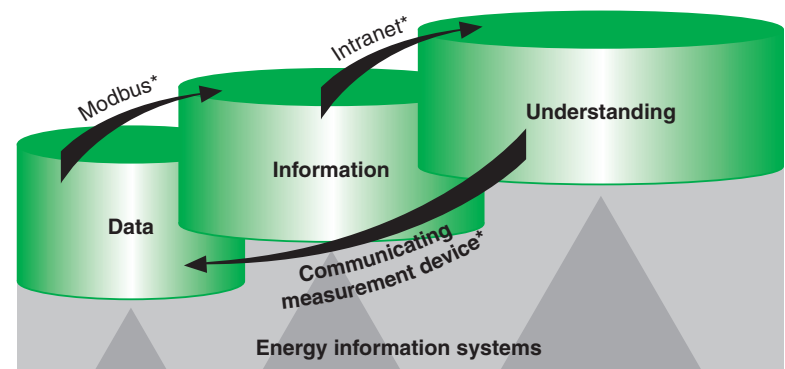
### 4.8 Communication and Information System

Most organisations will already have some level of energy information system, even if it is not identified or managed as one. It should be appreciated that in a changing working world, any information system will need to develop to meet its prime objective - supporting management decision making: a key point is to make the energy information visible at any level of the organization through the communication infrastructure.

Energy data is important data, it is one of the company's assets. The company has IT managers who are already in charge of managing its other IT systems. These are important players in the power monitoring system and above all in that for data exchange within the corporate organization.

#### Communication network at product, equipment and site level

The day-to-day working of the energy information system can be illustrated by a closed loop diagram (see Fig. K23).



\* Communication network

Fig. K23 : System hierarchy

Various resources are used to send data from metering and protection devices installed in the user's electrical cabinets, e.g. via Schneider Electric Transparent Ready™.

K23

### The Modbus communication protocol

Modbus is an industrial messaging protocol between equipment that is interconnected via a physical transmission link e.g. RS 485 or Ethernet (via TCP/IP) or modem (GSM, Radio etc). This protocol is very widely implemented on metering and protection products for electrical networks.

Initially created by Schneider Electric, Modbus is now a public resource managed by an independent organization Modbus-IDA – enabling total opening up of its specification. An industrial standard since 1979, Modbus allows millions of products to communicate with one another.

The IETF, international authority managing the Internet, has approved the creation of a port (502) for products connected to the Internet/Intranet and using the Ethernet Modbus TCP/IP communication protocol.

Modbus is a query/reply process between two pieces of equipment based on data reading and writing services (function codes).

The query is emitted by a single “master”, the reply is sent only by the “slave” equipment identified in the query (see **Fig. K24**).

Each “slave” product connected to the Modbus network is set by the user with an ID number, called the Modbus address, between 1 and 247.

The “master” – for example a web server included in an electrical cabinet – simultaneously queries all of the products with a message comprising its target’s address, function code, memory location in the product and quantity of information, at most 253 octets.

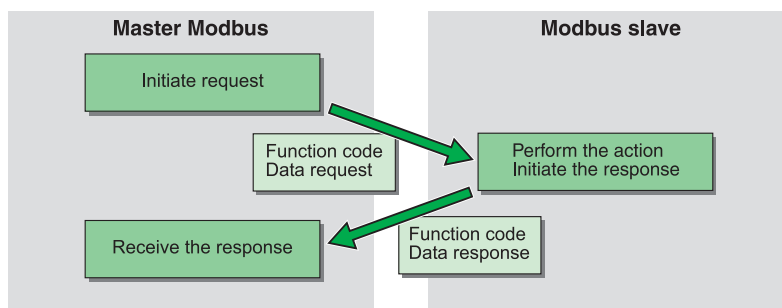
Only a product set with the corresponding address answers the request for data.

Exchange is only carried out on the initiative of the master (here the web server): this is the master-slave Modbus operating procedure.

This query procedure followed by a reply, implies that the master will have all of the data available in a product when it is queried.

The “master” manages all of the transaction queries successively if they are intended for the same product. This arrangement leads to the calculation of a maximum number of products connected to the master to optimize an acceptable response time for the query initiator, particularly when it is a low rate RS485 link.

K24



**Fig. K24** : The function codes allow writing or reading of data.

A transmission error software detection mechanism called CRC16 allows a message with an error to be repeated and only the product concerned to respond.

### Your Intranet network

Data exchange from industrial data basically uses web technologies implemented permanently on the corporate communication network, and more particularly on its Intranet.

The IT infrastructure manages the cohabitation of software applications: the company uses it to operate applications for the office, printing, data backup, for the corporate IT system, accounting, purchasing, ERP, production facility control, API, MES, etc. The cohabitation of data on the same communication network does not pose any particular technological problem.

When several PC's, printers and servers are connected to one another in the company's buildings, very probably using the Ethernet local network and web services: this company is then immediately eligible to have energy efficiency data delivered by its electrical cabinets. Without any software development, all they need is an Internet browser.

The data from these applications cross the local broadband Ethernet network up to 1 Gb/s: the communication media generally used in this world is copper or optic fiber, which allows connection everywhere, in commercial or industrial buildings and in electrical premises.

If the company also has an internal Intranet communication network for emailing and sharing web servers data, it uses an extremely common standardized communication protocol: TCP/IP.

The TCP/IP communication protocol is designed for widely used web services such as HTTP to access web pages, SMTP for electronic messaging between other services.

Applications	SNMP	NTP	RTPS	DHCP	TFTP	FTP	HTTP	SMTP	Modbus
Transport	UDP					TCP			
Link	IP								
Physical	Ethernet 802.3 and Ethernet II								

Electrical data recorded in industrial web servers installed in electrical cabinets are sent using the same standardized TCP/IP protocol in order to limit the recurrent IT maintenance costs that are intrinsic in an IT network. This is the operating principle of Schneider Electric Transparent Ready™ for communication of data on energy efficiency. The electrical cabinet is autonomous without the need for any additional IT system on a PC, all of the data related to energy efficiency is recorded and can be circulated in the usual way via the intranet, GSM, fixed telephone link, etc.

#### Security

Employees are well informed, more efficient and working in complete electrical safety: they no longer need to go into electrical rooms or make standard checks on electrical devices - they just have to consult data. Under these conditions, communicative systems give the company's employees immediate and significant gains and avoid worrying about making mistakes.

It becomes possible for electricians, maintenance or production technicians, on-site or visiting managers to work together in complete safety.

According to the sensitivity of data, the IT manager will simply give users the appropriate access rights.

#### Marginal impact on local network maintenance

The company's IT manager has technical resources to add and monitor equipment to the local company network.

Based on standard web services including the Modbus protocol on TCP/IP, and due to the low level of bandwidth requirement characteristic in electrical network monitoring systems as well as the use of technologies that are not impacted by viruses and worldwide IT standards, the IT manager does not have to make any specific investment to preserve the local network performance level or to protect against any additional security problems (virus, hacking, etc.).

#### Empowering external partners

According to the company's security policy, it becomes possible to use support services of the usual partners in the electrical sector: contractors, utilities managers, panelbuilders, systems integrators or Schneider Electric Services can provide remote assistance and electrical data analysis to the company consuming electricity. The messaging web service can regularly send data by email or web pages can be remotely consulted using the appropriate techniques.

### From Network Monitoring and Control System to Intelligent Power Equipment

Traditionally and for years, monitoring and control systems have been centralized and based on SCADA (Supervisory, Control and Data acquisition) automation systems.

Deciding on investing in such system – noted (3) in **Figure K25** – was really reserved for high demanding installation, because either they were big power consumers, or their process was very sensitive to Power non quality.

Based on automation technology, such systems were very often designed, customised by a system integrator, and then delivered on site. However the initial cost, the skills needed to correctly operate such system, and the cost of upgrades to follow the evolutions of the network may have discouraged potential users to invest. Then based on a dedicated solution for electrician, the other approach noted (2) is much more fitting the electrical network specific needs and really increases the payback of such system. However, due to its centralised architecture, the level cost of such solution may still appear high.

On some sites Type (2) and (3) can cohabit, providing the most accurate information to the electrician when needed.

Nowadays, a new concept of intelligent Power equipment – noted (1) – has come. considered as an entering step for going to level 2 or 3, due the ability of these solutions to co-exist on a site.

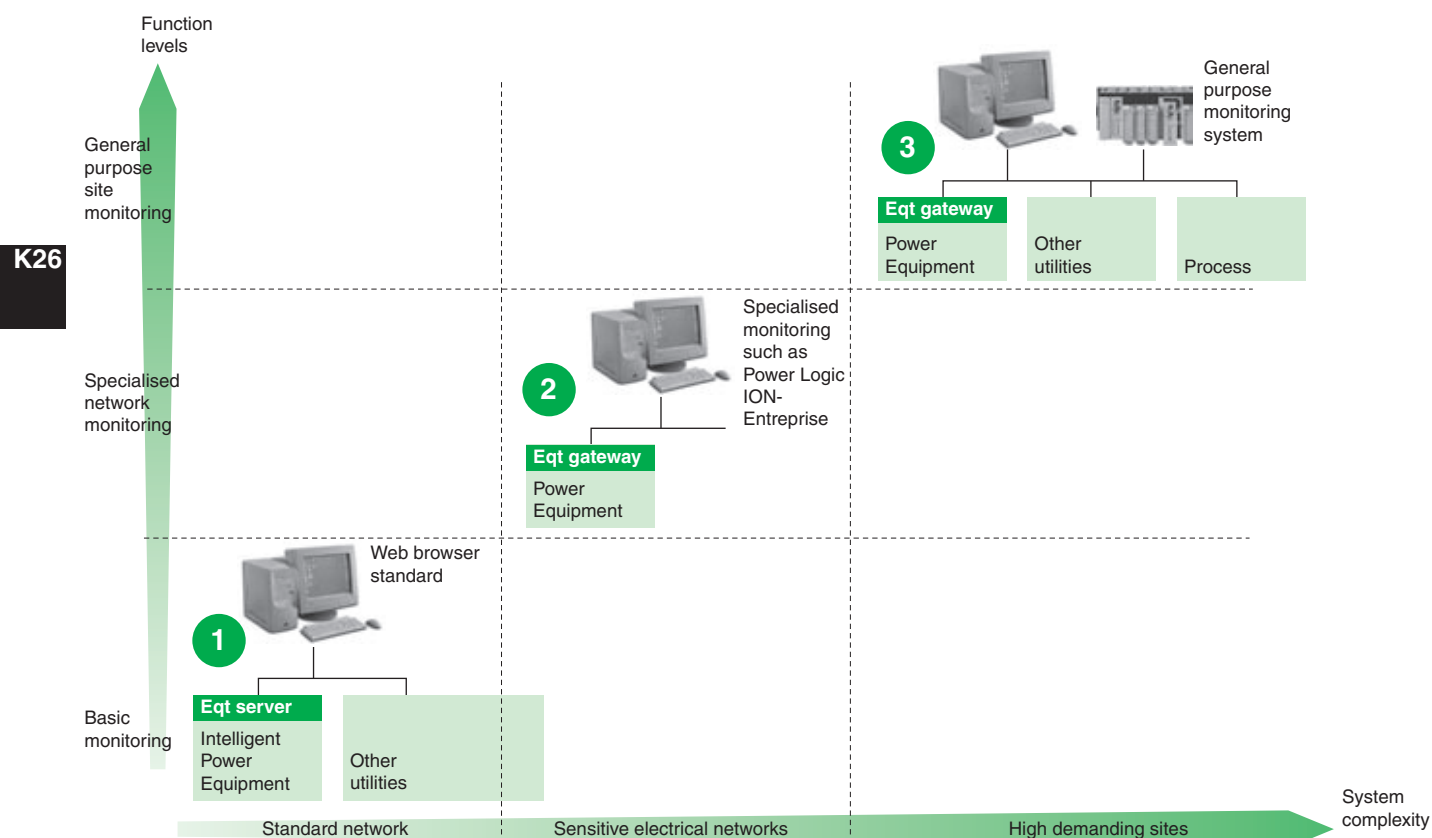


Fig. K26 : Monitoring system positioning

### ■ Level 1

#### Intelligent equipment based architecture (see Fig. K26)

This new architecture has appeared recently due to Web technology capabilities, and can really be positioned as an entry point into monitoring systems. Based on Web technologies it takes the maximum benefits of standard communication services and protocols, and license-free software. The access to electricity information can be done from everywhere in the site, and electrical staff can gain a lot in efficiency. Openness to the Internet is also offered for out of the site services.

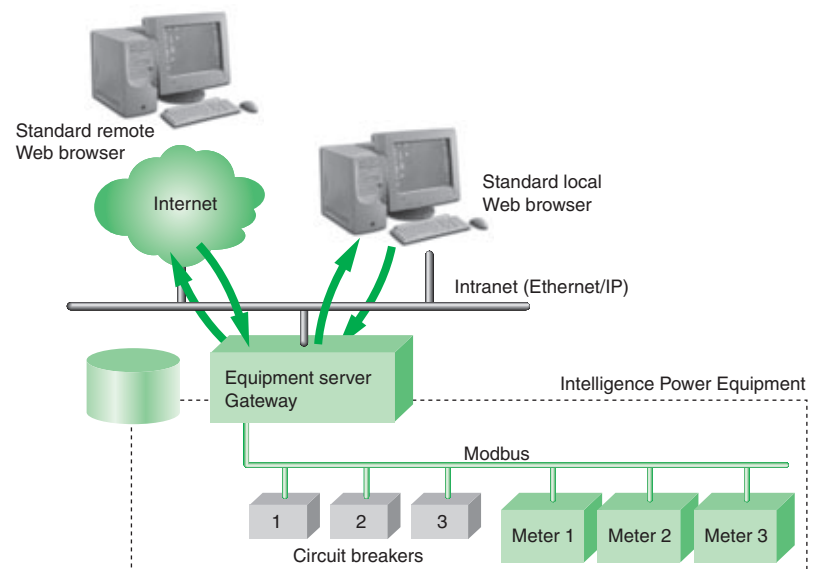


Fig. K26 : Intelligent equipment architecture

### ■ Level 2

#### Electrician specialized centralised architecture (see Fig. K27)

Dedicated to electrician, this architecture is based on a specific supervision centralised mean that fully match the needs for monitoring an electrical network. Then it offers naturally a lower level of skill to set up and maintain it – all Electrical Distribution devices are already present in a dedicated library. Finally its purchase cost is really minimized, due the low level of system integrator effort.

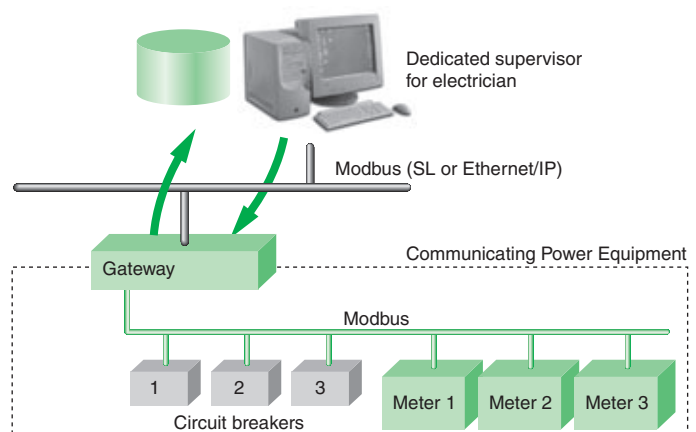


Fig. K27 : ED specialist monitoring system

## ■ Level 3

**Conventional general purpose centralised architecture (see Fig. K28)**

Here is a typical architecture based on standard automation pieces such as SCADA systems, and gateways.

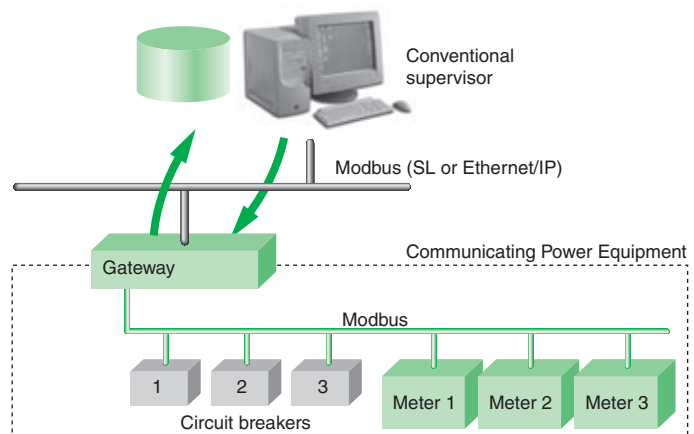
This architecture is typically used for high demanding installation which requires high availability of electricity.

In such case, real time performance is key, either to be achieved automatically or through 24/7 operation team on site.

In order to comply with very high availability constraint, such system very often requests to support transparently (i.e with no visible impact) a first fault of system level components such as the SCADA itself, the communication infrastructure, ...

Energy efficiency is also an important matter, and such solution should offer all the mean to clearly master the energy consumption and quality on site. Electrical assets protection is then the 3d main matter, and such solution should offer a mean to prevent any damage of these very expensive electrical and process assets.

Connectivity with the Process control system is also required, especially through the remote control of the operating mode of motors (MV and LV). Solutions such as PowerLogic SCADA (Modbus or IEC 61850 based) appear the most appropriate.



**Fig. K28** : Real-time conventional monitoring and control system

**e-Support becomes accessible**

The setting up of an information system to support a global energy efficiency approach very quickly leads to economic gains, in general with an ROI of less than 2 years for electricity.

An additional benefit, that is still underestimated today, is the leverage that this leads to in terms of information technologies in the electrical sector. The electrical network can be analyzed from time to time by third parties – in particular using external competencies via the internet for very specific issues:

- Electricity supply contracts. Changing of supplier at a given point in time, e.g. permanent economic analysis of the costs related to consumption becomes possible without having to wait for an annual review.
- Total management of electrical data – via internet – to transform it into relevant information that is fed back via a personalized web portal. Consumer usage information is now a value-added commodity, available to a wide range of users. It's easy to post customer usage data on the Internet – making it useful to the users is another matter.
- Complex electrical fault diagnosis to call in an electrotechnical expert, a rare resource that is easily accessible on the web.
- Monitoring of consumption and generating alerts in the case of abnormal consumption peaks.
- A maintenance service that is no more than necessary to meet pressure on overheads via facility management services.



Energy efficiency is no longer an issue that the company has to face on its own, many e-partners can back up the approach as necessary – in particular when the measurement and decision making assistance stage is reached, on condition that the electrical network is metered and communicative via internet.

Implementation can be gradual starting by making a few key pieces of equipment communicative and gradually extending the system so as to be more accurate or to give wider coverage of the installation.

The company can choose its policy: ask one or more partners to analyze the data, do it itself or combine these options.

The company may decide to manage its electrical energy itself, or ask a partner to monitor the quality to ensure active monitoring of performances in terms of aging.

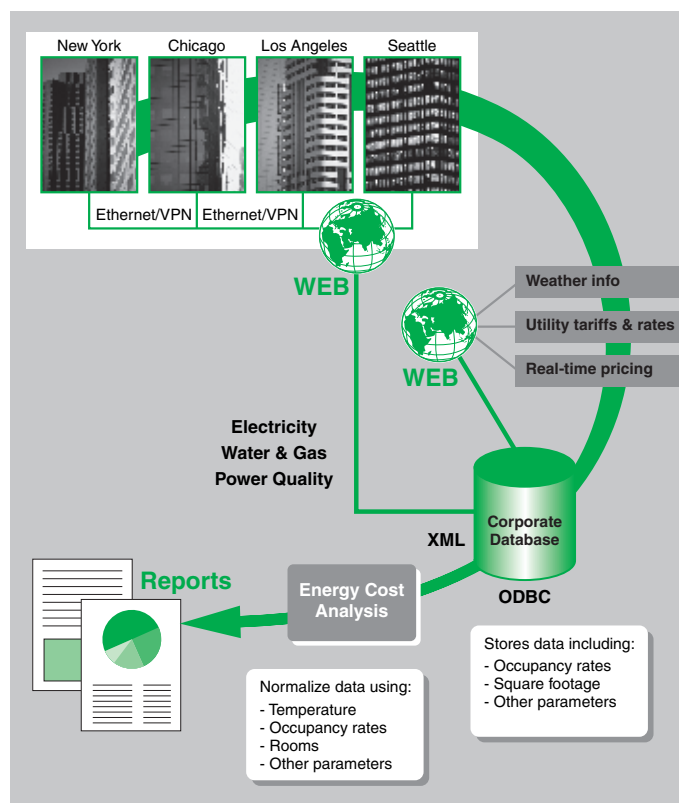
*Example:*

*Schneider Electric proposes e-Services that offers load data visualization and analysis application in ASP mode. It simplifies processes for tenants with geographically diverse locations by providing convenient integrated billing and usage information for all locations combined.*

*The system turns customer usage data into useful information, easily accessible to all internal users. It helps control costs by showing customers how their organizations use power.*

*A wide range of functionality serves the needs of staff from the same platform:*

*Data Access and Analysis , Historical and Estimated Bills, Rate Comparison, What-if Analysis - Assess the impact of operational changes, such as shifting energy between time periods or reducing usage by fixed amounts or percentages, Automatic Alarming, Memorized Reports, Benchmarking - Benchmark usage data from multiple facilities by applying normalization factors such as square footage, operating hours, and units of production. Multiple Commodities - Access usage data for gas and water as well as electricity etc.*



**Fig. K29 :** Typical solution example

## 4.9 Mapping of solutions:

	Energy savings	Cost optimization	Availability & Reliability
Variable speed drives	***	*	*
High efficiency motors and transformers	***		
MV motor supply	***		
Power factor correction	*	***	
Harmonic management	*	**	*
Configuration of circuits			***
Back-up generators		**	***
UPS (see page N11)			***
Soft starters	*	*	***
Protection coordination			***
iMCC		**	**
Intelligent Equipment based architecture Level 1	**	*	
Electrician specialized centralised architecture Level 2	***	**	*
Conventional general purpose centralised architecture Level 3	*	**	***

Fig. K31 : Mapping of solutions

*IPMVP (International Performance Measurement & Verification Protocol) is a methodology to value the energetic savings. Certain information in this chapter is taken from the IPMVP guide volume 1 published by EVO [www.evo-world.org](http://www.evo-world.org)*

## 5.1 Introduction to IPMVP and EVO

Today, the interest in energy efficiency project, for whatever purpose, industrial or public, has never been greater. It is noticed that one of the most important barriers to a widespread implementation of energy efficiency projects is the lack of reliable and commercially-viable financing result. The more we invest for a project, the bigger the need for a reliable proof is. Therefore, there is a continuing need for standard methods to quantify the results of energy efficiency investments.

That's why Efficiency Valuation Organization (EVO) published IPMVP: International Performance Measurement and Verification Protocol, a guidance document describing common practice in measuring, computing and reporting savings achieved by energy efficiency projects at end user facilities.

The first edition of IPMVP was published in March 1996 and the second in 2004.

Until now, EVO has published three volumes of IPMVP:

■ Volume I : Concepts and Options for Determining Energy and Water Savings

■ Volume II : Indoor Environmental Quality (IEQ) Issues

■ Volume III : Applications

The first volume is used by Schneider Electric in energy efficiency projects.

This publication provides methods, with different levels of cost and accuracy, for determining savings either for the whole facility or for the energy efficiency action only.

IPMVP also specifies the contents of a Measurement and Verification Plan (M&V Plan) which defines all activities necessary to demonstrate the short-term performance of an industrial retrofit project and its result.

## 5.2 Principles and options of IPMVP

### Principle of IPMVP

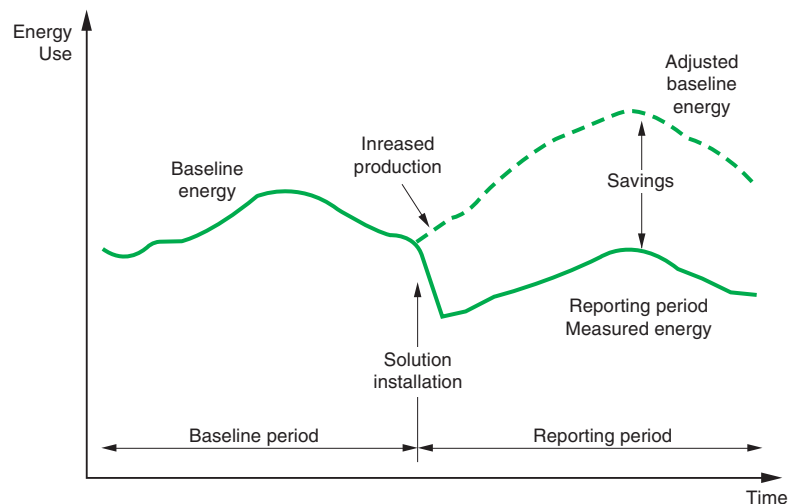


Fig. K31 : Principle of baseline definition

Before the installation of energy efficiency solution, a certain time interval is studied to determine the relationship between energy use and conditions of production, this period is called baseline. We can do the measurement during this time or more simply use the energy bill of the plant. Following the installation, this baseline relationship was used to estimate how much energy the plant would have used if there had been no solution (called the "adjusted-baseline energy"). The savings is the difference between the adjusted-baseline energy and the energy that was actually metered during the reporting period.

Savings = (Adjusted Baseline Period Use or Demand - Reporting-Period Use or Demand)  
Or

**Savings = Baseline Period Use or Demand - Reporting-Period Use or Demand ± Adjustments**

K31

### 5.3 Six qualities of IPMVP

When an M&V plan is drawn up for an IPMVP action, it must guarantee six principles:

- **Accurate:** M&V reports should be as accurate as the M&V budget will allow. M&V costs should normally be small relative to the monetary value of the savings being evaluated.
- **Complete:** The reporting of energy savings should consider all effects of a project.
- **Conservative:** Where judgements are made about uncertain quantities, M&V procedures should be designed to under-estimate savings.
- **Consistent:** The reporting of a project's energy effectiveness should be consistent between:
  - different types of energy efficiency projects;
  - different energy management professionals for any one project;
  - different periods of time for the same project;
  - and energy efficiency projects and new energy supply projects.
- **Relevant:** The determination of savings should measure the performance parameters of concern, or least well known, while other less critical or predictable parameters may be estimated.
- **Transparent:** All M&V activities should be clearly and fully disclosed.

### 5.4 IPMVP's options

	Option A	Option B	Option C	Option D
<b>Definition</b>	Retrofit isolation: key parameter measurement	Retrofit isolation: all parameter measurement	Whole facility	Calibrated simulation
<b>Description</b>	Savings are determined by field measurement of the key performance parameter(s) which define the energy use of the system affected by the energy efficiency solution. Parameters not selected for field measurement are estimated.	Savings are determined by field measurement of the energy use of the system affected by the solution.	Savings are determined by measuring energy use at the whole facility or sub-facility level. Continuous measurements of the entire facility's energy use are taken throughout the reporting period.	Savings are determined through simulation of the energy use of the whole facility, or of a sub-facility. Simulation routines are demonstrated to adequately model actual energy performance measured in the facility.
<b>Calculation of savings</b>	Engineering calculation of baseline and reporting period energy from: - short-term or continuous measurements of key operating parameter(s); and - estimated values.	Short-term or continuous measurements of baseline and reporting period energy	Analysis of whole facility baseline and reporting period data.  Routine adjustments are required, using techniques such as simple comparison or regression analysis.	Energy use simulation, calibrated with hourly or monthly utility billing data.
<b>When use this option?</b>	On one hand, this option can give a result with considerable uncertainty because of the estimation of some parameters. On the other hand, it is not expensive compared to the option B.	Option B is less cheap than option A as all parameters are measured. But if a customer asks for a high precision level, it would be a good choice.	When there is a multifaceted energy management program affecting many systems in a facility, a choice of option C can help in saving money and work.	Option D is used only when the baseline data is missed. Example: a facility where no meter existed before solution's installation and the measure of the baseline period takes too much time and money.

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## Option selection process

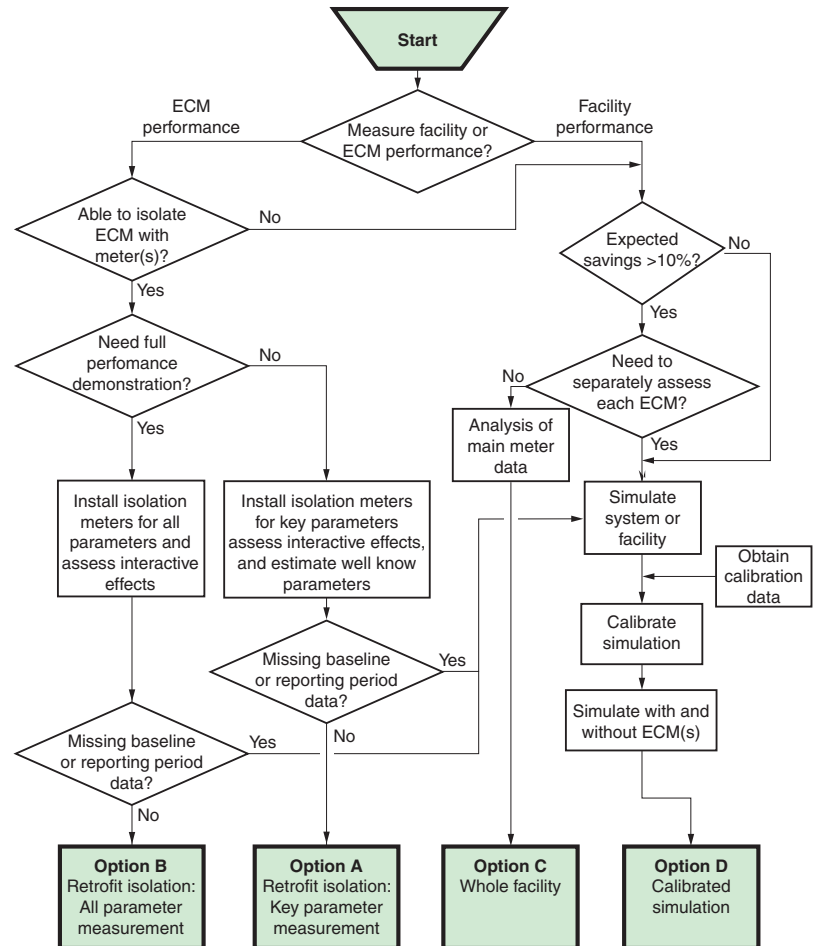
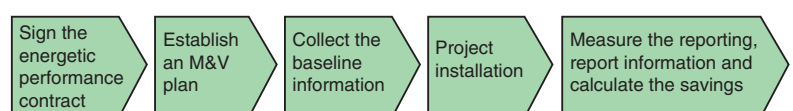


Fig. K32 : Option selection process

## 5.5 Fundamental points of an M&amp;V plan

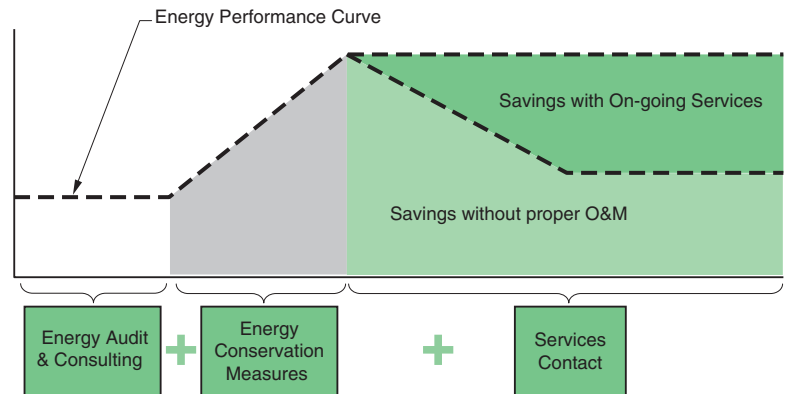
- Energy efficiency project's intent
- Selected IPMVP option and measurement boundary
- Baseline: period, energy and conditions
- Reporting period : duration and condition
- Basis for adjustment
- Analysis procedure: the data analysis procedures, algorithms and assumptions to be used.
- Energy prices
- Meter specifications
- Monitoring responsibilities
- Expected accuracy
- Budget for IPMVP activities
- Report format
- Quality assurance

## Our services with IPMVP



## 6 From returns on investment to sustained performance

Once energy audits have been conducted and energy savings measures are put in place with quantified return, it is imperative to implement follow up actions to sustain performance. Without an ongoing cycle of continuous improvement, energy performance tends to revert to a level close to that before the implementation of savings measures.



The continuous improvement cycle requires the existence, productive use and maintenance of a power monitoring system. Such system will be used for proactive on-going analysis of site energy usage, as well as recommendations for improvements to the electrical distribution system. In order to ensure optimal performance of such system and the best use of the collected data, it is industry common practice to perform the technical and operational services described below. Schneider Electric experts can deliver such services upon request.

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### 6.1 Technical support services

Power Monitoring systems which are not actively maintained tend to deteriorate for a variety of reasons.

- The software can lose communications with devices resulting in lost data.
- During the life of any software product upgrades, service packs and patches are released to address issues such as: uncovered bugs, operating system software updates, new hardware product support etc.
- Databases which are not maintained can become very large, unwieldy and even corrupt.
- The electrical distribution system itself may be changing so that the power monitoring system no longer matches it.
- Firmware updates for hardware devices are released periodically to address bugs or provide improved or additional functionality.

#### Remote services

Support is provided by email, telephone and VPN or other remote connection from the support center to the customer's server. Typical services available include:

- Toll free hotline for troubleshooting assistance
- Senior support representative assigned to site
- Free software upgrades during the contract validity
- Periodic remote system checks, maintenance and reporting
- Remote software upgrades
- 24/7 telephonic support

## 6 From returns on investment to sustained performance

### On site services

Monthly, quarterly, biannual or annual (as agreed) site visits for system maintenance. Typical services provided are:

- Install all PowerLogic software upgrades
- Perform firmware upgrades to all PowerLogic monitoring devices
- System troubleshooting to the device level
- Modification of graphic screens per customer input
- Modification of alarms and data logs per customer input
- Reconfiguration of system to match changes to the electrical distribution system

### 6.2 Operational support services

These contracts are designed to meet the need for energy analysis and improvement recommendations.

#### Hosted systems

In this scenario the user's usage data is pushed to a Schneider Electric hosted server. The user accesses his information via a web browser. Typical information made available is the following:

- Energy consumption data
- Carbon emissions data
- Degree day analysis
- Normalized performance indicators
- Regression analysis
- CUSUM analysis (Cumulative Sum)

#### On site systems

Here the user has a server at one or multiple sites. Different software packages can be in use depending on the need. The services include all the reports offered in the hosted system plus the following:

- An up front site energy audit with improvement recommendations
- Direct line to an energy consultant
- Periodic data analysis, reporting and recommendations (monthly, quarterly, biannual or annual as required)
- Consolidated data from multiple facilities
- Load profiles
- Power quality reporting





# Chapter L

## Power factor correction and harmonic filtering

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L1

# 1 Reactive energy and power factor

Alternating current systems supply two forms of energy:

- “Active” energy measured in kilowatt hours (kWh) which is converted into mechanical work, heat, light, etc
- “Reactive” energy, which again takes two forms:
  - “Reactive” energy required by inductive circuits (transformers, motors, etc.),
  - “Reactive” energy supplied by capacitive circuits (cable capacitance, power capacitors, etc)

## 1.1 The nature of reactive energy

All inductive (i.e. electromagnetic) machines and devices that operate on AC systems convert electrical energy from the power system generators into mechanical work and heat. This energy is measured by kWh meters, and is referred to as “active” or “wattful” energy. In order to perform this conversion, magnetic fields have to be established in the machines, and these fields are associated with another form of energy to be supplied from the power system, known as “reactive” or “wattless” energy.

The reason for this is that inductive circuit cyclically absorbs energy from the system (during the build-up of the magnetic fields) and re-injects that energy into the system (during the collapse of the magnetic fields) twice in every power-frequency cycle.

An exactly similar phenomenon occurs with shunt capacitive elements in a power system, such as cable capacitance or banks of power capacitors, etc. In this case, energy is stored electrostatically. The cyclic charging and discharging of capacitive circuit reacts on the generators of the system in the same manner as that described above for inductive circuit, but the current flow to and from capacitive circuit in exact phase opposition to that of the inductive circuit. This feature is the basis on which power factor correction schemes depend.

It should be noted that while this “wattless” current (more accurately, the “wattless” component of a load current) does not draw power from the system, it does cause power losses in transmission and distribution systems by heating the conductors.

In practical power systems, “wattless” components of load currents are invariably inductive, while the impedances of transmission and distribution systems are predominantly inductively reactive. The combination of inductive current passing through an inductive reactance produces the worst possible conditions of voltage drop (i.e. in direct phase opposition to the system voltage).

For these reasons (transmission power losses and voltage drop), the power-supply authorities reduce the amount of “wattless” (inductive) current as much as possible.

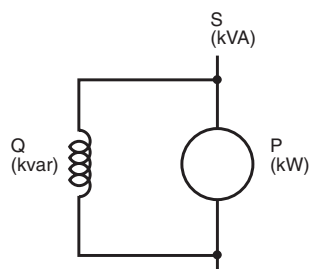
“Wattless” (capacitive) currents have the reverse effect on voltage levels and produce voltage-rises in power systems.

The power (kW) associated with “active” energy is usually represented by the letter P.

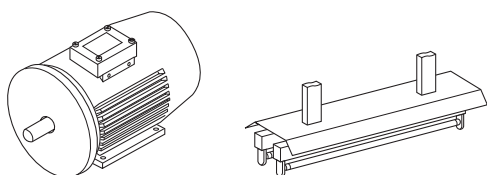
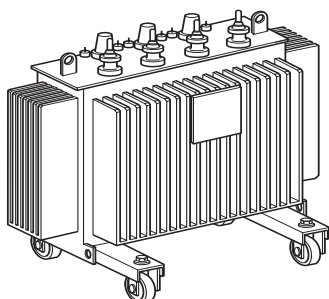
The reactive power (kvar) is represented by Q. Inductively-reactive power is conventionally positive (+ Q) while capacitively-reactive power is shown as a negative quantity (- Q).

The apparent power S (kVA) is a combination of P and Q (see **Fig. L1**).

Sub-clause 1.3 shows the relationship between P, Q, and S.



**Fig. L1** : An electric motor requires active power P and reactive power Q from the power system



**Fig. L2** : Power consuming items that also require reactive energy

## 1.2 Equipment and appliances requiring reactive energy

All AC equipment and appliances that include electromagnetic devices, or depend on magnetically-coupled windings, require some degree of reactive current to create magnetic flux.

The most common items in this class are transformers and reactors, motors and discharge lamps (with magnetic ballasts) (see **Fig. L2**).

The proportion of reactive power (kvar) with respect to active power (kW) when an item of equipment is fully loaded varies according to the item concerned being:

- 65-75% for asynchronous motors
- 5-10% for transformers

The power factor is the ratio of kW to kVA.  
The closer the power factor approaches its maximum possible value of 1, the greater the benefit to consumer and supplier.

$$PF = P \text{ (kW)} / S \text{ (kVA)}$$

P = Active power

S = Apparent power

## 1.3 The power factor

### Definition of power factor

The power factor of a load, which may be a single power-consuming item, or a number of items (for example an entire installation), is given by the ratio of P/S i.e. kW divided by kVA at any given moment.

The value of a power factor will range from 0 to 1.

If currents and voltages are perfectly sinusoidal signals, power factor equals  $\cos \varphi$ .

A power factor close to unity means that the reactive energy is small compared with the active energy, while a low value of power factor indicates the opposite condition.

### Power vector diagram

#### ■ Active power P (in kW)

□ Single phase (1 phase and neutral):  $P = V I \cos \varphi$

□ Single phase (phase to phase):  $P = U I \cos \varphi$

□ Three phase (3 wires or 3 wires + neutral):  $P = \sqrt{3} U I \cos \varphi$

#### ■ Reactive power Q (in kvar)

□ Single phase (1 phase and neutral):  $P = V I \sin \varphi$

□ Single phase (phase to phase):  $Q = U I \sin \varphi$

□ Three phase (3 wires or 3 wires + neutral):  $P = \sqrt{3} U I \sin \varphi$

#### ■ Apparent power S (in kVA)

□ Single phase (1 phase and neutral):  $S = V I$

□ Single phase (phase to phase):  $S = U I$

□ Three phase (3 wires or 3 wires + neutral):  $P = \sqrt{3} U I$

where:

V = Voltage between phase and neutral

U = Voltage between phases

I = Line current

$\varphi$  = Phase angle between vectors V and I.

□ For balanced and near-balanced loads on 4-wire systems

### Current and voltage vectors, and derivation of the power diagram

The power "vector" diagram is a useful artifice, derived directly from the true rotating vector diagram of currents and voltage, as follows:

The power-system voltages are taken as the reference quantities, and one phase only is considered on the assumption of balanced 3-phase loading.

The reference phase voltage (V) is co-incident with the horizontal axis, and the current (I) of that phase will, for practically all power-system loads, lag the voltage by an angle  $\varphi$ .

The component of I which is in phase with V is the "wattful" component of I and is equal to  $I \cos \varphi$ , while  $VI \cos \varphi$  equals the active power (in kW) in the circuit, if V is expressed in kV.

The component of I which lags 90 degrees behind V is the wattless component of I and is equal to  $I \sin \varphi$ , while  $VI \sin \varphi$  equals the reactive power (in kvar) in the circuit, if V is expressed in kV.

If the vector I is multiplied by V, expressed in kV, then VI equals the apparent power (in kVA) for the circuit.

The simple formula is obtained:  $S^2 = P^2 + Q^2$

The above kW, kvar and kVA values per phase, when multiplied by 3, can therefore conveniently represent the relationships of kVA, kW, kvar and power factor for a total 3-phase load, as shown in **Figure L3**.

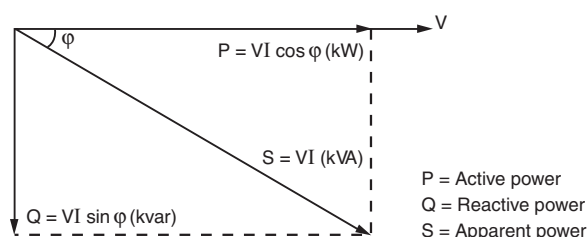


Fig. L3 : Power diagram

L3

An example of power calculations (see Fig. L4 )

Type of circuit	Apparent power S (kVA)	Active power P (kW)	Reactive power Q (kvar)
Single-phase (phase and neutral)	$S = VI$	$P = VI \cos \varphi$	$Q = VI \sin \varphi$
Single-phase (phase to phase)	$S = UI$	$P = UI \cos \varphi$	$Q = UI \sin \varphi$
Example 5 kW of load $\cos \varphi = 0.5$	10 kVA	5 kW	8.7 kvar
Three phase 3-wires or 3-wires + neutral	$S = \sqrt{3} UI$	$P = \sqrt{3} UI \cos \varphi$	$Q = \sqrt{3} UI \sin \varphi$
Example Motor $P_n = 51$ kW $\cos \varphi = 0.86$ $\rho = 0.91$ (motor efficiency)	65 kVA	56 kW	33 kvar

Fig. L4 : Example in the calculation of active and reactive power

## 1.4 Practical values of power factor

The calculations for the three-phase example above are as follows:

$P_n$  = delivered shaft power = 51 kW

$P$  = active power consumed

$$P = \frac{P_n}{\rho} = \frac{51}{0.91} = 56 \text{ kW}$$

$S$  = apparent power

$$S = \frac{P}{\cos \varphi} = \frac{56}{0.86} = 65 \text{ kVA}$$

So that, on referring to diagram Figure L5 or using a pocket calculator, the value of  $\tan \varphi$  corresponding to a  $\cos \varphi$  of 0.86 is found to be 0.59

$Q = P \tan \varphi = 56 \times 0.59 = 33 \text{ kvar}$  (see Figure L15).

Alternatively

$$Q = \sqrt{S^2 - P^2} = \sqrt{65^2 - 56^2} = 33 \text{ kvar}$$

Average power factor values for the most commonly-used equipment and appliances (see Fig. L6)

Equipment and appliances			$\cos \varphi$	$\tan \varphi$
■ Common loaded at induction motor	0%		0.17	5.80
	25%		0.55	1.52
	50%		0.73	0.94
	75%		0.80	0.75
	100%		0.85	0.62
■ Incandescent lamps			1.0	0
■ Fluorescent lamps (uncompensated)			0.5	1.73
■ Fluorescent lamps (compensated)			0.93	0.39
■ Discharge lamps			0.4 to 0.6	2.29 to 1.33
■ Ovens using resistance elements			1.0	0
■ Induction heating ovens (compensated)			0.85	0.62
■ Dielectric type heating ovens			0.85	0.62
■ Resistance-type soldering machines			0.8 to 0.9	0.75 to 0.48
■ Fixed 1-phase arc-welding set			0.5	1.73
■ Arc-welding motor-generating set			0.7 to 0.9	1.02 to 0.48
■ Arc-welding transformer-rectifier set			0.7 to 0.8	1.02 to 0.75
■ Arc furnace			0.8	0.75

Fig. L6 : Values of  $\cos \varphi$  and  $\tan \varphi$  for commonly-used equipment

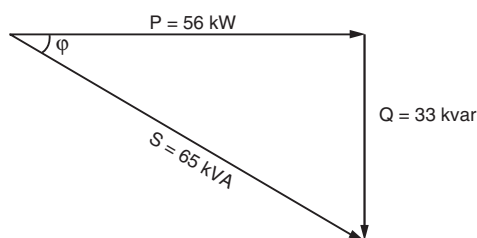


Fig. L5 : Calculation power diagram

## 2 Why to improve the power factor?

*An improvement of the power factor of an installation presents several technical and economic advantages, notably in the reduction of electricity bills*

### 2.1 Reduction in the cost of electricity

Good management in the consumption of reactive energy brings economic advantages.

These notes are based on an actual tariff structure commonly applied in Europe, designed to encourage consumers to minimize their consumption of reactive energy.

The installation of power-factor correction capacitors on installations permits the consumer to reduce his electricity bill by maintaining the level of reactive-power consumption below a value contractually agreed with the power supply authority. In this particular tariff, reactive energy is billed according to the  $\tan \varphi$  criterion.

As previously noted:

$$\tan \varphi = \frac{Q \text{ (kvarh)}}{P \text{ (kWh)}}$$

The power supply authority delivers reactive energy for free:

■ If the reactive energy represents less than 40% of the active energy ( $\tan \varphi < 0.4$ ) for a maximum period of 16 hours each day (from 06-00 h to 22-00 h) during the most-heavily loaded period (often in winter)

■ Without limitation during light-load periods in winter, and in spring and summer. During the periods of limitation, reactive energy consumption exceeding 40% of the active energy (i.e.  $\tan \varphi > 0.4$ ) is billed monthly at the current rates. Thus, the quantity of reactive energy billed in these periods will be:

kvarh (to be billed) = kWh ( $\tan \varphi > 0.4$ ) where:

- kWh is the active energy consumed during the periods of limitation
- kWh  $\tan \varphi$  is the total reactive energy during a period of limitation
- 0.4 kWh is the amount of reactive energy delivered free during a period of limitation

$\tan \varphi = 0.4$  corresponds to a power factor of 0.93 so that, if steps are taken to ensure that during the limitation periods the power factor never falls below 0.93, the consumer will have nothing to pay for the reactive power consumed.

Against the financial advantages of reduced billing, the consumer must balance the cost of purchasing, installing and maintaining the power factor improvement capacitors and controlling switchgear, automatic control equipment (where stepped levels of compensation are required) together with the additional kWh consumed by the dielectric losses of the capacitors, etc. It may be found that it is more economic to provide partial compensation only, and that paying for some of the reactive energy consumed is less expensive than providing 100% compensation.

The question of power-factor correction is a matter of optimization, except in very simple cases.

*Power factor improvement allows the use of smaller transformers, switchgear and cables, etc. as well as reducing power losses and voltage drop in an installation*

### 2.2 Technical/economic optimization

A high power factor allows the optimization of the components of an installation. Overrating of certain equipment can be avoided, but to achieve the best results, the correction should be effected as close to the individual inductive items as possible.

#### Reduction of cable size

**Figure L7** shows the required increase in the size of cables as the power factor is reduced from unity to 0.4, for the same active power transmitted.

Multiplying factor for the cross-sectional area of the cable core(s)	1	1.25	1.67	2.5
$\cos \varphi$	1	0.8	0.6	0.4

**Fig. L7** : Multiplying factor for cable size as a function of  $\cos \varphi$

## 2 Why to improve the power factor?

### Reduction of losses (P, kW) in cables

Losses in cables are proportional to the current squared, and are measured by the kWh meter of the installation. Reduction of the total current in a conductor by 10% for example, will reduce the losses by almost 20%.

### Reduction of voltage drop

Power factor correction capacitors reduce or even cancel completely the (inductive) reactive current in upstream conductors, thereby reducing or eliminating voltage drops.

**Note:** Over compensation will produce a voltage rise at the capacitor level.

### Increase in available power

By improving the power factor of a load supplied from a transformer, the current through the transformer will be reduced, thereby allowing more load to be added. In practice, it may be less expensive to improve the power factor <sup>(1)</sup>, than to replace the transformer by a larger unit.

This matter is further elaborated in clause 6.

(1) Since other benefits are obtained from a high value of power factor, as previously noted.

Improving the power factor of an installation requires a bank of capacitors which acts as a source of reactive energy. This arrangement is said to provide reactive energy compensation

## 3.1 Theoretical principles

An inductive load having a low power factor requires the generators and transmission/distribution systems to pass reactive current (lagging the system voltage by 90 degrees) with associated power losses and exaggerated voltage drops, as noted in sub-clause 1.1. If a bank of shunt capacitors is added to the load, its (capacitive) reactive current will take the same path through the power system as that of the load reactive current. Since, as pointed out in sub-clause 1.1, this capacitive current  $I_c$  (which leads the system voltage by 90 degrees) is in direct phase opposition to the load reactive current ( $I_L$ ), the two components flowing through the same path will cancel each other, such that if the capacitor bank is sufficiently large and  $I_c = I_L$  there will be no reactive current flow in the system upstream of the capacitors.

This is indicated in **Figure L8 (a)** and **(b)** which show the flow of the reactive components of current only.

In this figure:

R represents the active-power elements of the load

L represents the (inductive) reactive-power elements of the load

C represents the (capacitive) reactive-power elements of the power-factor correction equipment (i.e. capacitors).

It will be seen from diagram **(b)** of **Figure L9**, that the capacitor bank C appears to be supplying all the reactive current of the load. For this reason, capacitors are sometimes referred to as “generators of lagging vars”.

In diagram **(c)** of **Figure L9**, the active-power current component has been added, and shows that the (fully-compensated) load appears to the power system as having a power factor of 1.

In general, it is not economical to fully compensate an installation.

Figure L9 uses the power diagram discussed in sub-clause 1.3 (see Fig. L3) to illustrate the principle of compensation by reducing a large reactive power Q to a smaller value Q' by means of a bank of capacitors having a reactive power Qc.

In doing so, the magnitude of the apparent power S is seen to reduce to S'.

### Example:

A motor consumes 100 kW at a power factor of 0.75 (i.e.  $\tan \phi = 0.88$ ). To improve the power factor to 0.93 (i.e.  $\tan \phi' = 0.4$ ), the reactive power of the capacitor bank must be :  $Q_c = 100 (0.88 - 0.4) = 48 \text{ kvar}$

The selected level of compensation and the calculation of rating for the capacitor bank depend on the particular installation. The factors requiring attention are explained in a general way in clause 5, and in clauses 6 and 7 for transformers and motors.

**Note:** Before starting a compensation project, a number of precautions should be observed. In particular, oversizing of motors should be avoided, as well as the no-load running of motors. In this latter condition, the reactive energy consumed by a motor results in a very low power factor ( $\approx 0.17$ ); this is because the kW taken by the motor (when it is unloaded) are very small.

## 3.2 By using what equipment?

### Compensation at LV

At low voltage, compensation is provided by:

- Fixed-value capacitor
- Equipment providing automatic regulation, or banks which allow continuous adjustment according to requirements, as loading of the installation changes

**Note:** When the installed reactive power of compensation exceeds 800 kvar, and the load is continuous and stable, it is often found to be economically advantageous to instal capacitor banks at the medium voltage level.

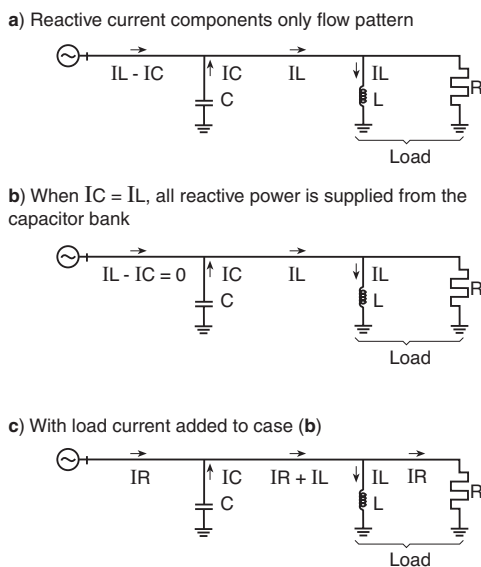


Fig. L8 : Showing the essential features of power-factor correction

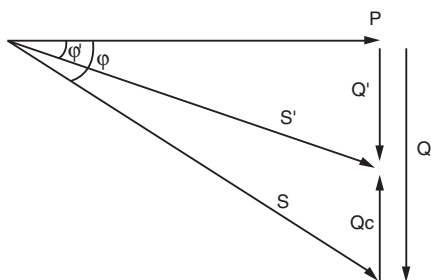


Fig. L9 : Diagram showing the principle of compensation:  $Q_c = P (\tan \phi - \tan \phi')$

*Compensation can be carried out by a fixed value of capacitance in favourable circumstances*

### Fixed capacitors (see Fig. L10)

This arrangement employs one or more capacitor(s) to form a constant level of compensation. Control may be:

- Manual: by circuit-breaker or load-break switch
- Semi-automatic: by contactor
- Direct connection to an appliance and switched with it

These capacitors are applied:

- At the terminals of inductive devices (motors and transformers)
- At busbars supplying numerous small motors and inductive appliance for which individual compensation would be too costly
- In cases where the level of load is reasonably constant



**Fig. L10** : Example of fixed-value compensation capacitors

*Compensation is more-commonly effected by means of an automatically-controlled stepped bank of capacitors*

### Automatic capacitor banks (see Fig. L11)

This kind of equipment provides automatic control of compensation, maintaining the power factor within close limits around a selected level. Such equipment is applied at points in an installation where the active-power and/or reactive-power variations are relatively large, for example:

- At the busbars of a general power distribution board
- At the terminals of a heavily-loaded feeder cable



**Fig. L11** : Example of automatic-compensation-regulating equipment



*Automatically-regulated banks of capacitors allow an immediate adaptation of compensation to match the level of load*

## The principles of, and reasons, for using automatic compensation

A bank of capacitors is divided into a number of sections, each of which is controlled by a contactor. Closure of a contactor switches its section into parallel operation with other sections already in service. The size of the bank can therefore be increased or decreased in steps, by the closure and opening of the controlling contactors.

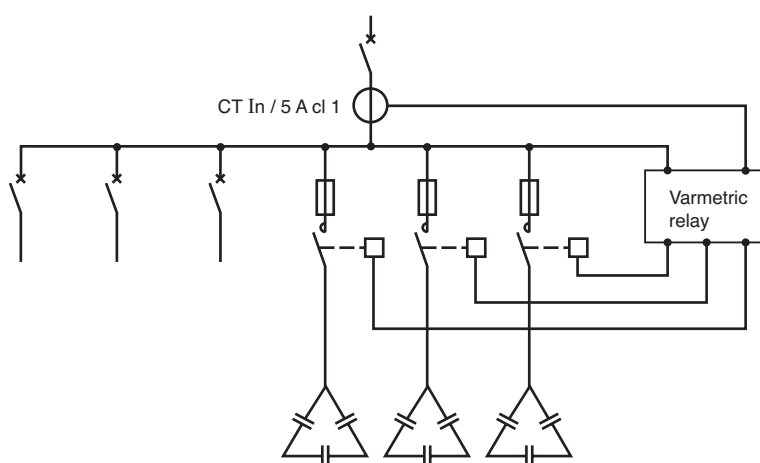
A control relay monitors the power factor of the controlled circuit(s) and is arranged to close and open appropriate contactors to maintain a reasonably constant system power factor (within the tolerance imposed by the size of each step of compensation). The current transformer for the monitoring relay must evidently be placed on one phase of the incoming cable which supplies the circuit(s) being controlled, as shown in **Figure L12**.

A Varset Fast capacitor bank is an automatic power factor correction equipment including static contactors (thyristors) instead of usual contactors. Static correction is particularly suitable for a certain number of installations using equipment with fast cycle and/or sensitive to transient surges.

The advantages of static contactors are :

- Immediate response to all power factor fluctuation (response time 2 s or 40 ms according to regulator option)
- Unlimited number of operations
- Elimination of transient phenomena on the network on capacitor switching
- Fully silent operation

By closely matching compensation to that required by the load, the possibility of producing overvoltages at times of low load will be avoided, thereby preventing an overvoltage condition, and possible damage to appliances and equipment. Overvoltages due to excessive reactive compensation depend partly on the value of source impedance.



**Fig. L12** : The principle of automatic-compensation control

## 3.3 The choice between a fixed or automatically-regulated bank of capacitors

### Commonly-applied rules

Where the kvar rating of the capacitors is less than, or equal to 15% of the supply transformer rating, a fixed value of compensation is appropriate. Above the 15% level, it is advisable to install an automatically-controlled bank of capacitors.

The location of low-voltage capacitors in an installation constitutes the mode of compensation, which may be global (one location for the entire installation), partial (section-by-section), local (at each individual device), or some combination of the latter two. In principle, the ideal compensation is applied at a point of consumption and at the level required at any instant.

In practice, technical and economic factors govern the choice.

## 4 Where to install correction capacitors?

Where a load is continuous and stable, global compensation can be applied

### 4.1 Global compensation (see Fig. L13)

#### Principle

The capacitor bank is connected to the busbars of the main LV distribution board for the installation, and remains in service during the period of normal load.

#### Advantages

The global type of compensation:

- Reduces the tariff penalties for excessive consumption of kvars
- Reduces the apparent power kVA demand, on which standing charges are usually based
- Relieves the supply transformer, which is then able to accept more load if necessary

#### Comments

- Reactive current still flows in all conductors of cables leaving (i.e. downstream of) the main LV distribution board
- For the above reason, the sizing of these cables, and power losses in them, are not improved by the global mode of compensation.

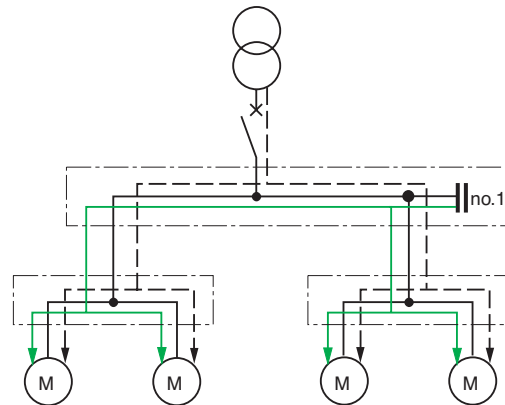


Fig. L13 : Global compensation

Compensation by sector is recommended when the installation is extensive, and where the load/time patterns differ from one part of the installation to another

### 4.2 Compensation by sector (see Fig. L14)

#### Principle

Capacitor banks are connected to busbars of each local distribution board, as shown in Figure L14.

A significant part of the installation benefits from this arrangement, notably the feeder cables from the main distribution board to each of the local distribution boards at which the compensation measures are applied.

#### Advantages

The compensation by sector:

- Reduces the tariff penalties for excessive consumption of kvars
- Reduces the apparent power kVA demand, on which standing charges are usually based
- Relieves the supply transformer, which is then able to accept more load if necessary
- The size of the cables supplying the local distribution boards may be reduced, or will have additional capacity for possible load increases
- Losses in the same cables will be reduced

#### Comments

- Reactive current still flows in all cables downstream of the local distribution boards
- For the above reason, the sizing of these cables, and the power losses in them, are not improved by compensation by sector
- Where large changes in loads occur, there is always a risk of overcompensation and consequent overvoltage problems

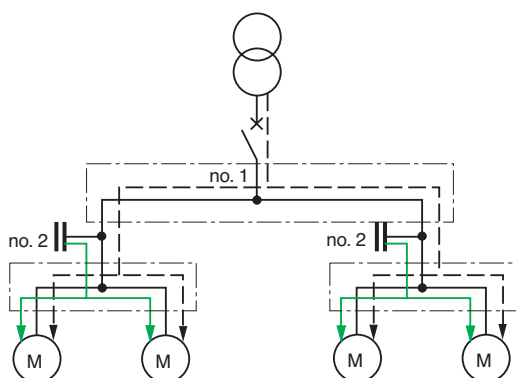


Fig. L14 : Compensation by sector

## 4 Where to install correction capacitors?

*Individual compensation should be considered when the power of motor is significant with respect to power of the installation*

### 4.3 Individual compensation

#### Principle

Capacitors are connected directly to the terminals of inductive circuit (notably motors, see further in Clause 7). Individual compensation should be considered when the power of the motor is significant with respect to the declared power requirement (kVA) of the installation.

The kvar rating of the capacitor bank is in the order of 25% of the kW rating of the motor. Complementary compensation at the origin of the installation (transformer) may also be beneficial.

#### Advantages

Individual compensation:

- Reduces the tariff penalties for excessive consumption of kvars
- Reduces the apparent power kVA demand
- Reduces the size of all cables as well as the cable losses

#### Comments

- Significant reactive currents no longer exist in the installation

## 5 How to decide the optimum level of compensation?

### 5.1 General method

#### Listing of reactive power demands at the design stage

This listing can be made in the same way (and at the same time) as that for the power loading described in chapter A. The levels of active and reactive power loading, at each level of the installation (generally at points of distribution and sub-distribution of circuits) can then be determined.

#### Technical-economic optimization for an existing installation

The optimum rating of compensation capacitors for an existing installation can be determined from the following principal considerations:

- Electricity bills prior to the installation of capacitors
- Future electricity bills anticipated following the installation of capacitors
- Costs of:
  - Purchase of capacitors and control equipment (contactors, relaying, cabinets, etc.)
  - Installation and maintenance costs
  - Cost of dielectric heating losses in the capacitors, versus reduced losses in cables, transformer, etc., following the installation of capacitors

Several simplified methods applied to typical tariffs (common in Europe) are shown in sub-clauses 5.3 and 5.4.

### 5.2 Simplified method

#### General principle

An approximate calculation is generally adequate for most practical cases, and may be based on the assumption of a power factor of 0.8 (lagging) before compensation. In order to improve the power factor to a value sufficient to avoid tariff penalties (this depends on local tariff structures, but is assumed here to be 0.93) and to reduce losses, volt-drops, etc. in the installation, reference can be made to **Figure L15** next page.

From the figure, it can be seen that, to raise the power factor of the installation from 0.8 to 0.93 will require 0.355 kvar per kW of load. The rating of a bank of capacitors at the busbars of the main distribution board of the installation would be

$$Q \text{ (kvar)} = 0.355 \times P \text{ (kW)}.$$

This simple approach allows a rapid determination of the compensation capacitors required, albeit in the global, partial or independent mode.

#### Example

It is required to improve the power factor of a 666 kVA installation from 0.75 to 0.928. The active power demand is  $666 \times 0.75 = 500 \text{ kW}$ .

In Figure L15, the intersection of the row  $\cos \varphi = 0.75$  (before correction) with the column  $\cos \varphi = 0.93$  (after correction) indicates a value of 0.487 kvar of compensation per kW of load.

For a load of 500 kW, therefore,  $500 \times 0.487 = 244 \text{ kvar}$  of capacitive compensation is required.

**Note:** this method is valid for any voltage level, i.e. is independent of voltage.

# 5 How to decide the optimum level of compensation?

Before compensation		kvar rating of capacitor bank to install per kW of load, to improve cos φ (the power factor) or tan φ, to a given value													
		tan φ	0.75	0.59	0.48	0.46	0.43	0.40	0.36	0.33	0.29	0.25	0.20	0.14	0.0
tan φ	cos φ	cos φ	0.80	0.86	0.90	0.91	0.92	0.93	0.94	0.95	0.96	0.97	0.98	0.99	1
2.29	0.40		1.557	1.691	1.805	1.832	1.861	1.895	1.924	1.959	1.998	2.037	2.085	2.146	2.288
2.22	0.41		1.474	1.625	1.742	1.769	1.798	1.831	1.840	1.896	1.935	1.973	2.021	2.082	2.225
2.16	0.42		1.413	1.561	1.681	1.709	1.738	1.771	1.800	1.836	1.874	1.913	1.961	2.022	2.164
2.10	0.43		1.356	1.499	1.624	1.651	1.680	1.713	1.742	1.778	1.816	1.855	1.903	1.964	2.107
2.04	0.44		1.290	1.441	1.558	1.585	1.614	1.647	1.677	1.712	1.751	1.790	1.837	1.899	2.041
1.98	0.45		1.230	1.384	1.501	1.532	1.561	1.592	1.628	1.659	1.695	1.737	1.784	1.846	1.988
1.93	0.46		1.179	1.330	1.446	1.473	1.502	1.533	1.567	1.600	1.636	1.677	1.725	1.786	1.929
1.88	0.47		1.130	1.278	1.397	1.425	1.454	1.485	1.519	1.532	1.588	1.629	1.677	1.758	1.881
1.83	0.48		1.076	1.228	1.343	1.370	1.400	1.430	1.464	1.497	1.534	1.575	1.623	1.684	1.826
1.78	0.49		1.030	1.179	1.297	1.326	1.355	1.386	1.420	1.453	1.489	1.530	1.578	1.639	1.782
1.73	0.50		0.982	1.232	1.248	1.276	1.303	1.337	1.369	1.403	1.441	1.481	1.529	1.590	1.732
1.69	0.51		0.936	1.087	1.202	1.230	1.257	1.291	1.323	1.357	1.395	1.435	1.483	1.544	1.686
1.64	0.52		0.894	1.043	1.160	1.188	1.215	1.249	1.281	1.315	1.353	1.393	1.441	1.502	1.644
1.60	0.53		0.850	1.000	1.116	1.144	1.171	1.205	1.237	1.271	1.309	1.349	1.397	1.458	1.600
1.56	0.54		0.809	0.959	1.075	1.103	1.130	1.164	1.196	1.230	1.268	1.308	1.356	1.417	1.559
1.52	0.55		0.769	0.918	1.035	1.063	1.090	1.124	1.156	1.190	1.228	1.268	1.316	1.377	1.519
1.48	0.56		0.730	0.879	0.996	1.024	1.051	1.085	1.117	1.151	1.189	1.229	1.277	1.338	1.480
1.44	0.57		0.692	0.841	0.958	0.986	1.013	1.047	1.079	1.113	1.151	1.191	1.239	1.300	1.442
1.40	0.58		0.665	0.805	0.921	0.949	0.976	1.010	1.042	1.076	1.114	1.154	1.202	1.263	1.405
1.37	0.59		0.618	0.768	0.884	0.912	0.939	0.973	1.005	1.039	1.077	1.117	1.165	1.226	1.368
1.33	0.60		0.584	0.733	0.849	0.878	0.905	0.939	0.971	1.005	1.043	1.083	1.131	1.192	1.334
1.30	0.61		0.549	0.699	0.815	0.843	0.870	0.904	0.936	0.970	1.008	1.048	1.096	1.157	1.299
1.27	0.62		0.515	0.665	0.781	0.809	0.836	0.870	0.902	0.936	0.974	1.014	1.062	1.123	1.265
1.23	0.63		0.483	0.633	0.749	0.777	0.804	0.838	0.870	0.904	0.942	0.982	1.030	1.091	1.233
1.20	0.64		0.450	0.601	0.716	0.744	0.771	0.805	0.837	0.871	0.909	0.949	0.997	1.058	1.200
1.17	0.65		0.419	0.569	0.685	0.713	0.740	0.774	0.806	0.840	0.878	0.918	0.966	1.007	1.169
1.14	0.66		0.388	0.538	0.654	0.682	0.709	0.743	0.775	0.809	0.847	0.887	0.935	0.996	1.138
1.11	0.67		0.358	0.508	0.624	0.652	0.679	0.713	0.745	0.779	0.817	0.857	0.905	0.966	1.108
1.08	0.68		0.329	0.478	0.595	0.623	0.650	0.684	0.716	0.750	0.788	0.828	0.876	0.937	1.079
1.05	0.69		0.299	0.449	0.565	0.593	0.620	0.654	0.686	0.720	0.758	0.798	0.840	0.907	1.049
1.02	0.70		0.270	0.420	0.536	0.564	0.591	0.625	0.657	0.691	0.729	0.769	0.811	0.878	1.020
0.99	0.71		0.242	0.392	0.508	0.536	0.563	0.597	0.629	0.663	0.701	0.741	0.783	0.850	0.992
0.96	0.72		0.213	0.364	0.479	0.507	0.534	0.568	0.600	0.634	0.672	0.712	0.754	0.821	0.963
0.94	0.73		0.186	0.336	0.452	0.480	0.507	0.541	0.573	0.607	0.645	0.685	0.727	0.794	0.936
0.91	0.74		0.159	0.309	0.425	0.453	0.480	0.514	0.546	0.580	0.618	0.658	0.700	0.767	0.909
0.88	0.75		0.132	0.282	0.398	0.426	0.453	0.487	0.519	0.553	0.591	0.631	0.673	0.740	0.882
0.86	0.76		0.105	0.255	0.371	0.399	0.426	0.460	0.492	0.526	0.564	0.604	0.652	0.713	0.855
0.83	0.77		0.079	0.229	0.345	0.373	0.400	0.434	0.466	0.500	0.538	0.578	0.620	0.687	0.829
0.80	0.78		0.053	0.202	0.319	0.347	0.374	0.408	0.440	0.474	0.512	0.552	0.594	0.661	0.803
0.78	0.79		0.026	0.176	0.292	0.320	0.347	0.381	0.413	0.447	0.485	0.525	0.567	0.634	0.776
0.75	0.80			0.150	0.266	0.294	0.321	0.355	0.387	0.421	0.459	0.499	0.541	0.608	0.750
0.72	0.81			0.124	0.240	0.268	0.295	0.329	0.361	0.395	0.433	0.473	0.515	0.582	0.724
0.70	0.82			0.098	0.214	0.242	0.269	0.303	0.335	0.369	0.407	0.447	0.489	0.556	0.698
0.67	0.83			0.072	0.188	0.216	0.243	0.277	0.309	0.343	0.381	0.421	0.463	0.530	0.672
0.65	0.84			0.046	0.162	0.190	0.217	0.251	0.283	0.317	0.355	0.395	0.437	0.504	0.645
0.62	0.85			0.020	0.136	0.164	0.191	0.225	0.257	0.291	0.329	0.369	0.417	0.478	0.620
0.59	0.86				0.109	0.140	0.167	0.198	0.230	0.264	0.301	0.343	0.390	0.450	0.593
0.57	0.87				0.083	0.114	0.141	0.172	0.204	0.238	0.275	0.317	0.364	0.424	0.567
0.54	0.88				0.054	0.085	0.112	0.143	0.175	0.209	0.246	0.288	0.335	0.395	0.538
0.51	0.89				0.028	0.059	0.086	0.117	0.149	0.183	0.230	0.262	0.309	0.369	0.512
0.48	0.90					0.031	0.058	0.089	0.121	0.155	0.192	0.234	0.281	0.341	0.484

Value selected as an example on section 5.2

Value selected as an example on section 5.4

Fig. L15 : kvar to be installed per kW of load, to improve the power factor of an installation

L13

*In the case of certain (common) types of tariff, an examination of several bills covering the most heavily-loaded period of the year allows determination of the kvar level of compensation required to avoid kvarh (reactive-energy) charges. The pay-back period of a bank of power-factor-correction capacitors and associated equipment is generally about 18 months*

## 5.3 Method based on the avoidance of tariff penalties

The following method allows calculation of the rating of a proposed capacitor bank, based on billing details, where the tariff structure corresponds with (or is similar to) the one described in sub-clause 2.1 of this chapter.

The method determines the minimum compensation required to avoid these charges which are based on kvarh consumption.

The procedure is as follows:

■ Refer to the bills covering consumption for the 5 months of winter (in France these are November to March inclusive).

**Note:** in tropical climates the summer months may constitute the period of heaviest loading and highest peaks (owing to extensive air conditioning loads) so that a consequent variation of high-tariff periods is necessary in this case. The remainder of this example will assume Winter conditions in France.

■ Identify the line on the bills referring to “reactive-energy consumed” and “kvarh to be charged”. Choose the bill which shows the highest charge for kvarh (after checking that this was not due to some exceptional situation).

For example: 15,966 kvarh in January.

■ Evaluate the total period of loaded operation of the installation for that month, for instance: 220 hours (22 days x 10 hours). The hours which must be counted are those occurring during the heaviest load and the highest peak loads occurring on the power system. These are given in the tariff documents, and are (commonly) during a 16-hour period each day, either from 06.00 h to 22.00 h or from 07.00 h to 23.00 h according to the region. Outside these periods, no charge is made for kvarh consumption.

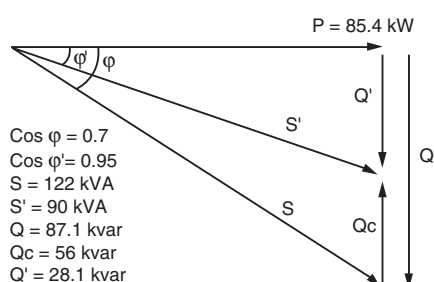
■ The necessary value of compensation in kvar = kvarh billed/number of hours of operation<sup>(1)</sup> = Qc

The rating of the installed capacitor bank is generally chosen to be slightly larger than that calculated.

Certain manufacturers can provide “slide rules” especially designed to facilitate these kinds of calculation, according to particular tariffs. These devices and accompanying documentation advice on suitable equipment and control schemes, as well as drawing attention to constraints imposed by harmonic voltages on the power system. Such voltages require either over dimensioned capacitors (in terms of heat-dissipation, voltage and current ratings) and/or harmonic-suppression inductors or filters.

L14

*For 2-part tariffs based partly on a declared value of kVA, Figure L17 allows determination of the kvar of compensation required to reduce the value of kVA declared, and to avoid exceeding it*



**Fig. L16 :** Reduction of declared maximum kVA by power-factor improvement

## 5.4 Method based on reduction of declared maximum apparent power (kVA)

For consumers whose tariffs are based on a fixed charge per kVA declared, plus a charge per kWh consumed, it is evident that a reduction in declared kVA would be beneficial. The diagram of **Figure L16** shows that as the power factor improves, the kVA value diminishes for a given value of kW (P). The improvement of the power factor is aimed at (apart from other advantages previously mentioned) reducing the declared level and never exceeding it, thereby avoiding the payment of an excessive price per kVA during the periods of excess, and/or tripping of the the main circuit-breaker. Figure L15 (previous page) indicates the value of kvar of compensation per kW of load, required to improve from one value of power factor to another.

**Example:**

A supermarket has a declared load of 122 kVA at a power factor of 0.7 lagging, i.e. an active-power load of 85.4 kW. The particular contract for this consumer was based on stepped values of declared kVA (in steps of 6 kVA up to 108 kVA, and 12 kVA steps above that value, this is a common feature in many types of two-part tariff). In the case being considered, the consumer was billed on the basis of 132 kVA. Referring to Figure L15, it can be seen that a 60 kvar bank of capacitors will improve the power factor of the load from 0.7 to 0.95 ( $0.691 \times 85.4 = 59 \text{ kvar}$

in the figure). The declared value of kVA will then be  $\frac{85.4}{0.95} = 90 \text{ kVA}$ , i.e. an improvement of 30%.

(1) In the billing period, during the hours for which reactive energy is charged for the case considered above:

$$Q_c = \frac{15,996 \text{ kvarh}}{220 \text{ h}} = 73 \text{ kvar}$$

## 6 Compensation at the terminals of a transformer

The installation of a capacitor bank can avoid the need to change a transformer in the event of a load increase

### 6.1 Compensation to increase the available active power output

Steps similar to those taken to reduce the declared maximum kVA, i.e. improvement of the load power factor, as discussed in subclause 5.4, will maximise the available transformer capacity, i.e. to supply more active power.

Cases can arise where the replacement of a transformer by a larger unit, to overcome a load growth, may be avoided by this means. Figure L17 shows directly the power (kW) capability of fully-loaded transformers at different load power factors, from which the increase of active-power output can be obtained as the value of power factor increases.

tan φ	cos φ	Nominal rating of transformers (in kVA)											
		100	160	250	315	400	500	630	800	1000	1250	1600	2000
0.00	1	100	160	250	315	400	500	630	800	1000	1250	1600	2000
0.20	0.98	98	157	245	309	392	490	617	784	980	1225	1568	1960
0.29	0.96	96	154	240	302	384	480	605	768	960	1200	1536	1920
0.36	0.94	94	150	235	296	376	470	592	752	940	1175	1504	1880
0.43	0.92	92	147	230	290	368	460	580	736	920	1150	1472	1840
0.48	0.90	90	144	225	284	360	450	567	720	900	1125	1440	1800
0.54	0.88	88	141	220	277	352	440	554	704	880	1100	1408	1760
0.59	0.86	86	138	215	271	344	430	541	688	860	1075	1376	1720
0.65	0.84	84	134	210	265	336	420	529	672	840	1050	1344	1680
0.70	0.82	82	131	205	258	328	410	517	656	820	1025	1312	1640
0.75	0.80	80	128	200	252	320	400	504	640	800	1000	1280	1600
0.80	0.78	78	125	195	246	312	390	491	624	780	975	1248	1560
0.86	0.76	76	122	190	239	304	380	479	608	760	950	1216	1520
0.91	0.74	74	118	185	233	296	370	466	592	740	925	1184	1480
0.96	0.72	72	115	180	227	288	360	454	576	720	900	1152	1440
1.02	0.70	70	112	175	220	280	350	441	560	700	875	1120	1400

Fig. L17 : Active-power capability of fully-loaded transformers, when supplying loads at different values of power factor

**Example:** (see Fig. L18 )

An installation is supplied from a 630 kVA transformer loaded at 450 kW (P1) with a mean power factor of 0.8 lagging. The apparent power  $S_1 = \frac{450}{0.8} = 562$  kVA

The corresponding reactive power

$$Q_1 = \sqrt{S_1^2 - P_1^2} = 337 \text{ kvar}$$

The anticipated load increase P2 = 100 kW at a power factor of 0.7 lagging.

The apparent power  $S_2 = \frac{100}{0.7} = 143$  kVA

The corresponding reactive power

$$Q_2 = \sqrt{S_2^2 - P_2^2} = 102 \text{ kvar}$$

What is the minimum value of capacitive kvar to be installed, in order to avoid a change of transformer?

Total power now to be supplied:

$$P = P_1 + P_2 = 550 \text{ kW}$$

The maximum reactive power capability of the 630 kVA transformer when delivering 550 kW is:

$$Q_m = \sqrt{S^2 - P^2} \quad Q_m = \sqrt{630^2 - 550^2} = 307 \text{ kvar}$$

Total reactive power required by the installation before compensation:

$$Q_1 + Q_2 = 337 + 102 = 439 \text{ kvar}$$

So that the minimum size of capacitor bank to install:

$$Q_{\text{kvar}} = 439 - 307 = 132 \text{ kvar}$$

It should be noted that this calculation has not taken account of load peaks and their duration.

The best possible improvement, i.e. correction which attains a power factor of 1 would permit a power reserve for the transformer of  $630 - 550 = 80$  kW.

The capacitor bank would then have to be rated at 439 kvar.

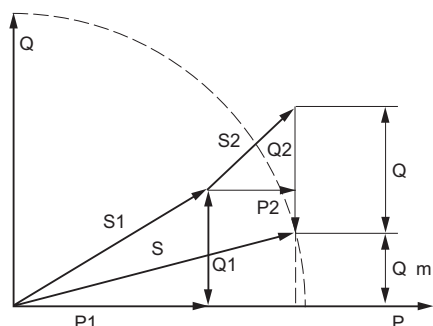


Fig. L18 : Compensation Q allows the installation-load extension S2 to be added, without the need to replace the existing transformer, the output of which is limited to S



Where metering is carried out at the MV side of a transformer, the reactive-energy losses in the transformer may need to be compensated (depending on the tariff)

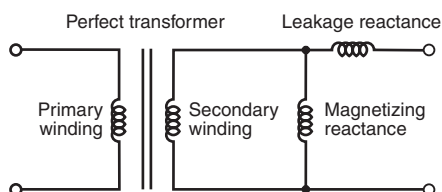


Fig. L19 : Transformer reactances per phase

The reactive power absorbed by a transformer cannot be neglected, and can amount to (about) 5% of the transformer rating when supplying its full load. Compensation can be provided by a bank of capacitors. In transformers, reactive power is absorbed by both shunt (magnetizing) and series (leakage flux) reactances. Complete compensation can be provided by a bank of shunt-connected LV capacitors

## 6.2 Compensation of reactive energy absorbed by the transformer

### The nature of transformer inductive reactances

All previous references have been to shunt connected devices such as those used in normal loads, and power factor-correcting capacitor banks etc. The reason for this is that shunt connected equipment requires (by far) the largest quantities of reactive energy in power systems; however, series-connected reactances, such as the inductive reactances of power lines and the leakage reactance of transformer windings, etc., also absorb reactive energy.

Where metering is carried out at the MV side of a transformer, the reactive-energy losses in the transformer may (depending on the tariff) need to be compensated. As far as reactive-energy losses only are concerned, a transformer may be represented by the elementary diagram of **Figure L19**. All reactance values are referred to the secondary side of the transformer, where the shunt branch represents the magnetizing-current path. The magnetizing current remains practically constant (at about 1.8% of full-load current) from no load to full load, in normal circumstances, i.e. with a constant primary voltage, so that a shunt capacitor of fixed value can be installed at the MV or LV side, to compensate for the reactive energy absorbed.

### Reactive-power absorption in series-connected (leakage flux) reactance $X_L$

A simple illustration of this phenomenon is given by the vector diagram of **Figure L20**.

The reactive-current component through the load =  $I \sin \phi$  so that  $Q_L = VI \sin \phi$ .

The reactive-current component from the source =  $I \sin \phi'$  so that  $Q_E = EI \sin \phi'$ .

It can be seen that  $E > V$  and  $\sin \phi' > \sin \phi$ .

The difference between  $EI \sin \phi'$  and  $VI \sin \phi$  gives the kvar per phase absorbed by  $X_L$ .

It can be shown that this kvar value is equal to  $I^2 X_L$  (which is analogous to the  $I^2 R$  active power (kW) losses due to the series resistance of power lines, etc.).

From the  $I^2 X_L$  formula it is very simple to deduce the kvar absorbed at any load value for a given transformer, as follows:

If per-unit values are used (instead of percentage values) direct multiplication of  $I$  and  $X_L$  can be carried out.

#### Example:

A 630 kVA transformer with a short-circuit reactance voltage of 4% is fully loaded.

What is its reactive-power (kvar) loss?

$4\% = 0.04 \text{ pu}$   $I_{pu} = 1$

loss =  $I^2 X_L = 1^2 \times 0.04 = 0.04 \text{ pu kvar}$

where 1 pu = 630 kVA

The 3-phase kvar losses are  $630 \times 0.04 = 25.2 \text{ kvar}$  (or, quite simply, 4% of 630 kVA).

At half load i.e.  $I = 0.5 \text{ pu}$  the losses will be

$0.5^2 \times 0.04 = 0.01 \text{ pu} = 630 \times 0.01 = 6.3 \text{ kvar}$  and so on...

This example, and the vector diagram of **Figure L20** show that:

- The power factor at the primary side of a loaded transformer is different (normally lower) than that at the secondary side (due to the absorption of vars)
- Full-load kvar losses due to leakage reactance are equal to the transformer percentage reactance (4% reactance means a kvar loss equal to 4% of the kVA rating of the transformer)
- kvar losses due to leakage reactance vary according to the current (or kVA loading) squared

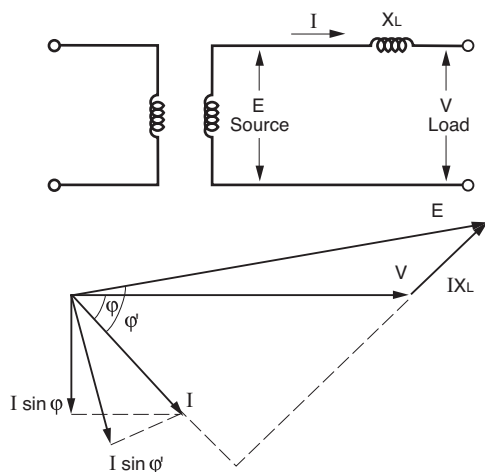


Fig. L20 : Reactive power absorption by series inductance

L16



## 6 Compensation at the terminals of a transformer

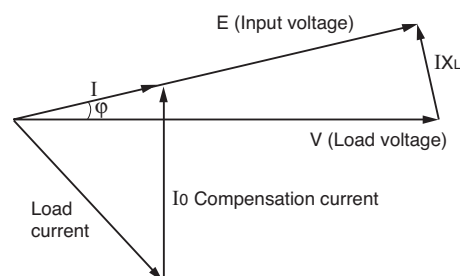
To determine the total kvar losses of a transformer the constant magnetizing-current circuit losses (approx. 1.8% of the transformer kVA rating) must be added to the foregoing "series" losses. **Figure L21** shows the no-load and full-load kvar losses for typical distribution transformers. In principle, series inductances can be compensated by fixed series capacitors (as is commonly the case for long MV transmission lines). This arrangement is operationally difficult, however, so that, at the voltage levels covered by this guide, shunt compensation is always applied.

In the case of MV metering, it is sufficient to raise the power factor to a point where the transformer plus load reactive-power consumption is below the level at which a billing charge is made. This level depends on the tariff, but often corresponds to a  $\tan \phi$  value of 0.31 ( $\cos \phi$  of 0.955).

Rated power (kVA)	Reactive power (kvar) to be compensated	
	No load	Full load
100	2.5	6.1
160	3.7	9.6
250	5.3	14.7
315	6.3	18.4
400	7.6	22.9
500	9.5	28.7
630	11.3	35.7
800	20	54.5
1000	23.9	72.4
1250	27.4	94.5
1600	31.9	126
2000	37.8	176

**Fig. L21** : Reactive power consumption of distribution transformers with 20 kV primary windings

As a matter of interest, the kvar losses in a transformer can be completely compensated by adjusting the capacitor bank to give the load a (slightly) leading power factor. In such a case, all of the kvar of the transformer is being supplied from the capacitor bank, while the input to the MV side of the transformer is at unity power factor, as shown in **Figure L22**.



**Fig. L22** : Overcompensation of load to completely compensate transformer reactive-power losses

In practical terms, therefore, compensation for transformer-absorbed kvar is included in the capacitors primarily intended for powerfactor correction of the load, either globally, partially, or in the individual mode. Unlike most other kvar-absorbing items, the transformer absorption (i.e. the part due to the leakage reactance) changes significantly with variations of load level, so that, if individual compensation is applied to the transformer, then an average level of loading will have to be assumed.

Fortunately, this kvar consumption generally forms only a relatively small part of the total reactive power of an installation, and so mismatching of compensation at times of load change is not likely to be a problem.

Figure L21 indicates typical kvar loss values for the magnetizing circuit ("no-load kvar" columns), as well as for the total losses at full load, for a standard range of distribution transformers supplied at 20 kV (which include the losses due to the leakage reactance).

## 7 Power factor correction of induction motors

Individual motor compensation is recommended where the motor power (kVA) is large with respect to the declared power of the installation

### 7.1 Connection of a capacitor bank and protection settings

#### General precautions

Because of the small kW consumption, the power factor of a motor is very low at no-load or on light load. The reactive current of the motor remains practically constant at all loads, so that a number of unloaded motors constitute a consumption of reactive power which is generally detrimental to an installation, for reasons explained in preceding sections.

Two good general rules therefore are that unloaded motors should be switched off, and motors should not be oversized (since they will then be lightly loaded).

#### Connection

The bank of capacitors should be connected directly to the terminals of the motor.

#### Special motors

It is recommended that special motors (stepping, plugging, inching, reversing motors, etc.) should not be compensated.

#### Effect on protection settings

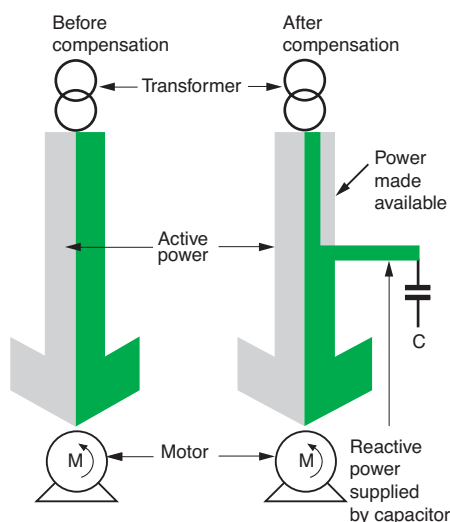
After applying compensation to a motor, the current to the motor-capacitor combination will be lower than before, assuming the same motor-driven load conditions. This is because a significant part of the reactive component of the motor current is being supplied from the capacitor, as shown in **Figure L23**.

Where the overcurrent protection devices of the motor are located upstream of the motor capacitor connection (and this will always be the case for terminal-connected capacitors), the overcurrent relay settings must be reduced in the ratio:

$\cos \varphi$  before compensation /  $\cos \varphi$  after compensation

For motors compensated in accordance with the kvar values indicated in **Figure L24** (maximum values recommended for avoidance of self-excitation of standard induction motors, as discussed in sub-clause 7.2), the above-mentioned ratio will have a value similar to that indicated for the corresponding motor speed in **Figure L25**.

L18



**Fig. L23 :** Before compensation, the transformer supplies all the reactive power; after compensation, the capacitor supplies a large part of the reactive power

3-phase motors 230/400 V					
Nominal power		kvar to be installed			
		Speed of rotation (rpm)			
kW	hp	3000	1500	1000	750
22	30	6	8	9	10
30	40	7.5	10	11	12.5
37	50	9	11	12.5	16
45	60	11	13	14	17
55	75	13	17	18	21
75	100	17	22	25	28
90	125	20	25	27	30
110	150	24	29	33	37
132	180	31	36	38	43
160	218	35	41	44	52
200	274	43	47	53	61
250	340	52	57	63	71
280	380	57	63	70	79
355	482	67	76	86	98
400	544	78	82	97	106
450	610	87	93	107	117

**Figure L24 :** Maximum kvar of power factor correction applicable to motor terminals without risk of self excitation

Speed in rpm	Reduction factor
750	0.88
1000	0.90
1500	0.91
3000	0.93

**Fig. L25 :** Reduction factor for overcurrent protection after compensation

*When a capacitor bank is connected to the terminals of an induction motor, it is important to check that the size of the bank is less than that at which self-excitation can occur*

## 7.2 How self-excitation of an induction motor can be avoided

When a motor is driving a high-inertia load, the motor will continue to rotate (unless deliberately braked) after the motor supply has been switched off.

The “magnetic inertia” of the rotor circuit means that an emf will be generated in the stator windings for a short period after switching off, and would normally reduce to zero after 1 or 2 cycles, in the case of an uncompensated motor.

Compensation capacitors however, constitute a 3-phase “wattless” load for this decaying emf, which causes capacitive currents to flow through the stator windings. These stator currents will produce a rotating magnetic field in the rotor which acts exactly along the same axis and in the same direction as that of the decaying magnetic field.

The rotor flux consequently increases; the stator currents increase; and the voltage at the terminals of the motor increases; sometimes to dangerously-high levels. This phenomenon is known as self-excitation and is one reason why AC generators are not normally operated at leading power factors, i.e. there is a tendency to spontaneously (and uncontrollably) self excite.

### Notes:

1. The characteristics of a motor being driven by the inertia of the load are not rigorously identical to its no-load characteristics. This assumption, however, is sufficiently accurate for practical purposes.
2. With the motor acting as a generator, the currents circulating are largely reactive, so that the braking (retarding) effect on the motor is mainly due only to the load represented by the cooling fan in the motor.
3. The (almost 90° lagging) current taken from the supply in normal circumstances by the unloaded motor, and the (almost 90° leading) current supplied to the capacitors by the motor acting as a generator, both have the same phase relationship to the terminal voltage. It is for this reason that the two characteristics may be superimposed on the graph.

In order to avoid self-excitation as described above, the kvar rating of the capacitor bank must be limited to the following maximum value:

$Q_c \leq 0.9 \times I_o \times U_n \times \sqrt{3}$  where  $I_o$  = the no-load current of the motor and  $U_n$  = phase-to-phase nominal voltage of the motor in kV. Figure L24 previous page gives appropriate values of  $Q_c$  corresponding to this criterion.

### Example

A 75 kW, 3,000 rpm, 400 V, 3-phase motor may have a capacitor bank no larger than 17 kvar according to Figure L24. The table values are, in general, too small to adequately compensate the motor to the level of  $\cos \phi$  normally required. Additional compensation can, however, be applied to the system, for example an overall bank, installed for global compensation of a number of smaller appliances.

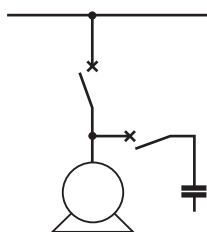
### High-inertia motors and/or loads

In any installation where high-inertia motor driven loads exist, the circuit-breakers or contactors controlling such motors should, in the event of total loss of power supply, be rapidly tripped.

If this precaution is not taken, then self excitation to very high voltages is likely to occur, since all other banks of capacitors in the installation will effectively be in parallel with those of the high-inertia motors.

The protection scheme for these motors should therefore include an overvoltage tripping relay, together with reverse-power checking contacts (the motor will feed power to the rest of the installation, until the stored inertial energy is dissipated). If the capacitor bank associated with a high inertia motor is larger than that recommended in Figure L24, then it should be separately controlled by a circuit-breaker or contactor, which trips simultaneously with the main motor-controlling circuit-breaker or contactor, as shown in Figure L26.

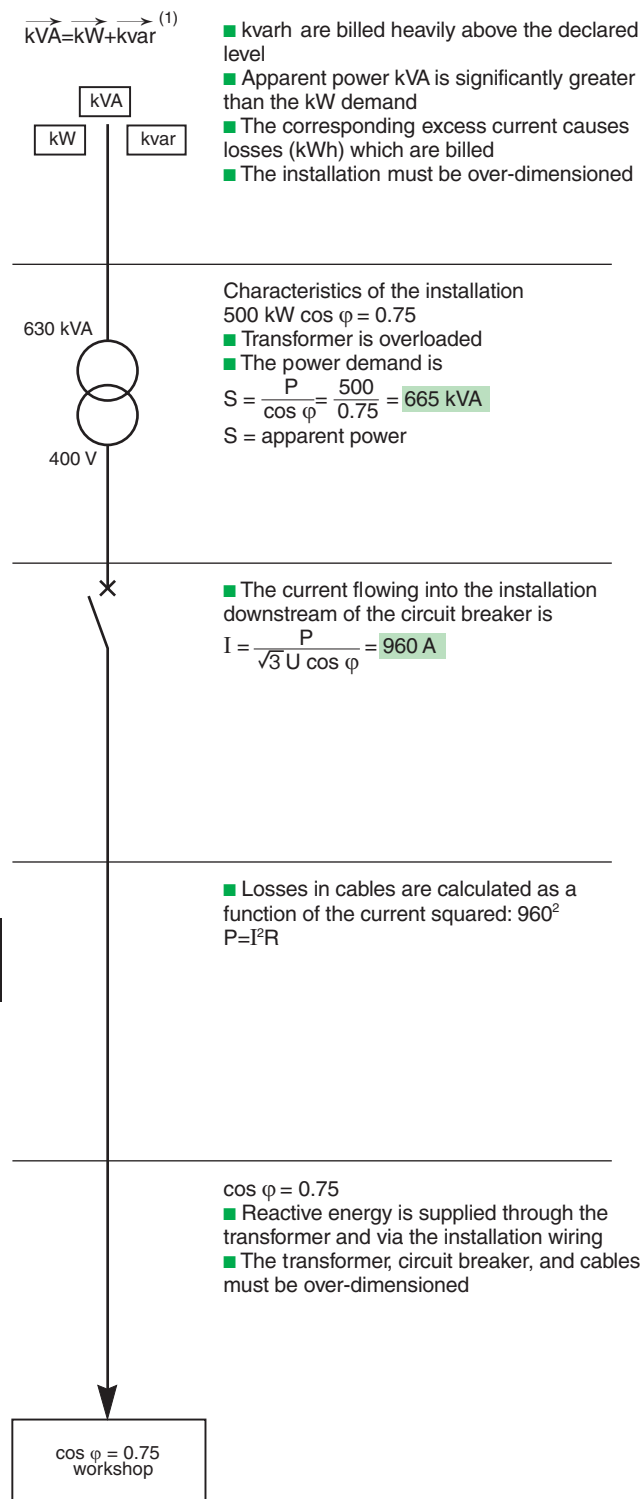
Closing of the main contactor is commonly subject to the capacitor contactor being previously closed.



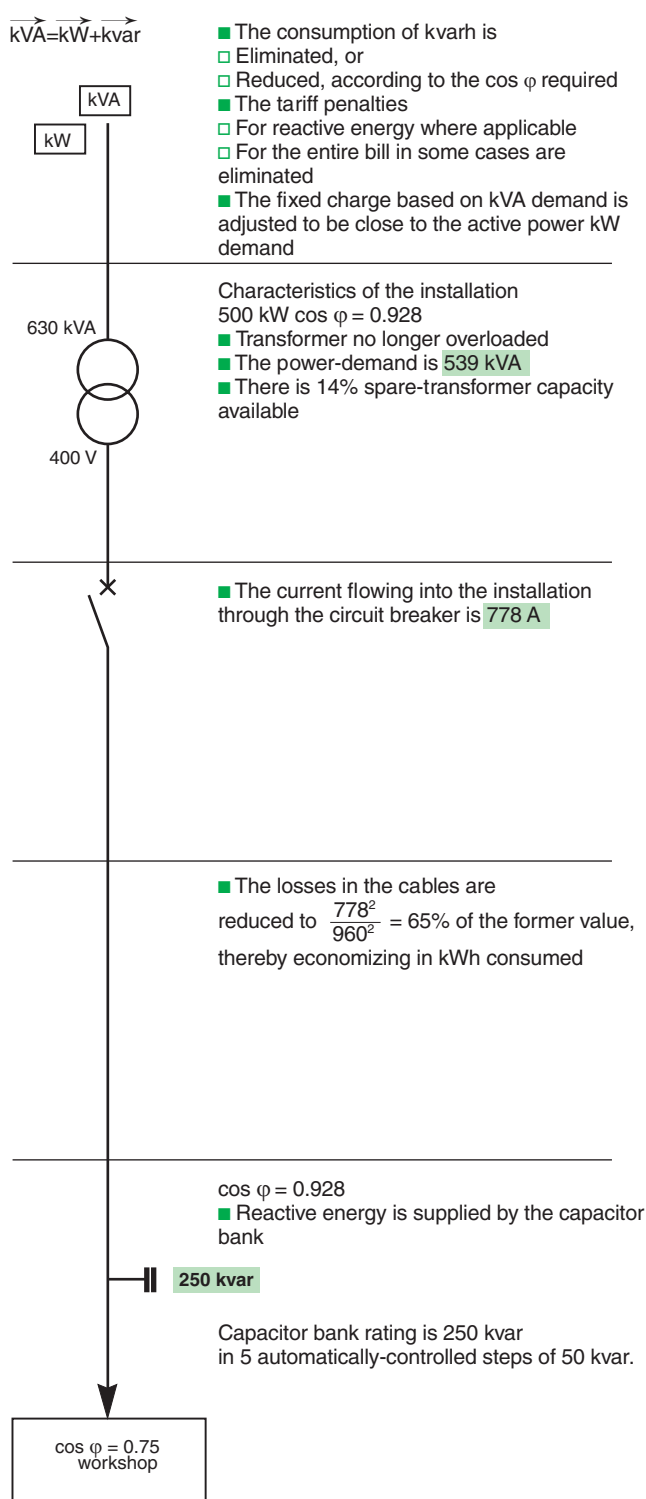
**Fig. L26 :** Connection of the capacitor bank to the motor

## 8 Example of an installation before and after power-factor correction

### Installation before P.F. correction



### Installation after P.F. correction



**Note:** In fact, the  $\cos \varphi$  of the workshop remains at 0.75 but  $\cos \varphi$  for all the installation upstream of the capacitor bank to the transformer LV terminals is 0.928.  
As mentioned in Sub-clause 6.2 the  $\cos \varphi$  at the HV side of the transformer will be slightly lower <sup>(2)</sup>, due to the reactive power losses in the transformer.

Fig. K27 : Technical-economic comparison of an installation before and after power-factor correction

(1) The arrows denote vector quantities.  
(2) Particularly in the pre-corrected case.

## 9.1 Problems arising from power-system harmonics

Equipment which uses power electronics components (variable-speed motor controllers, thyristor-controlled rectifiers, etc.) have considerably increased the problems caused by harmonics in power supply systems.

Harmonics have existed from the earliest days of the industry and were (and still are) caused by the non-linear magnetizing impedances of transformers, reactors, fluorescent lamp ballasts, etc.

Harmonics on symmetrical 3-phase power systems are generally odd-numbered: 3<sup>rd</sup>, 5<sup>th</sup>, 7<sup>th</sup>, 9<sup>th</sup>..., and the magnitude decreases as the order of the harmonic increases. A number of features may be used in various ways to reduce specific harmonics to negligible values - total elimination is not possible. In this section, practical means of reducing the influence of harmonics are recommended, with particular reference to capacitor banks.

Capacitors are especially sensitive to harmonic components of the supply voltage due to the fact that capacitive reactance decreases as the frequency increases. In practice, this means that a relatively small percentage of harmonic voltage can cause a significant current to flow in the capacitor circuit.

The presence of harmonic components causes the (normally sinusoidal) wave form of voltage or current to be distorted; the greater the harmonic content, the greater the degree of distortion.

If the natural frequency of the capacitor bank/ power-system reactance combination is close to a particular harmonic, then partial resonance will occur, with amplified values of voltage and current at the harmonic frequency concerned. In this particular case, the elevated current will cause overheating of the capacitor, with degradation of the dielectric, which may result in its eventual failure.

Several solutions to these problems are available. This can be accomplished by

- Shunt connected harmonic filter and/or harmonic-suppression reactors or
- Active power filters or
- Hybrid filters

Harmonics are taken into account mainly by oversizing capacitors and including harmonic-suppression reactors in series with them

## 9.2 Possible solutions

### Passive filter (see Fig. L28)

#### Countering the effects of harmonics

The presence of harmonics in the supply voltage results in abnormally high current levels through the capacitors. An allowance is made for this by designing for an r.m.s. value of current equal to 1.3 times the nominal rated current. All series elements, such as connections, fuses, switches, etc., associated with the capacitors are similarly oversized, between 1.3 to 1.5 times nominal rating.

Harmonic distortion of the voltage wave frequently produces a "peaky" wave form, in which the peak value of the normal sinusoidal wave is increased. This possibility, together with other overvoltage conditions likely to occur when countering the effects of resonance, as described below, are taken into account by increasing the insulation level above that of "standard" capacitors. In many instances, these two counter measures are all that is necessary to achieve satisfactory operation.

#### Countering the effects of resonance

Capacitors are linear reactive devices, and consequently do not generate harmonics. The installation of capacitors in a power system (in which the impedances are predominantly inductive) can, however, result in total or partial resonance occurring at one of the harmonic frequencies.

The harmonic order  $h_0$  of the natural resonant frequency between the system inductance and the capacitor bank is given by

$$h_0 = \sqrt{\frac{S_{sc}}{Q}}$$

where

$S_{sc}$  = the level of system short-circuit kVA at the point of connection of the capacitor

$Q$  = capacitor bank rating in kvar; and  $h_0$  = the harmonic order of the natural

frequency  $f_0$  i.e.  $\frac{f_0}{50}$  for a 50 Hz system, or  $\frac{f_0}{60}$  for a 60 Hz system.

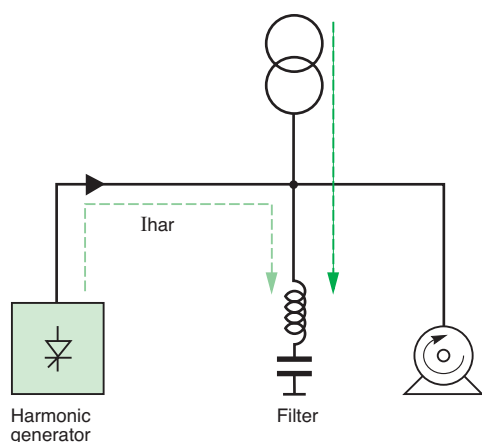


Fig. L28 : Operation principle of passive filter

L21

For example:  $h_o = \sqrt{\frac{S_{sc}}{Q}}$  may give a value for  $h_o$  of 2.93 which shows that the

natural frequency of the capacitor/system-inductance combination is close to the 3<sup>rd</sup> harmonic frequency of the system.

From  $h_o = \frac{f_o}{50}$  it can be seen that  $f_o = 50 h_o = 50 \times 2.93 = 146.5$  Hz

The closer a natural frequency approaches one of the harmonics present on the system, the greater will be the (undesirable) effect. In the above example, strong resonant conditions with the 3<sup>rd</sup> harmonic component of a distorted wave would certainly occur.

In such cases, steps are taken to change the natural frequency to a value which will not resonate with any of the harmonics known to be present. This is achieved by the addition of a harmonic-suppression inductor connected in series with the capacitor bank.

On 50 Hz systems, these reactors are often adjusted to bring the resonant frequency of the combination, i.e. the capacitor bank + reactors to 190 Hz. The reactors are adjusted to 228 Hz for a 60 Hz system. These frequencies correspond to a value for  $h_o$  of 3.8 for a 50 Hz system, i.e. approximately mid-way between the 3<sup>rd</sup> and 5<sup>th</sup> harmonics.

In this arrangement, the presence of the reactor increases the fundamental frequency (50 Hz or 60 Hz) current by a small amount (7-8%) and therefore the voltage across the capacitor in the same proportion.

This feature is taken into account, for example, by using capacitors which are designed for 440 V operation on 400 V systems.

## Active filter (see Fig. L29)

Active filters are based on power electronic technology. They are generally installed in parallel with the non linear load.

Active filters analyse the harmonics drawn by the load and then inject the same harmonic current to the load with the appropriate phase. As a result, the harmonic currents are totally neutralised at the point considered. This means they no longer flow upstream and are no longer supplied by the source.

A main advantage of active conditioners is that they continue to guarantee efficient harmonic compensation even when changes are made to the installation. They are also exceptionally easy to use as they feature:

- Auto-configuration to harmonic loads whatever their order of magnitude
- Elimination of overload risks
- Compatibility with electrical generator sets
- Connection to any point of the electrical network
- Several conditioners can be used in the same installation to increase depollution efficiency (for example when a new machine is installed)

Active filters may provide also power factor correction.

## Hybrid filter (see Fig. L30)

This type of filter combines advantages of passive and active filter. One frequency can be filtered by passive filter and all the other frequencies are filtered by active filter.

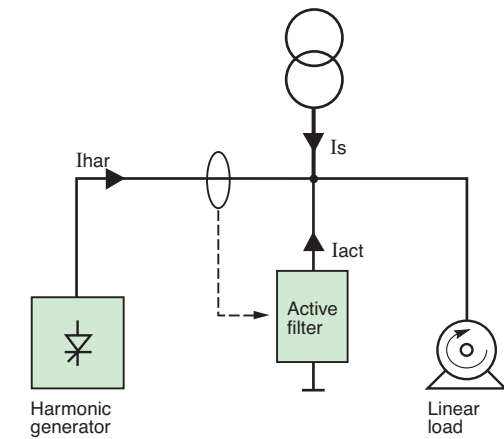


Fig. L29 : Operation principle of active filter

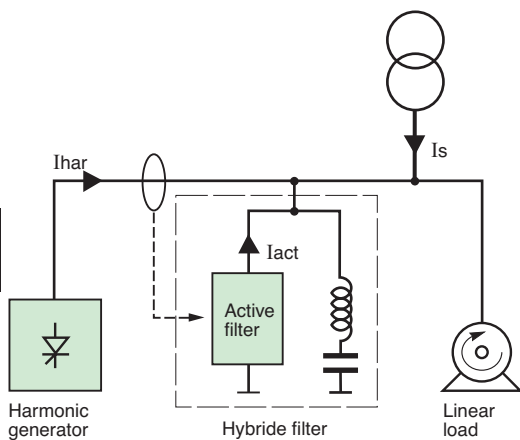


Fig. L30 : Operation principle of hybrid filter

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### 9.3 Choosing the optimum solution

**Figure L31** below shows the criteria that can be taken into account to select the most suitable technology depending on the application.

	Passive filter	Active filter	Hybrid filter
Applications	Industrial	Tertiary	Industrial
... with total power of non linear loads (variable speed drive, UPS, rectifier...)	greater than 200 kVA	lower than 200 kVA	greater than 200 kVA
Power factor correction		No	
Necessity of reducing the harmonic distortion in voltage for sensitive loads			
Necessity of reducing the harmonic distortion in current to avoid cable overload			
Necessity of being in accordance with strict limits of harmonic rejected	No		

**Fig. L31** : Selection of the most suitable technology depending on the application

For passive filter, a choice is made from the following parameters:

- Gh = the sum of the kVA ratings of all harmonic-generating devices (static converters, inverters, speed controllers, etc.) connected to the busbars from which the capacitor bank is supplied. If the ratings of some of these devices are quoted in kW only, assume an average power factor of 0.7 to obtain the kVA ratings
- Ssc = the 3-phase short-circuit level in kVA at the terminals of the capacitor bank
- Sn = the sum of the kVA ratings of all transformers supplying (i.e. directly connected to) the system level of which the busbars form a part

If a number of transformers are operating in parallel, the removal from service of one or more, will significantly change the values of Ssc and Sn. From these parameters, a choice of capacitor specification which will ensure an acceptable level of operation with the system harmonic voltages and currents, can be made, by reference to **Figure L32**.

- General rule valid for any size of transformer

$Gh \leq \frac{S_{sc}}{120}$	$\frac{S_{sc}}{120} \leq Gh \leq \frac{S_{sc}}{70}$	$Gh > \frac{S_{sc}}{70}$
Standard capacitors	Capacitor voltage rating increased by 10% (except 230 V units)	Capacitor voltage rating increased by 10% + harmonic-suppression reactor

- Simplified rule if transformer(s) rating  $S_n \leq 2$  MVA

$Gh \leq 0.15 S_n$	$0.15 S_n < Gh \leq 0.25 S_n$	$0.25 S_n < Gh \leq 0.60 S_n$	$Gh > 0.60 S_n$
Standard capacitors	Capacitor voltage rating increased by 10% (except 230 V units)	Capacitor voltage rating increased by 10% + harmonic suppression reactor	Filters

**Fig. L32** : Choice of solutions for limiting harmonics associated with a LV capacitor bank supplied via transformer(s)



# 10 Implementation of capacitor banks

## 10.1 Capacitor elements

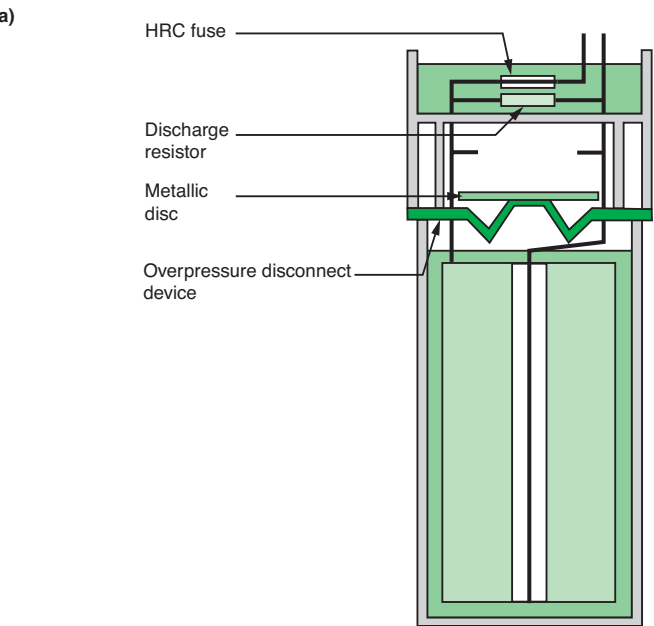
### Technology

The capacitors are dry-type units (i.e. are not impregnated by liquid dielectric) comprising metallized polypropylene self-healing film in the form of a two-film roll. They are protected by a high-quality system (overpressure disconnecter used with a high breaking capacity fuse) which switches off the capacitor if an internal fault occurs.

The protection scheme operates as follows:

- A short-circuit through the dielectric will blow the fuse
- Current levels greater than normal, but insufficient to blow the fuse sometimes occur, e.g. due to a microscopic flow in the dielectric film. Such “faults” often re-seal due to local heating caused by the leakage current, i.e. the units are said to be “self-healing”
- If the leakage current persists, the defect may develop into a short-circuit, and the fuse will blow
- Gas produced by vaporizing of the metallisation at the faulty location will gradually build up a pressure within the plastic container, and will eventually operate a pressure-sensitive device to short-circuit the unit, thereby causing the fuse to blow

Capacitors are made of insulating material providing them with double insulation and avoiding the need for a ground connection (see Fig. L33).



b)

Electrical characteristics		
Standard		IEC 60439-1, NFC 54-104, VDE 0560 CSA Standards, UL tests
Operating range	Rated voltage	400 V
	Rated frequency	50 Hz
Capacitance tolerance		- 5% to + 10%
Temperature range (up to 65 kvar)	Maximum temperature	55 °C
	Average temperature over 24 h	45 °C
	Average annual temperature	35 °C
	Minimum temperature	- 25 °C
Insulation level	50 Hz 1 min withstand voltage : 6 kV 1.2/50 μs impulse withstand voltage : 25 kV	
Permissible current overload	Classic range <sup>(1)</sup>	Comfort range <sup>(1)</sup>
	30%	50%
Permissible voltage overload	10%	20%

Fig. L33 : Capacitor element, (a) cross-section, (b) electrical characteristics

(1) Merlin-Gerin designation



## 10.2 Choice of protection, control devices and connecting cables

The choice of upstream cables and protection and control devices depends on the current loading.

For capacitors, the current is a function of:

- The applied voltage and its harmonics
- The capacitance value

The nominal current  $I_n$  of a 3-phase capacitor bank is equal to:

$$I_n = \frac{Q}{U_n \sqrt{3}} \text{ with:}$$

- Q: kvar rating
- $U_n$ : Phase-to-phase voltage (kV)

The permitted range of applied voltage at fundamental frequency, plus harmonic components, together with manufacturing tolerances of actual capacitance (for a declared nominal value) can result in a 50% increase above the calculated value of current. Approximately 30% of this increase is due to the voltage increases, while a further 15% is due to the range of manufacturing tolerances, so that  $1.3 \times 1.15 = 1.5$

All components carrying the capacitor current therefore, must be adequate to cover this "worst-case" condition, in an ambient temperature of 50 °C maximum. In the case where temperatures higher than 50 °C occur in enclosures, etc. derating of the components will be necessary.

### Protection

The size of the circuit-breaker can be chosen in order to allow the setting of long time delay at:

- $1.36 \times I_n$  for Classic range<sup>(1)</sup>
- $1.50 \times I_n$  for Comfort range<sup>(1)</sup>
- $1.12 \times I_n$  for Harmony range<sup>(1)</sup> (tuned at 2.7 f)<sup>(2)</sup>
- $1.19 \times I_n$  for Harmony range<sup>(1)</sup> (tuned at 3.8 f)
- $1.31 \times I_n$  for Harmony range<sup>(1)</sup> (tuned at 4.3 f)

Short time delay setting (short-circuit protection) must be insensitive to inrush current. The setting will be  $10 \times I_n$  for Classic, Comfort and Harmony range<sup>(1)</sup>.

#### Example 1

50 kvar – 400V – 50 Hz – Classic range

$$I_n = \frac{50,000}{(400 \times 1.732)} = 72 \text{ A}$$

Long time delay setting:  $1.36 \times 72 = 98 \text{ A}$

Short time delay setting:  $10 \times I_n = 720 \text{ A}$

#### Example 2

50 kvar – 400V – 50 Hz – Harmony range (tuned at 4.3 f)

$I_n = 72 \text{ A}$

Long time delay setting:  $1.31 \times 72 = 94 \text{ A}$

Short time delay setting:  $10 \times I_n = 720 \text{ A}$

### Upstream cables

**Figure L34** next page gives the minimum cross section area of the upstream cable for Rectiphase capacitors.

### Cables for control

The minimum cross section area of these cables will be 1.5 mm<sup>2</sup> for 230 V.

For the secondary side of the transformer, the recommended cross section area is  $\geq 2.5 \text{ mm}^2$ .

(1) Merlin-Gerin designation

(2) Harmony capacitor banks are equipped with a harmonic suppression reactor.

Bank power (kvar)		Copper cross-section (mm <sup>2</sup> )	Aluminium cross-section (mm <sup>2</sup> )
230 V	400 V		
5	10	2.5	16
10	20	4	16
15	30	6	16
20	40	10	16
25	50	16	25
30	60	25	35
40	80	35	50
50	100	50	70
60	120	70	95
70	140	95	120
90-100	180	120	185
	200	150	240
120	240	185	2 x 95
150	250	240	2 x 120
	300	2 x 95	2 x 150
180-210	360	2 x 120	2 x 185
245	420	2 x 150	2 x 240
280	480	2 x 185	2 x 300
315	540	2 x 240	3 x 185
350	600	2 x 300	3 x 240
385	660	3 x 150	3 x 240
420	720	3 x 185	3 x 300

Fig L34 : Cross-section of cables connecting medium and high power capacitor banks<sup>(1)</sup>

### Voltage transients

High-frequency voltage and current transients occur when switching a capacitor bank into service. The maximum voltage peak does not exceed (in the absence of harmonics) twice the peak value of the rated voltage when switching uncharged capacitors.

In the case of a capacitor being already charged at the instant of switch closure, however, the voltage transient can reach a maximum value approaching 3 times the normal rated peak value.

This maximum condition occurs only if:

- The existing voltage at the capacitor is equal to the peak value of rated voltage, and
- The switch contacts close at the instant of peak supply voltage, and
- The polarity of the power-supply voltage is opposite to that of the charged capacitor

In such a situation, the current transient will be at its maximum possible value, viz: Twice that of its maximum when closing on to an initially uncharged capacitor, as previously noted.

For any other values of voltage and polarity on the pre-charged capacitor, the transient peaks of voltage and current will be less than those mentioned above. In the particular case of peak rated voltage on the capacitor having the same polarity as that of the supply voltage, and closing the switch at the instant of supply-voltage peak, there would be no voltage or current transients.

Where automatic switching of stepped banks of capacitors is considered, therefore, care must be taken to ensure that a section of capacitors about to be energized is fully discharged.

The discharge delay time may be shortened, if necessary, by using discharge resistors of a lower resistance value.

(1) Minimum cross-section not allowing for any correction factors (installation mode, temperature, etc.). The calculations were made for single-pole cables laid in open air at 30 °C.

# Chapter M

## Harmonic management

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M1

# 1 The problem: why is it necessary to detect and eliminate harmonics?

## **Disturbances caused by harmonics**

Harmonics flowing in distribution networks downgrade the quality of electrical power. This can have a number of negative effects:

- Overloads on distribution networks due to the increase in rms current
- Overloads in neutral conductors due to the cumulative increase in third-order harmonics created by single-phase loads
- Overloads, vibration and premature ageing of generators, transformers and motors as well as increased transformer hum
- Overloads and premature ageing of power-factor correction capacitors
- Distortion of the supply voltage that can disturb sensitive loads
- Disturbances in communication networks and on telephone lines

## **Economic impact of disturbances**

Harmonics have a major economic impact:

- Premature ageing of equipment means it must be replaced sooner unless oversized right from the start
- Overloads on the distribution network can require higher subscribed power levels and increase losses
- Distortion of current waveforms provokes nuisance tripping that can stop production

## **Increasingly serious consequences**

Only ten years ago, harmonics were not yet considered a real problem because their effects on distribution networks were generally minor. However, the massive introduction of power electronics in equipment has made the phenomenon far more serious in all sectors of economic activity.

In addition, the equipment causing the harmonics is often vital to the company or organisation.

## **Which harmonics must be measured and eliminated?**

The most frequently encountered harmonics in three-phase distribution networks are the odd orders. Harmonic amplitudes normally decrease as the frequency increases. Above order 50, harmonics are negligible and measurements are no longer meaningful. Sufficiently accurate measurements are obtained by measuring harmonics up to order 30.

Utilities monitor harmonic orders 3, 5, 7, 11 and 13. Generally speaking, harmonic conditioning of the lowest orders (up to 13) is sufficient. More comprehensive conditioning takes into account harmonic orders up to 25.

Harmonic emissions are subject to various standards and regulations:

- Compatibility standards for distribution networks
- Emissions standards applying to the equipment causing harmonics
- Recommendations issued by utilities and applicable to installations

In view of rapidly attenuating the effects of harmonics, a triple system of standards and regulations is currently in force based on the documents listed below.

## Standards governing compatibility between distribution networks and products

These standards determine the necessary compatibility between distribution networks and products:

- The harmonics caused by a device must not disturb the distribution network beyond certain limits
- Each device must be capable of operating normally in the presence of disturbances up to specific levels
- Standard IEC 61000-2-2 for public low-voltage power supply systems
- Standard IEC 61000-2-4 for LV and MV industrial installations

## Standards governing the quality of distribution networks

- Standard EN 50160 stipulates the characteristics of electricity supplied by public distribution networks
- Standard IEEE 519 presents a joint approach between Utilities and customers to limit the impact of non-linear loads. What is more, Utilities encourage preventive action in view of reducing the deterioration of power quality, temperature rise and the reduction of power factor. They will be increasingly inclined to charge customers for major sources of harmonics

## Standards governing equipment

- Standard IEC 61000-3-2 or EN 61000-3-2 for low-voltage equipment with rated current under 16 A
- Standard IEC 61000-3-12 for low-voltage equipment with rated current higher than 16 A and lower than 75 A

## Maximum permissible harmonic levels

International studies have collected data resulting in an estimation of typical harmonic contents often encountered in electrical distribution networks. **Figure M1** presents the levels that, in the opinion of many utilities, should not be exceeded.

Odd harmonic orders non-multiples of 3				Odd harmonic orders multiples of 3				Even harmonic orders			
Order h	LV	MV	EMV	Order h	LV	MV	EMV	Order h	LV	MV	EMV
5	6	6	2	3	5	2.5	1.5	2	2	1.5	1.5
7	5	5	2	9	1.5	1.5	1	4	1	1	1
11	3.5	3.5	1.5	15	0.3	0.3	0.3	6	0.5	0.5	0.5
13	3	3	1.5	21	0.2	0.2	0.2	8	0.5	0.2	0.2
17	2	2	1	> 21	0.2	0.2	0.2	10	0.5	0.2	0.2
19	1.5	1.5	1					12	0.2	0.2	0.2
23	1.5	1	0.7					> 12	0.2	0.2	0.2
25	1.5	1	0.7								
> 25	0.2 + 25/h	0.2 + 25/h	0.1 + 25/h								

**Fig. M1** : Maximum permissible harmonic levels

M3

The presence of harmonics indicates a distorted current or voltage wave. The distortion of the current or voltage wave means that the distribution of electrical energy is disturbed and power quality is not optimum.

Harmonic currents are caused by non-linear loads connected to the distribution network. The flow of harmonic currents causes harmonic voltages via distribution-network impedances and consequently distortion of the supply voltage.

## Origin of harmonics

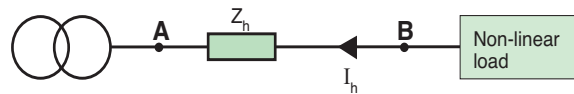
Devices and systems that cause harmonics are present in all sectors, i.e. industrial, commercial and residential. Harmonics are caused by non-linear loads (i.e. loads that draw current with a waveform that is not the same as that of the supply voltage).

Examples of non-linear loads are:

- Industrial equipment (welding machines, arc furnaces, induction furnaces, rectifiers)
- Variable-speed drives for asynchronous or DC motors
- UPSs
- Office equipment (computers, photocopy machines, fax machines, etc.)
- Home appliances (television sets, micro-wave ovens, fluorescent lighting)
- Certain devices involving magnetic saturation (transformers)

## Disturbances caused by non-linear loads: harmonic current and voltage

Non-linear loads draw harmonic currents that flow in the distribution network. Harmonic voltages are caused by the flow of harmonic currents through the impedances of the supply circuits (transformer and distribution network for situations similar to that shown in **Figure M2**).



**Fig. M2** : Single-line diagram showing the impedance of the supply circuit for a harmonic of order  $h$

The reactance of a conductor increases as a function of the frequency of the current flowing through the conductor. For each harmonic current (order  $h$ ), there is therefore an impedance  $Z_h$  in the supply circuit.

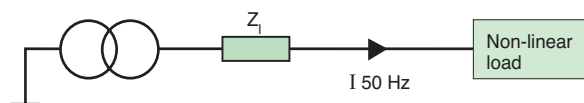
When the harmonic current of order  $h$  flows through impedance  $Z_h$ , it creates a harmonic voltage  $U_h$ , where  $U_h = Z_h \times I_h$  (Ohm law). The voltage at point B is therefore distorted. All devices supplied via point B receive a distorted voltage.

For a given harmonic current, the distortion is proportional to the impedance in the distribution network.

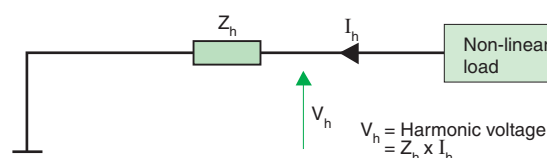
## Flow of harmonic currents in distribution networks

The non-linear loads can be considered to reinject the harmonic currents upstream into the distribution network, toward the source.

**Figures M3** and **M4** next page show an installation disturbed by harmonics. Figure M3 shows the flow of the current at 50 Hz in the installation and Figure M4 shows the harmonic current (order  $h$ ).



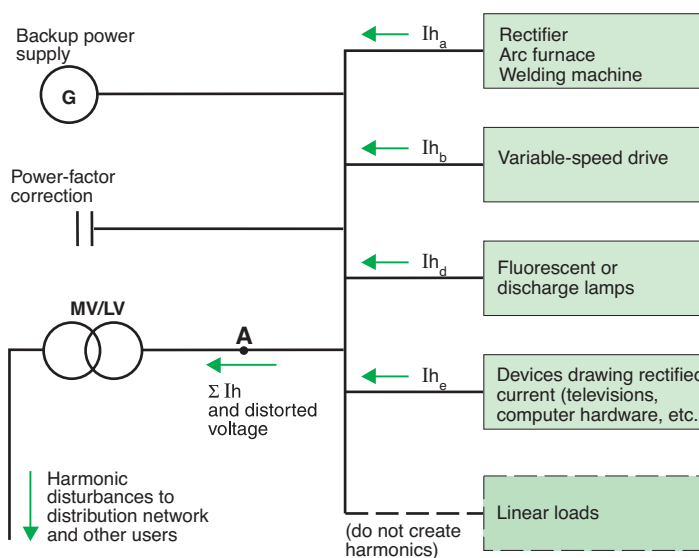
**Fig. M3 :** Installation supplying a non-linear load, where only the phenomena concerning the 50 Hz frequency (fundamental frequency) are shown



**Fig. M4 :** Same installation, where only the phenomena concerning the frequency of harmonic order  $h$  are shown

Supply of the non-linear load creates the flow of a current  $I_{50\text{Hz}}$  (shown in figure M3), to which is added each of the harmonic currents  $I_h$  (shown in figure M4), corresponding to each harmonic order  $h$ .

Still considering that the loads reinject harmonic current upstream into the distribution network, it is possible to create a diagram showing the harmonic currents in the network (see **Fig. M5**).



**M5**

Note in the diagram that though certain loads create harmonic currents in the distribution network, other loads can absorb the harmonic currents.

**Fig. M5 :** Flow of harmonic currents in a distribution network

Harmonics have major economic effects in installations:

- Increases in energy costs
- Premature ageing of equipment
- Production losses

## 4 Main effects of harmonics in installations

### 4.1 Resonance

The simultaneous use of capacitive and inductive devices in distribution networks results in parallel or series resonance manifested by very high or very low impedance values respectively. The variations in impedance modify the current and voltage in the distribution network. Here, only parallel resonance phenomena, the most common, will be discussed.

Consider the following simplified diagram (see **Fig. M6**) representing an installation made up of:

- A supply transformer
- Linear loads
- Non-linear loads drawing harmonic currents
- Power factor correction capacitors

For harmonic analysis, the equivalent diagram (see **Fig. M7**) is shown below.

Impedance  $Z$  is calculated by:

$$Z = \frac{jLs\omega}{1 - LsC\omega^2}$$

neglecting  $R$  and where:

$Ls$  = Supply inductance (upstream network + transformer + line)

$C$  = Capacitance of the power factor correction capacitors

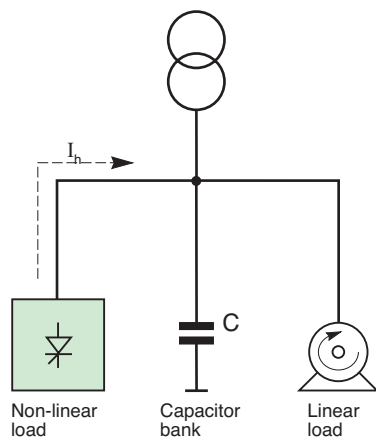
$R$  = Resistance of the linear loads

$I_h$  = Harmonic current

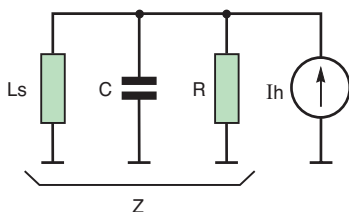
Resonance occurs when the denominator  $1 - LsC\omega^2$  tends toward zero. The corresponding frequency is called the resonance frequency of the circuit. At that frequency, impedance is at its maximum and high amounts of harmonic voltages appear with the resulting major distortion in the voltage. The voltage distortion is accompanied, in the  $Ls+C$  circuit, by the flow of harmonic currents greater than those drawn by the loads.

The distribution network and the power factor correction capacitors are subjected to high harmonic currents and the resulting risk of overloads. To avoid resonance, anti-harmonic coils can be installed in series with the capacitors.

M6



**Fig. M6** : Diagram of an installation



**Fig. M7** : Equivalent diagram of the installation shown in Figure M6

### 4.2 Increased losses

#### Losses in conductors

The active power transmitted to a load is a function of the fundamental component  $I_1$  of the current.

When the current drawn by the load contains harmonics, the rms value of the current,  $I_{rms}$ , is greater than the fundamental  $I_1$ .

The definition of THD being:

$$THD = \sqrt{\left(\frac{I_{rms}}{I_1}\right)^2} - 1$$

it may be deduced that:  $I_{rms} = I_1 \sqrt{1 + THD^2}$

**Figure M8** (next page) shows, as a function of the harmonic distortion:

- The increase in the rms current  $I_{rms}$  for a load drawing a given fundamental current

- The increase in Joule losses, not taking into account the skin effect

(The reference point in the graph is 1 for  $I_{rms}$  and Joules losses, the case when there are no harmonics)

The harmonic currents provoke an increase in the Joule losses in all conductors in which they flow and additional temperature rise in transformers, devices, cables, etc.

#### Losses in asynchronous machines

The harmonic voltages (order  $h$ ) supplied to asynchronous machines provoke in the rotor the flow of currents with frequencies higher than 50 Hz that are the cause of additional losses.



## 4 Main effects of harmonics in installations

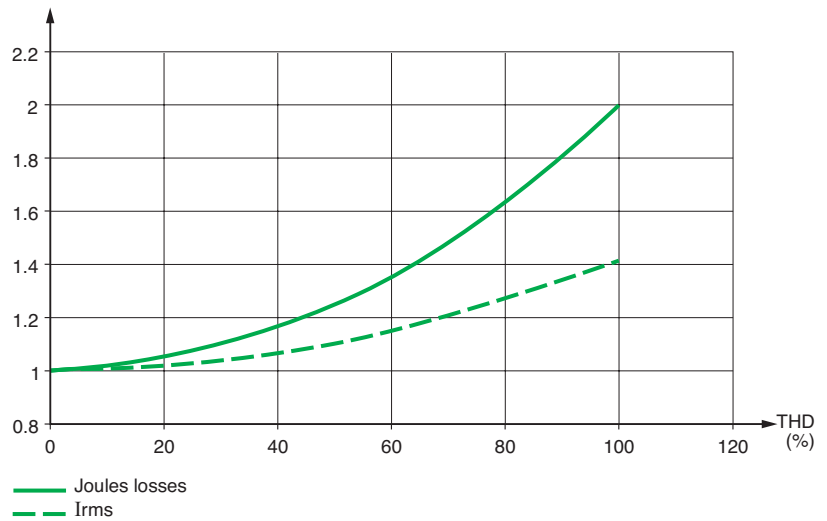


Fig. M8 : Increase in rms current and Joule losses as a function of the THD

### Orders of magnitude

- A virtually rectangular supply voltage provokes a **20% increase** in losses
- A supply voltage with harmonics  $u_5 = 8\%$  (of  $U_1$ , the fundamental voltage),  $u_7 = 5\%$ ,  $u_{11} = 3\%$ ,  $u_{13} = 1\%$ , i.e. total harmonic distortion  $THDu$  equal to 10%, results in additional losses of 6%

### Losses in transformers

Harmonic currents flowing in transformers provoke an increase in the “copper” losses due to the Joule effect and increased “iron” losses due to eddy currents. The harmonic voltages are responsible for “iron” losses due to hysteresis.

It is generally considered that losses in windings increase as the square of the  $THDi$  and that core losses increase linearly with the  $THDu$ .

In utility-distribution transformers, where distortion levels are limited, losses increase between 10 and 15%.

### Losses in capacitors

The harmonic voltages applied to capacitors provoke the flow of currents proportional to the frequency of the harmonics. These currents cause additional losses.

#### Example

A supply voltage has the following harmonics:  
Fundamental voltage  $U_1$ , harmonic voltages  $u_5 = 8\%$  (of  $U_1$ ),  $u_7 = 5\%$ ,  $u_{11} = 3\%$ ,  $u_{13} = 1\%$ , i.e. total harmonic distortion  $THDu$  equal to 10%. The amperage of the current is multiplied by 1.19. Joule losses are multiplied by  $1.19^2$ , i.e. 1.4.

## 4.3 Overloads on equipment

### Generators

Generators supplying non-linear loads must be derated due to the additional losses caused by harmonic currents.

The level of derating is approximately 10% for a generator where the overall load is made up of 30% of non-linear loads. It is therefore necessary to oversize the generator.

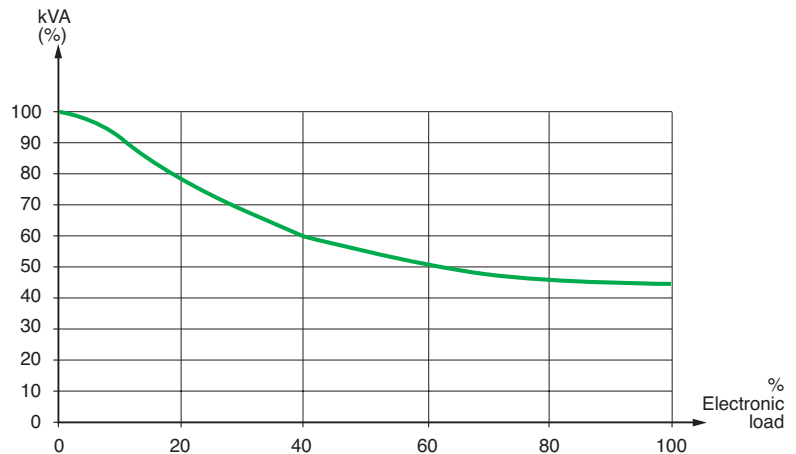
### Uninterruptible power systems (UPS)

The current drawn by computer systems has a very high crest factor. A UPS sized taking into account exclusively the rms current may not be capable of supplying the necessary peak current and may be overloaded.

## 4 Main effects of harmonics in installations

### Transformers

■ The curve presented below (see **Fig. M9**) shows the typical derating required for a transformer supplying electronic loads



**Fig. M9** : Derating required for a transformer supplying electronic loads

### Example

If the transformer supplies an overall load comprising 40% of electronic loads, it must be derated by 40%.

■ Standard UTE C15-112 provides a derating factor for transformers as a function of the harmonic currents.

$$k = \frac{1}{\sqrt{1 + 0.1 \left( \sum_{h=2}^{40} h^{1.6} T_h^2 \right)}}$$

$$T_h = \frac{I_h}{I_1}$$

Typical values:

- Current with a rectangular waveform (1/h spectrum <sup>(1)</sup>):  $k = 0.86$
- Frequency-converter current (THD  $\approx 50\%$ ):  $k = 0.80$

### Asynchronous machines

Standard IEC 60892 defines a weighted harmonic factor (Harmonic voltage factor) for which the equation and maximum value are provided below.

$$HVF = \sqrt{\sum_{h=2}^{13} \frac{U_h^2}{h^2}} \leq 0.02$$

### Example

A supply voltage has a fundamental voltage  $U_1$  and harmonic voltages  $u_3 = 2\%$  of  $U_1$ ,  $u_5 = 3\%$ ,  $u_7 = 1\%$ . The THDu is 3.7% and the MVF is 0.018. The MVF value is very close to the maximum value above which the machine must be derated. Practically speaking, for supply to the machine, a THDu of 10% must not be exceeded.

### Capacitors

According to IEC 60831-1 standard, the rms current flowing in the capacitors must not exceed 1.3 times the rated current.

Using the example mentioned above, the fundamental voltage  $U_1$ , harmonic voltages  $u_5 = 8\%$  (of  $U_1$ ),  $u_7 = 5\%$ ,  $u_{11} = 3\%$ ,  $u_{13} = 1\%$ , i.e. total harmonic

distortion THDu equal to 10%, the result is  $\frac{I_{rms}}{I_1} = 1.19$ , at the rated voltage. For a voltage equal to 1.1 times the rated voltage, the current limit  $\frac{I_{rms}}{I_1} = 1.3$  is reached and it is necessary to resize the capacitors.

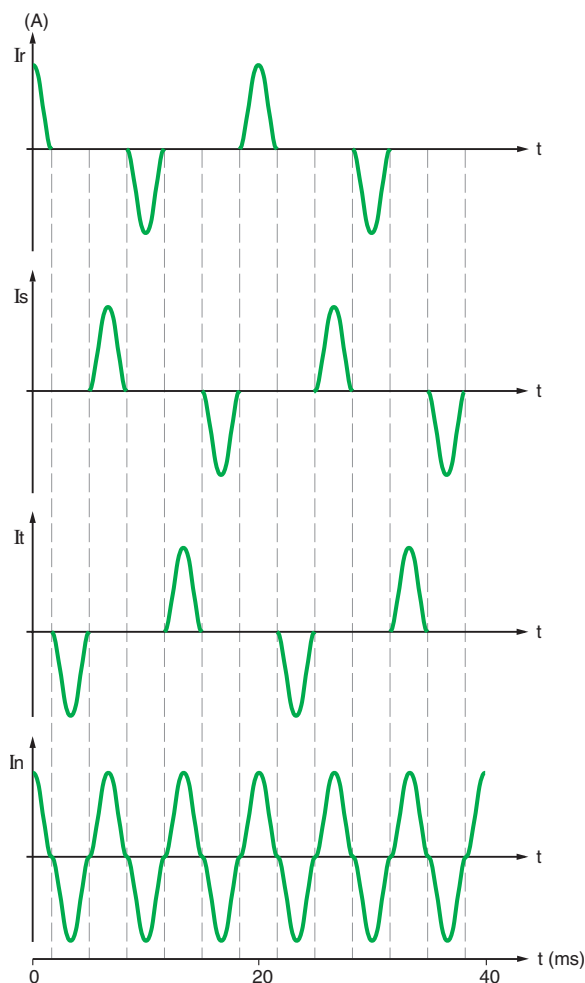
(1) In fact, the current waveform is similar to a rectangular waveform. This is the case for all current rectifiers (three-phase rectifiers, induction furnaces).

## 4 Main effects of harmonics in installations

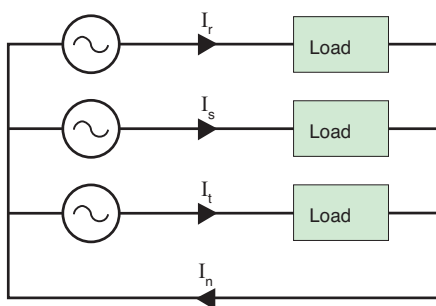
### Neutral conductors

Consider a system made up of a balanced three-phase source and three identical single-phase loads connected between the phases and the neutral (see **Fig. M10**). **Figure M11** shows an example of the currents flowing in the three phases and the resulting current in the neutral conductor.

In this example, the current in the neutral conductor has an rms value that is higher than the rms value of the current in a phase by a factor equal to the square root of 3. The neutral conductor must therefore be sized accordingly.



**Fig. M11** : Example of the currents flowing in the various conductors connected to a three-phase load ( $I_n = I_r + I_s + I_t$ )



**Fig. M10** : Flow of currents in the various conductors connected to a three-phase source

### 4.4 Disturbances affecting sensitive loads

#### Effects of distortion in the supply voltage

Distortion of the supply voltage can disturb the operation of sensitive devices:

- Regulation devices (temperature)
- Computer hardware
- Control and monitoring devices (protection relays)

#### Distortion of telephone signals

Harmonics cause disturbances in control circuits (low current levels). The level of distortion depends on the distance that the power and control cables run in parallel, the distance between the cables and the frequency of the harmonics.

## 4 Main effects of harmonics in installations

### 4.5 Economic impact

#### Energy losses

Harmonics cause additional losses (Joule effect) in conductors and equipment.

#### Higher subscription costs

The presence of harmonic currents can require a higher subscribed power level and consequently higher costs.

What is more, utilities will be increasingly inclined to charge customers for major sources of harmonics.

#### Oversizing of equipment

- Derating of power sources (generators, transformers and UPSs) means they must be oversized
- Conductors must be sized taking into account the flow of harmonic currents. In addition, due to the skin effect, the resistance of these conductors increases with frequency. To avoid excessive losses due to the Joule effect, it is necessary to oversize conductors
- Flow of harmonics in the neutral conductor means that it must be oversized as well

#### Reduced service life of equipment

When the level of distortion in the supply voltage approaches 10%, the duration of the service life of equipment is significantly reduced. The reduction has been estimated at:

- 32.5% for single-phase machines
- 18% for three-phase machines
- 5% for transformers

To maintain the service lives corresponding to the rated load, equipment must be oversized.

#### Nuisance tripping and installation shutdown

Circuit-breakers in the installation are subjected to current peaks caused by harmonics.

These current peaks cause nuisance tripping with the resulting production losses, as well as the costs corresponding to the time required to start the installation up again.

#### Examples

Given the economic consequences for the installations mentioned below, it was necessary to install harmonic filters.

##### Computer centre for an insurance company

In this centre, nuisance tripping of a circuit-breaker was calculated to have cost 100 k€ per hour of down time.

##### Pharmaceutical laboratory

Harmonics caused the failure of a generator set and the interruption of a long-duration test on a new medication. The consequences were a loss estimated at 17 M€.

##### Metallurgy factory

A set of induction furnaces caused the overload and destruction of three transformers ranging from 1500 to 2500 kVA over a single year. The cost of the interruptions in production were estimated at 20 k€ per hour.

##### Factory producing garden furniture

The failure of variable-speed drives resulted in production shutdowns estimated at 10 k€ per hour.

## 5 Essential indicators of harmonic distortion and measurement principles

A number of indicators are used to quantify and evaluate the harmonic distortion in current and voltage waveforms, namely:

- Power factor
- Crest factor
- Distortion power
- Harmonic spectrum
- Harmonic-distortion values

These indicators are indispensable in determining any necessary corrective action.

### 5.1 Power factor

#### Definition

The power factor PF is the ratio between the active power P and the apparent power S.

$$PF = \frac{P}{S}$$

Among electricians, there is often confusion with:

$$\cos \varphi = \frac{P_1}{S_1}$$

Where

P<sub>1</sub> = active power of the fundamental

S<sub>1</sub> = apparent power of the fundamental

The cos φ concerns exclusively the fundamental frequency and therefore differs from the power factor PF when there are harmonics in the installation.

#### Interpreting the power factor

An initial indication that there are significant amounts of harmonics is a measured power factor PF that is different (lower) than the measured cos φ.

### 5.2 Crest factor

#### Definition

The crest factor is the ratio between the value of the peak current or voltage (I<sub>m</sub> or U<sub>m</sub>) and its rms value.

- For a sinusoidal signal, the crest factor is therefore equal to  $\sqrt{2}$ .
- For a non-sinusoidal signal, the crest factor can be either greater than or less than  $\sqrt{2}$ .

In the latter case, the crest factor signals divergent peak values with respect to the rms value.

#### Interpretation of the crest factor

The typical crest factor for the current drawn by non-linear loads is much higher than  $\sqrt{2}$ . It is generally between 1.5 and 2 and can even reach 5 in critical cases. A high crest factor signals high transient overcurrents which, when detected by protection devices, can cause nuisance tripping.

### 5.3 Power values and harmonics

#### Active power

The active power P of a signal comprising harmonics is the sum of the active powers resulting from the currents and voltages of the same order.

#### Reactive power

Reactive power is defined exclusively in terms of the fundamental, i.e.

$$Q = U_1 \times I_1 \times \sin \varphi_1$$

#### Distortion power

When harmonics are present, the distortion power D is defined as  $D = (S^2 - P^2 - Q^2)^{1/2}$  where S is the apparent power.

## 5 Essential indicators of harmonic distortion and measurement principles

### 5.4 Harmonic spectrum and harmonic distortion

#### Principle

Each type of device causing harmonics draws a particular form of harmonic current (amplitude and phase displacement).

These values, notably the amplitude for each harmonic order, are essential for analysis.

#### Individual harmonic distortion (or harmonic distortion of order h)

The individual harmonic distortion is defined as the percentage of harmonics for order h with respect to the fundamental.

$$u_h(\%) = 100 \frac{U_h}{U_1}$$

or

$$i_h(\%) = 100 \frac{I_h}{I_1}$$

#### Harmonic spectrum

By representing the amplitude of each harmonic order with respect to its frequency, it is possible to obtain a graph called the harmonic spectrum.

**Figure M12** shows an example of the harmonic spectrum for a rectangular signal.

#### Rms value

The rms value of the voltage and current can be calculated as a function of the rms value of the various harmonic orders.

$$I_{rms} = \sqrt{\sum_{h=1}^{\infty} I_h^2}$$

and

$$U_{rms} = \sqrt{\sum_{h=1}^{\infty} U_h^2}$$

### 5.5 Total harmonic distortion (THD)

The term THD means Total Harmonic Distortion and is a widely used notion in defining the level of harmonic content in alternating signals.

#### Definition of THD

For a signal y, the THD is defined as:

$$THD = \frac{\sqrt{\sum_{h=2}^{\infty} y_h^2}}{y_1}$$

This complies with the definition given in standard IEC 61000-2-2.

Note that the value can exceed 1.

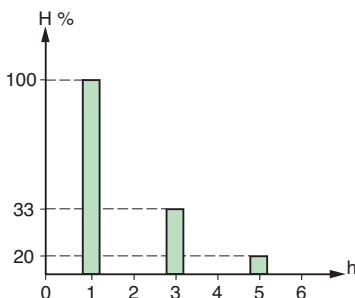
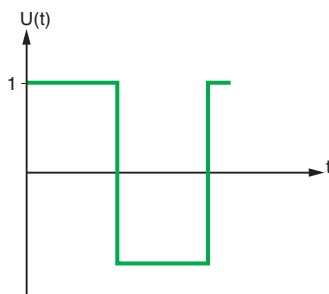
According to the standard, the variable h can be limited to 50. The THD is the means to express as a single number the distortion affecting a current or voltage flowing at a given point in the installation.

The THD is generally expressed as a percentage.

#### Current or voltage THD

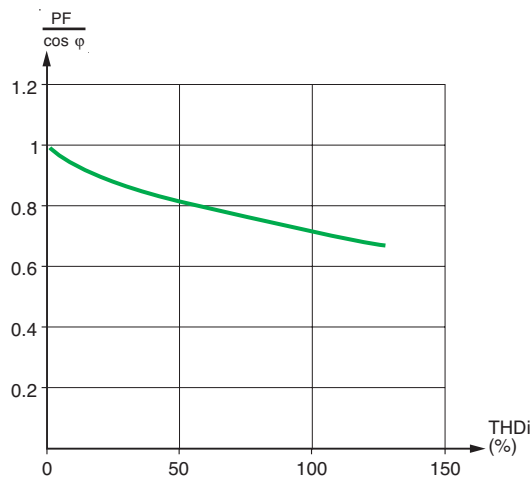
For current harmonics, the equation is:

$$THD_i = \frac{\sqrt{\sum_{h=2}^{\infty} I_h^2}}{I_1}$$



**Fig. M12 :** Harmonic spectrum of a rectangular signal, for a voltage U (t)

## 5 Essential indicators of harmonic distortion and measurement principles



**Fig. M13** : Variation in  $\frac{PF}{\cos \varphi}$  as a function of the THDi, where  $THDu = 0$

The equation below is equivalent to the above, but easier and more direct when the total rms value is available:

$$THDi = \sqrt{\left(\frac{I_{rms}}{I_1}\right)^2 - 1}$$

For voltage harmonics, the equation is:

$$THDu = \frac{\sqrt{\sum_{h=2}^{\infty} U_h^2}}{U_1}$$

### Relation between power factor and THD (see Fig. M13)

When the voltage is sinusoidal or virtually sinusoidal, it may be said that:

$$P \approx P_1 = U_1 \cdot I_1 \cdot \cos \varphi_1$$

$$\text{Consequently : } PF = \frac{P}{S} \approx \frac{U_1 \cdot I_1 \cdot \cos \varphi_1}{U_1 \cdot I_{rms}}$$

$$\text{as: } \frac{I_1}{I_{rms}} = \frac{1}{\sqrt{1 + THDi^2}}$$

$$\text{hence: } PF \approx \frac{\cos \varphi_1}{\sqrt{1 + THDi^2}}$$

Figure M13 shows a graph of  $\frac{PF}{\cos \varphi}$  as a function of THDi.

### 5.6 Usefulness of the various indicators

The THDu characterises the distortion of the voltage wave.

Below are a number of THDu values and the corresponding phenomena in the installation:

- THDu under 5% - normal situation, no risk of malfunctions
- 5 to 8% - significant harmonic pollution, some malfunctions are possible
- Higher than 8% - major harmonic pollution, malfunctions are probable. In-depth analysis and the installation of attenuation devices are required

The THDi characterises the distortion of the current wave.

The disturbing device is located by measuring the THDi on the incomer and each outgoing of the various circuits and thus following the harmonic trail.

Below are a number of THDi values and the corresponding phenomena in the installation:

- THDi under 10% - normal situation, no risk of malfunctions
- 10 to 50% - significant harmonic pollution with a risk of temperature rise and the resulting need to oversize cables and sources
- Higher than 50% - major harmonic pollution, malfunctions are probable. In-depth analysis and the installation of attenuation devices are required

#### Power factor PF

Used to evaluate the necessary oversizing for the power source of the installation.

#### Crest factor

Used to characterise the aptitude of a generator (or UPS) to supply high instantaneous currents. For example, computer equipment draws highly distorted current for which the crest factor can reach 3 to 5.

#### Spectrum (decomposition of the signal into frequencies)

It provides a different representation of electrical signals and can be used to evaluate their distortion.

**M13**

## 6 Measuring the indicators

### 6.1 Devices used to measure the indicators

#### Device selection

The traditional observation and measurement methods include:

- Observations using an oscilloscope

An initial indication on the distortion affecting a signal can be obtained by viewing the current or the voltage on an oscilloscope.

The waveform, when it diverges from a sinusoidal, clearly indicates the presence of harmonics. Current and voltage peaks can be viewed.

Note, however, that this method does not offer precise quantification of the harmonic components

- Analogue spectral analysers

They are made up of passband filters coupled with an rms voltmeter. They offer mediocre performance and do not provide information on phase displacement.

**Only the recent digital analysers can determine sufficiently precisely the values of all the mentioned indicators.**

#### Functions of digital analysers

The microprocessors in digital analysers:

- Calculate the values of the harmonic indicators (power factor, crest factor, distortion power, THD)

- Carry out various complementary functions (corrections, statistical detection, measurement management, display, communication, etc.)

- In multi-channel analysers, supply virtually in real time the simultaneous spectral decomposition of the currents and voltages

#### Analyser operation and data processing

The analogue signals are converted into a series of numerical values.

Using this data, an algorithm implementing the Fast Fourier Transform (FFT) calculates the amplitudes and the phases of the harmonics over a large number of time windows.

Most digital analysers measure harmonics up to order 20 or 25 when calculating the THD.

Processing of the successive values calculated using the FFT (smoothing, classification, statistics) can be carried out by the measurement device or by external software.

### 6.2 Procedures for harmonic analysis of distribution networks

Measurements are carried out on industrial or commercial site:

- Preventively, to obtain an overall idea on distribution-network status (network map)

- In view of corrective action:

- To determine the origin of a disturbance and determine the solutions required to eliminate it

- To check the validity of a solution (followed by modifications in the distribution network to check the reduction in harmonics)

#### Operating mode

The current and voltage are studied:

- At the supply source

- On the busbars of the main distribution switchboard (or on the MV busbars)

- On each outgoing circuit in the main distribution switchboard (or on the MV busbars)

For the measurements, it is necessary to know the precise operating conditions of the installation and particularly the status of the capacitor banks (operating, not operating, the number of disconnected steps).

#### Analysis results

- Determine any necessary derating of equipment in the installation or

- Quantify any necessary harmonic protection and filtering systems to be installed in the distribution network

- Enable comparison between the measured values and the reference values of the utility (maximum harmonic values, acceptable values, reference values)



### Use of measurement devices

Measurement devices serve to show both the instantaneous and long-term effects of harmonics. Analysis requires values spanning durations ranging from a few seconds to several minutes over observation periods of a number of days.

The required values include:

- The amplitudes of the harmonic currents and voltages
- The individual harmonic content of each harmonic order of the current and voltage
- The THD for the current and voltage
- Where applicable, the phase displacement between the harmonic voltage and current of the same harmonic order and the phase of the harmonics with respect to a common reference (e.g. the fundamental voltage)

## 6.3 Keeping a close eye on harmonics

The harmonic indicators can be measured:

- Either by devices permanently installed in the distribution network
- Or by an expert present at least a half day on the site (limited perception)

### Permanent devices are preferable

For a number of reasons, the installation of permanent measurement devices in the distribution network is preferable.

- The presence of an expert is limited in time. Only a number of measurements at different points in the installation and over a sufficiently long period (one week to a month) provide an overall view of operation and take into account all the situations that can occur following:
  - Fluctuations in the supply source
  - Variations in the operation of the installation
  - The addition of new equipment in the installation
- Measurement devices installed in the distribution network prepare and facilitate the diagnosis of the experts, thus reducing the number and duration of their visits
- Permanent measurement devices detect any new disturbances arising following the installation of new equipment, the implementation of new operating modes or fluctuations in the supply network

### Take advantage of built-in measurement and detection devices

Measurement and detection devices built into the electrical distribution equipment:

- For an overall evaluation of network status (preventive analysis), avoid:
  - Renting measurement equipment
  - Calling in experts
  - Having to connect and disconnect the measurement equipment.

For the overall evaluation of network status, the analysis on the main low-voltage distribution switchboards (MLVS) can often be carried out by the incoming device and/or the measurement devices equipping each outgoing circuit

- For corrective action, are the means to:
  - Determine the operating conditions at the time of the incident
  - Draw up a map of the distribution network and evaluate the implemented solution

The diagnosis is improved by the use of equipment intended for the studied problem.

*PowerLogic System with Power Meter and Circuit Monitor, Micrologic offer a complete range of devices for the detection of harmonic distortion*

Measurements are the first step in gaining control over harmonic pollution. Depending on the conditions in each installation, different types of equipment provide the necessary solution.

### Power-monitoring units

#### Power Meter and Circuit Monitor in the PowerLogic System

These products offer high-performance measurement capabilities for low and medium-voltage distribution networks. They are digital units that include power-quality monitoring functions.

PowerLogic System is a complete offer comprising Power Meter (PM) and Circuit Monitor (CM). This highly modular offer covers needs ranging from the most simple (Power Meter) up to highly complex requirements (Circuit Monitor). These products can be used in new or existing installations where the level of power quality must be excellent. The operating mode can be local and/or remote.

Depending on its position in the distribution network, a Power Meter provides an initial indication on power quality. The main measurements carried out by a Power Meter are:

- Current and voltage THD
- Power factor

Depending on the version, these measurements can be combined with time-stamping and alarm functions.

A Circuit Monitor (see **Fig. M14**) carries out a detailed analysis of power quality and also analyses disturbances on the distribution network. The main functions of a Circuit Monitor are:

- Measurement of over 100 electrical parameters
- Storage in memory and time-stamping of minimum and maximum values for each electrical parameter
- Alarm functions tripped by electrical parameter values
- Recording of event data
- Recording of current and voltage disturbances
- Harmonic analysis
- Waveform capture (disturbance monitoring)

#### Micrologic - a power-monitoring unit built into the circuit-breaker

For new installations, the Micrologic H control unit (see **Fig. M15**), an integral part of Masterpact power circuit-breakers, is particularly useful for measurements at the head of an installation or on large outgoing circuits.

The Micrologic H control unit offers precise analysis of power quality and detailed diagnostics on events. It is designed for operation in conjunction with a switchboard display unit or a supervisor. It can:

- Measure current, voltage, active and reactive power
- Measure current and voltage THD
- Display the amplitude and phase of current and voltage harmonics up to the 51<sup>st</sup> order
- Carry out waveform capture (disturbance monitoring)

The functions offered by the Micrologic H control unit are equivalent to those of a Circuit Monitor.

### Operation of power-monitoring units

#### Software for remote operation and analysis

In the more general framework of a distribution network requiring monitoring, the possibility of interconnecting these various devices can be offered in a communication network, thus making it possible to centralise information and obtain an overall view of disturbances throughout the distribution network.

Depending on the application, the operator can then carry out measurements in real time, calculate demand values, run waveform captures, anticipate on alarms, etc.

The power-monitoring units transmit all the available data over either a Modbus, Digiport or Ethernet network.

The essential goal of this system is to assist in identifying and planning maintenance work. It is an effective means to reduce servicing time and the cost of temporarily installing devices for on-site measurements or the sizing of equipment (filters).

#### Supervision software SMS

SMS is a very complete software used to analyse distribution networks, in conjunction with the products in the PowerLogic System. Installed on a standard PC, it can:

- Display measurements in real time
- Display historical logs over a given period
- Select the manner in which data is presented (tables, various curves)
- Carry out statistical processing of data (display bar charts)



**M16** Fig. M14 : Circuit monitor



**Fig. M15** : Micrologic H control unit with harmonic metering for Masterpact NT and NW circuit-breakers

## 8 Solutions to attenuate harmonics

There are three different types of solutions to attenuate harmonics:

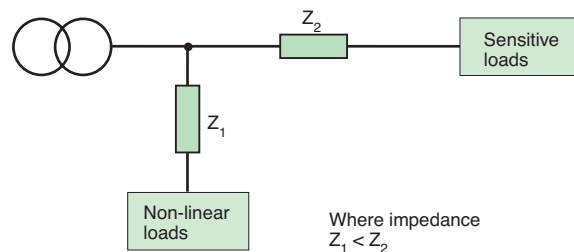
- Modifications in the installation
- Special devices in the supply system
- Filtering

### 8.1 Basic solutions

To limit the propagation of harmonics in the distribution network, different solutions are available and should be taken into account particularly when designing a new installation.

#### Position the non-linear loads upstream in the system

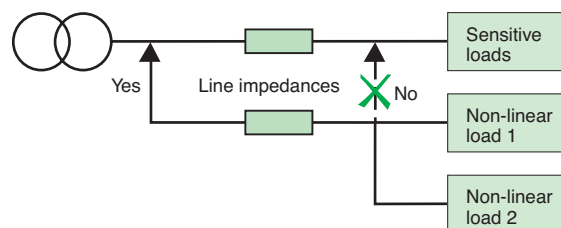
Overall harmonic disturbances increase as the short-circuit power decreases. All economic considerations aside, it is preferable to connect the non-linear loads as far upstream as possible (see **Fig. M16**).



**Fig. M16** : Non-linear loads positioned as far upstream as possible (recommended layout)

#### Group the non-linear loads

When preparing the single-line diagram, the non-linear devices should be separated from the others (see **Fig. M17**). The two groups of devices should be supplied by different sets of busbars.



**Fig. M17** : Grouping of non-linear loads and connection as far upstream as possible (recommended layout)

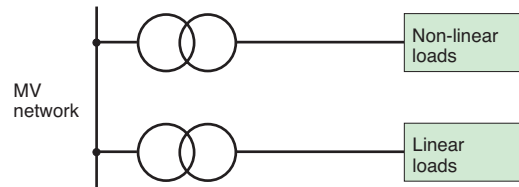
#### Create separate sources

In attempting to limit harmonics, an additional improvement can be obtained by creating a source via a separate transformer as indicated in the **Figure M18** next page.

The disadvantage is the increase in the cost of the installation.

**M17**

## 8 Solutions to attenuate harmonics

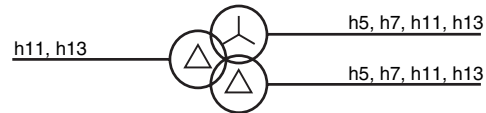


**Fig. M18** : Supply of non-linear loads via a separate transformer

### Transformers with special connections

Different transformer connections can eliminate certain harmonic orders, as indicated in the examples below:

- A Dyd connection suppresses 5<sup>th</sup> and 7<sup>th</sup> harmonics (see **Fig. M19**)
- A Dy connection suppresses the 3<sup>rd</sup> harmonic
- A DZ 5 connection suppresses the 5<sup>th</sup> harmonic



**Fig. M19** : A Dyd transformer blocks propagation of the 5<sup>th</sup> and 7<sup>th</sup> harmonics to the upstream network

### Install reactors

When variable-speed drives are supplied, it is possible to smooth the current by installing line reactors. By increasing the impedance of the supply circuit, the harmonic current is limited.

Installation of harmonic suppression reactors on capacitor banks increases the impedance of the reactor/capacitor combination for high-order harmonics.

This avoids resonance and protects the capacitors.

### Select the suitable system earthing arrangement

#### TNC system

In the TNC system, a single conductor (PEN) provides protection in the event of an earth fault and the flow of unbalance currents.

Under steady-state conditions, the harmonic currents flow in the PEN. The latter, however, has a certain impedance with as a result slight differences in potential (a few volts) between devices that can cause electronic equipment to malfunction.

The TNC system must therefore be reserved for the supply of power circuits at the head of the installation and must not be used to supply sensitive loads.

#### TNS system

This system is recommended if harmonics are present.

The neutral conductor and the protection conductor PE are completely separate and the potential throughout the distribution network is therefore more uniform.

## 8.2 Harmonic filtering

In cases where the preventive action presented above is insufficient, it is necessary to equip the installation with filtering systems.

There are three types of filters:

- Passive
- Active
- Hybrid

## 8 Solutions to attenuate harmonics

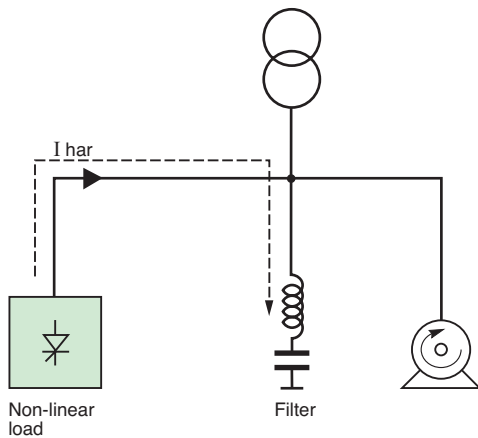


Fig. M20 : Operating principle of a passive filter

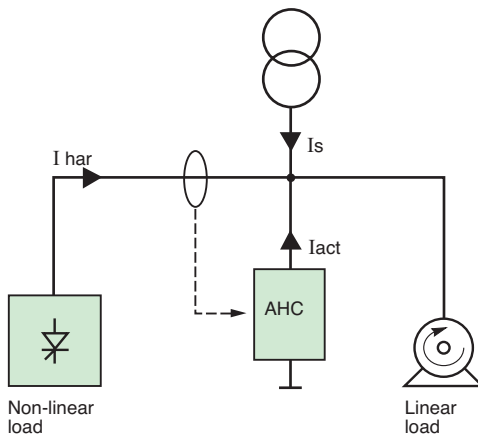


Fig. M21 : Operating principle of an active filter

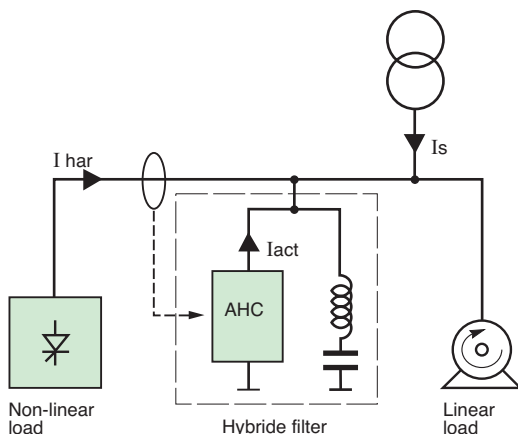


Fig. M22 : Operating principle of a hybrid filter

### Passive filters

#### Typical applications

- Industrial installations with a set of non-linear loads representing more than 200 kVA (variable-speed drives, UPSs, rectifiers, etc.)
- Installations requiring power-factor correction
- Installations where voltage distortion must be reduced to avoid disturbing sensitive loads
- Installations where current distortion must be reduced to avoid overloads

#### Operating principle

An LC circuit, tuned to each harmonic order to be filtered, is installed in parallel with the non-linear load (see Fig. M20). This bypass circuit absorbs the harmonics, thus avoiding their flow in the distribution network.

Generally speaking, the passive filter is tuned to a harmonic order close to the order to be eliminated. Several parallel-connected branches of filters can be used if a significant reduction in the distortion of a number of harmonic orders is required.

### Active filters (active harmonic conditioner)

#### Typical applications

- Commercial installations with a set of non-linear loads representing less than 200 kVA (variable-speed drives, UPSs, office equipment, etc.)
- Installations where current distortion must be reduced to avoid overloads.

#### Operating principle

These systems, comprising power electronics and installed in series or parallel with the non-linear load, compensate the harmonic current or voltage drawn by the load.

Figure M21 shows a parallel-connected active harmonic conditioner (AHC) compensating the harmonic current ( $I_{har} = -I_{act}$ ).

The AHC injects in opposite phase the harmonics drawn by the non-linear load, such that the line current  $I_s$  remains sinusoidal.

### Hybrid filters

#### Typical applications

- Industrial installations with a set of non-linear loads representing more than 200 kVA (variable-speed drives, UPSs, rectifiers, etc.)
- Installations requiring power-factor correction
- Installations where voltage distortion must be reduced to avoid disturbing sensitive loads
- Installations where current distortion must be reduced to avoid overloads
- Installations where strict limits on harmonic emissions must be met

#### Operating principle

Passive and active filters are combined in a single system to constitute a hybrid filter (see Fig. M22). This new filtering solution offers the advantages of both types of filters and covers a wide range of power and performance levels.

### Selection criteria

#### Passive filter

It offers both power-factor correction and high current-filtering capacity. Passive filters also reduce the harmonic voltages in installations where the supply voltage is disturbed. If the level of reactive power supplied is high, it is advised to turn off the passive filter at times when the percent load is low. Preliminary studies for a filter must take into account the possible presence of a power factor correction capacitor bank which may have to be eliminated.

#### Active harmonic conditioners

They filter harmonics over a wide range of frequencies and can adapt to any type of load.

On the other hand, power ratings are low.

#### Hybrid filters

They combine the performance of both active and passive filters.

M19

## 8 Solutions to attenuate harmonics

*A complete set of services can be offered to eliminate harmonics:*

- Installation analysis
- Measurement and monitoring systems
- Filtering solutions

### 8.3 The method

The best solution, in both technical and financial terms, is based on the results of an in-depth study.

#### Harmonic audit of MV and LV networks

By calling on an expert, you are guaranteed that the proposed solution will produce effective results (e.g. a guaranteed maximum THDu).

A harmonic audit is carried out by an engineer specialised in the disturbances affecting electrical distribution networks and equipped with powerful analysis and simulation equipment and software.

The steps in an audit are the following:

- Measurement of disturbances affecting current and phase-to-phase and phase-to-neutral voltages at the supply source, the disturbed outgoing circuits and the non-linear loads
- Computer modelling of the phenomena to obtain a precise explanation of the causes and determine the best solutions
- A complete audit report presenting:
  - The current levels of disturbances
  - The maximum permissible levels of disturbances (IEC 61000, IEC 34, etc.)
- A proposal containing solutions with guaranteed levels of performance
- Finally, implementation of the selected solution, using the necessary means and resources.

The entire audit process is certified ISO 9002.

### 8.4 Specific products

#### Passive filters

Passive filters are made up of coils and capacitors set up in resonant circuits tuned to the specific harmonic order that must be eliminated.

A system may comprise a number of filters to eliminate several harmonic orders. Suitable for 400 V three-phase voltages, the power ratings can reach:

- 265 kvar / 470 A for harmonic order 5
- 145 kvar / 225 A for harmonic order 7
- 105 kvar / 145 A for harmonic order 11

Passive filters can be created for all voltage and current levels.

#### Active filters

- SineWave active harmonic conditioners
  - Suitable for 400 V three-phase voltages, they can deliver between 20 and 120 A per phase
  - SineWave covers all harmonic orders from 2 to 25. Conditioning can be total or target specific harmonic orders
  - Attenuation: THDi load / THDi upstream greater than 10 at rated capacity
  - Functions include power factor correction, conditioning of zero-sequence harmonics, diagnostics and maintenance system, parallel connection, remote control, Ibus/RS485 communication interface
- Accusine active filters
  - Suitable for 400 and 480 V three-phase voltages, they can filter between 50 and 30 A per phase
  - All harmonic orders up to 50 are filtered
  - Functions include power factor correction, parallel connection, instantaneous response to load variations

#### Hybrid filters

These filters combine the advantages of both a passive filter and the SineWave active harmonic conditioner in a single system.

# Chapter N

## Characteristics of particular sources and loads

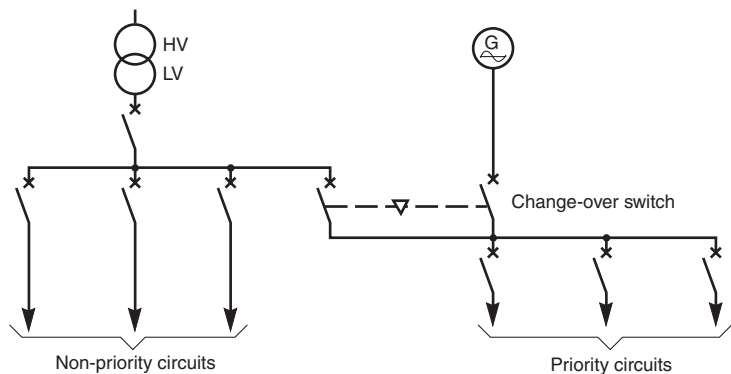
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# 1 Protection of a LV generator set and the downstream circuits

Most industrial and large commercial electrical installations include certain important loads for which a power supply must be maintained, in the event that the utility electrical supply fails:

- Either, because safety systems are involved (emergency lighting, automatic fire-protection equipment, smoke dispersal fans, alarms and signalization, and so on...) or
- Because it concerns priority circuits, such as certain equipment, the stoppage of which would entail a loss of production, or the destruction of a machine tool, etc.

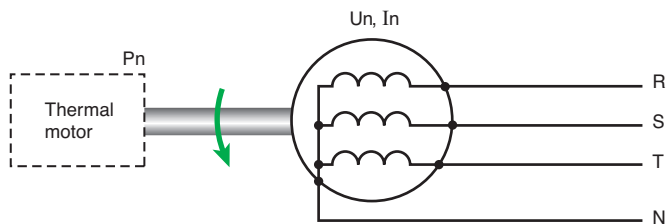
One of the current means of maintaining a supply to the so-called “priority” loads, in the event that other sources fail, is to install a diesel generator set connected, via a change-over switch, to an emergency-power standby switchboard, from which the priority services are fed (see **Fig. N1**).



**Fig N1** : Example of circuits supplied from a transformer or from an alternator

## 1.1 Generator protection

**Figure N2** below shows the electrical sizing parameters of a Generator Set.  $P_n$ ,  $U_n$  and  $I_n$  are, respectively, the power of the thermal motor, the rated voltage and the rated current of the generator.



**Fig N2** : Block diagram of a generator set

### Overload protection

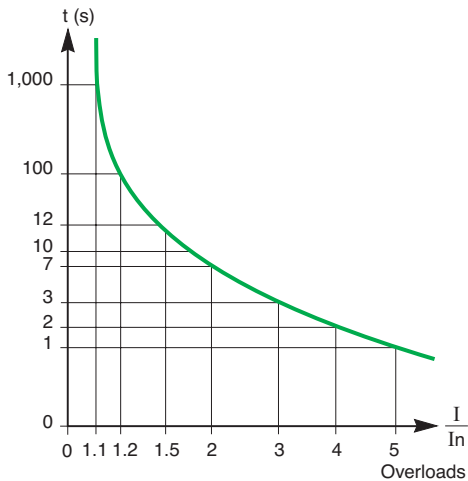
The generator protection curve must be analysed (see **Fig. N3**). Standards and requirements of applications can also stipulate specific overload conditions. For example:

$I/I_n$	$t$
1.1	> 1 h
1.5	30 s

The setting possibilities of the overload protection devices (or Long Time Delay) will closely follow these requirements.

#### Note on overloads

- For economic reasons, the thermal motor of a replacement set may be strictly sized for its nominal power. If there is an active power overload, the diesel motor will stall. The active power balance of the priority loads must take this into account
- A production set must be able to withstand operating overloads:
  - One hour overload
  - One hour 10% overload every 12 hours (Prime Power)



**Fig N3** : Example of an overload curve  $t = f(I/I_n)$



# 1 Protection of a LV generator set and the downstream circuits

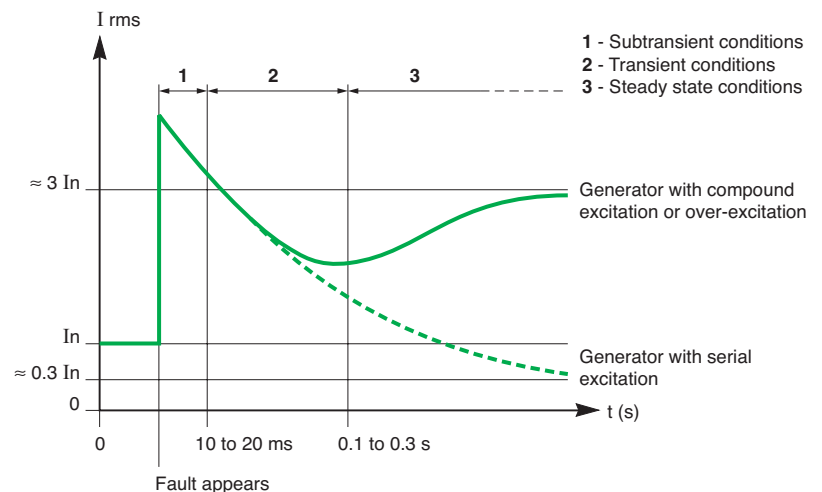
## Short-circuit current protection

### Making the short-circuit current

The short-circuit current is the sum:

- Of an aperiodic current
- Of a damped sinusoidal current

The short-circuit current equation shows that it is composed of three successive phases (see **Fig. N4**).



**Fig N4** : Short-circuit current level during the 3 phases

#### ■ Subtransient phase

When a short-circuit appears at the terminals of a generator, the current is first made at a relatively high value of around 6 to 12  $I_n$  during the first cycle (0 to 20 ms).

The amplitude of the short-circuit output current is defined by three parameters:

- The subtransient reactance of the generator
- The level of excitation prior to the time of the fault and
- The impedance of the faulty circuit.

The short-circuit impedance of the generator to be considered is the subtransient reactance  $x''_d$  expressed in % by the manufacturer. The typical value is 10 to 15%. We determine the subtransient short-circuit impedance of the generator:

$$X''_d(\text{ohms}) = \frac{U_n^2 x''_d}{100 S} \text{ where } S = \sqrt{3} U_n I_n$$

#### ■ Transient phase

The transient phase is placed 100 to 500 ms after the time of the fault. Starting from the value of the fault current of the subtransient period, the current drops to 1.5 to 2 times the current  $I_n$ .

The short-circuit impedance to be considered for this period is the transient reactance  $x'_d$  expressed in % by the manufacturer. The typical value is 20 to 30%.

#### ■ Steady state phase

The steady state occurs after 500 ms.

When the fault persists, the output voltage collapses and the exciter regulation seeks to raise this output voltage. The result is a stabilised sustained short-circuit current:

- If generator excitation does not increase during a short-circuit (no field overexcitation) but is maintained at the level preceding the fault, the current stabilises at a value that is given by the synchronous reactance  $X_d$  of the generator. The typical value of  $x_d$  is greater than 200%. Consequently, the final current will be less than the full-load current of the generator, normally around 0.5  $I_n$ .
- If the generator is equipped with maximum field excitation (field overriding) or with compound excitation, the excitation "surge" voltage will cause the fault current to increase for 10 seconds, normally to 2 to 3 times the full-load current of the generator.

# 1 Protection of a LV generator set and the downstream circuits

## Calculating the short-circuit current

Manufacturers normally specify the impedance values and time constants required for analysis of operation in transient or steady state conditions (see **Fig. N5**).

(kVA)	75	200	400	800	1,600	2,500
x''d	10.5	10.4	12.9	10.5	18.8	19.1
x'd	21	15.6	19.4	18	33.8	30.2
xd	280	291	358	280	404	292

**Fig N5** : Example of impedance table (in %)

Resistances are always negligible compared with reactances. The parameters for the short-circuit current study are:

■ Value of the short-circuit current at generator terminals

Short-circuit current amplitude in transient conditions is:

$$I_{sc3} = \frac{I_n}{X'd} \frac{1}{\sqrt{3}} \quad (X'd \text{ in ohms})$$

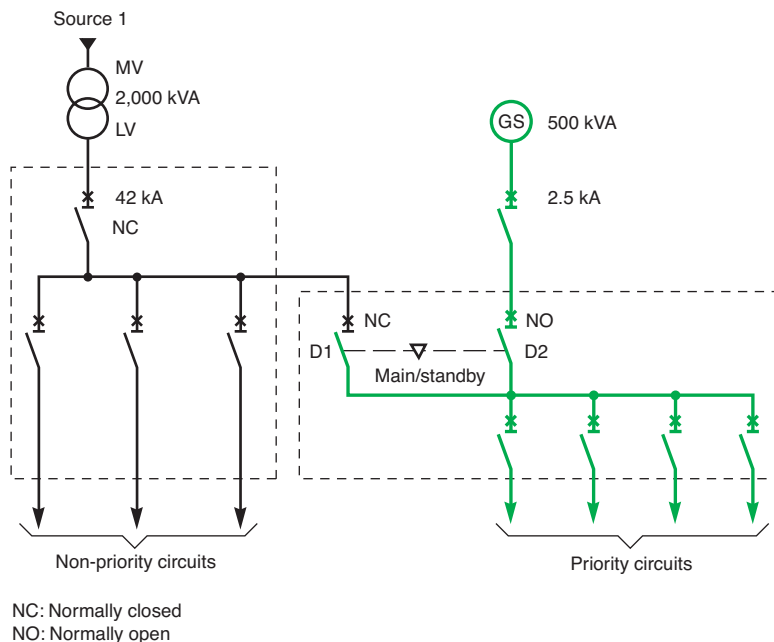
or

$$I_{sc3} = \frac{I_n}{x'd} 100 \quad (x'd \text{ in \%})$$

$I_n$  is the generator phase-to-phase output voltage.

**Note:** This value can be compared with the short-circuit current at the terminals of a transformer. Thus, for the same power, currents in event of a short-circuit close to a generator will be 5 to 6 times weaker than those that may occur with a transformer (main source).

This difference is accentuated still further by the fact that generator set power is normally less than that of the transformer (see **Fig. N6**).



**Fig N6** : Example of a priority services switchboard supplied (in an emergency) from a standby generator set

When the LV network is supplied by the Main source 1 of 2,000 kVA, the short-circuit current is 42 kA at the main LV board busbar. When the LV network is supplied by the Replacement Source 2 of 500 kVA with transient reactance of 30%, the short-circuit current is made at approx. 2.5 kA, i.e. at a value 16 times weaker than with the Main source.

# 1 Protection of a LV generator set and the downstream circuits

## 1.2 Downstream LV network protection

### Priority circuit protection

#### Choice of breaking capacity

This must be systematically checked with the characteristics of the main source (MV/LV transformer).

#### Setting of the Short Time Delay (STD) tripping current

##### ■ Subdistribution boards

The ratings of the protection devices for the subdistribution and final distribution circuits are always lower than the generator rated current. Consequently, except in special cases, conditions are the same as with transformer supply.

##### ■ Main LV switchboard

□ The sizing of the main feeder protection devices is normally similar to that of the generator set. Setting of the STD must allow for the short-circuit characteristic of the generator set (see "Short-circuit current protection" before)

□ Discrimination of protection devices on the priority feeders must be provided in generator set operation (it can even be compulsory for safety feeders). It is necessary to check proper staggering of STD setting of the protection devices of the main feeders with that of the subdistribution protection devices downstream (normally set for distribution circuits at 10 In).

**Note:** When operating on the generator set, use of a low sensitivity Residual Current Device enables management of the insulation fault and ensures very simple discrimination.

### Safety of people

In the IT (2<sup>nd</sup> fault) and TN grounding systems, protection of people against indirect contacts is provided by the STD protection of circuit-breakers. Their operation on a fault must be ensured, whether the installation is supplied by the main source (Transformer) or by the replacement source (generator set).

#### Calculating the insulation fault current

Zero-sequence reactance formulated as a% of U<sub>0</sub> by the manufacturer x'o.

The typical value is 8%.

The phase-to-neutral single-phase short-circuit current is given by:

$$I_f = \frac{U_n \sqrt{3}}{2 X'd + X'o}$$

The insulation fault current in the TN system is slightly greater than the three phase fault current. For example, in event of an insulation fault on the system in the previous example, the insulation fault current is equal to 3 kA.

## 1.3 The monitoring functions

Due to the specific characteristics of the generator and its regulation, the proper operating parameters of the generator set must be monitored when special loads are implemented.

The behaviour of the generator is different from that of the transformer:

- The active power it supplies is optimised for a power factor = 0.8
- At less than power factor 0.8, the generator may, by increased excitation, supply part of the reactive power

### Capacitor bank

An off-load generator connected to a capacitor bank may self-excite, consequently increasing its overvoltage.

The capacitor banks used for power factor regulation must therefore be disconnected. This operation can be performed by sending the stopping setpoint to the regulator (if it is connected to the system managing the source switchings) or by opening the circuit-breaker supplying the capacitors.

If capacitors continue to be necessary, do not use regulation of the power factor relay in this case (incorrect and over-slow setting).

### Motor restart and re-acceleration

A generator can supply at most in transient period a current of between 3 and 5 times its nominal current.

A motor absorbs roughly 6 In for 2 to 20 s during start-up.

# 1 Protection of a LV generator set and the downstream circuits

If the sum of the motor power is high, simultaneous start-up of loads generates a high pick-up current that can be damaging. A large voltage drop, due to the high value of the generator transient and subtransient reactances will occur (20% to 30%), with a risk of:

- Non-starting of motors
- Temperature rise linked to the prolonged starting time due to the voltage drop
- Tripping of the thermal protection devices

Moreover, all the network and actuators are disturbed by the voltage drop.

## Application (see Fig. N7)

A generator supplies a set of motors.

Generator characteristics:  $P_n = 130 \text{ kVA}$  at a power factor of 0.8,

$I_n = 150 \text{ A}$

$x'd = 20\%$  (for example) hence  $I_{sc} = 750 \text{ A}$ .

- The  $\Sigma P_{motors}$  is 45 kW (45% of generator power)

Calculating voltage drop at start-up:

$\Sigma P_{Motors} = 45 \text{ kW}$ ,  $I_m = 81 \text{ A}$ , hence a starting current  $I_d = 480 \text{ A}$  for 2 to 20 s.

Voltage drop on the busbar for simultaneous motor starting:

$$\frac{\Delta U}{U} = \left( \frac{I_d - I_n}{I_{sc} - I_n} \right) \text{ in } \%$$

$$\Delta U = 55\%$$

which is not tolerable for motors (failure to start).

- the  $\Sigma P_{motors}$  is 20 kW (20% of generator power)

Calculating voltage drop at start-up:

$\Sigma P_{Motors} = 20 \text{ kW}$ ,  $I_m = 35 \text{ A}$ , hence a starting current  $I_d = 210 \text{ A}$  for 2 to 20 s.

Voltage drop on the busbar:

$$\frac{\Delta U}{U} = \left( \frac{I_d - I_n}{I_{sc} - I_n} \right) \text{ in } \%$$

$$\Delta U = 10\%$$

which is high but tolerable (depending on the type of loads).

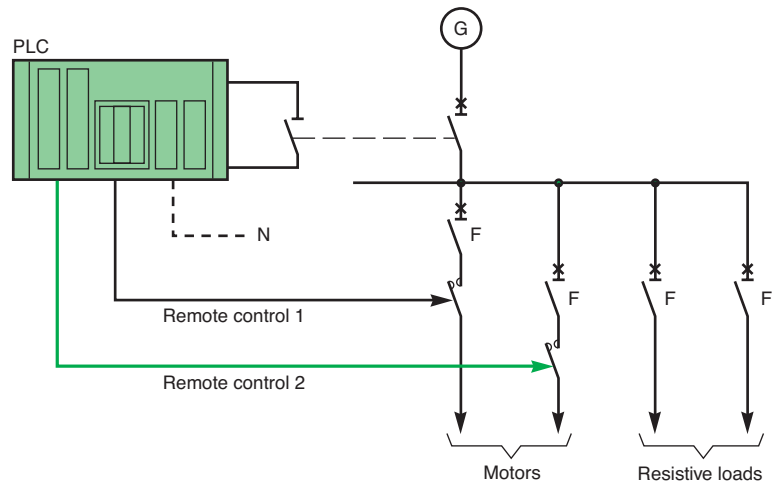


Fig N7 : Restarting of priority motors ( $\Sigma P > 1/3 P_n$ )

## Restarting tips

- If the  $P_{max}$  of the largest motor  $> \frac{1}{3} P_n$ , a soft starter must be installed on this motor

- If  $\Sigma P_{motors} > \frac{1}{3} P_n$ , motor cascade restarting must be managed by a PLC

- If  $\Sigma P_{motors} < \frac{1}{3} P_n$ , there are no restarting problems

# 1 Protection of a LV generator set and the downstream circuits

## Non-linear loads – Example of a UPS

### Non-linear loads

These are mainly:

- Saturated magnetic circuits
- Discharge lamps, fluorescent lights
- Electronic converters
- Information Technology Equipment: PC, computers, etc.

These loads generate harmonic currents: supplied by a Generator Set, this can create high voltage distortion due to the low short-circuit power of the generator.

### Uninterruptible Power Supply (UPS) (see Fig. N8)

The combination of a UPS and generator set is the best solution for ensuring quality power supply with long autonomy for the supply of sensitive loads.

It is also a non-linear load due to the input rectifier. On source switching, the autonomy of the UPS on battery must allow starting and connection of the Generator Set.

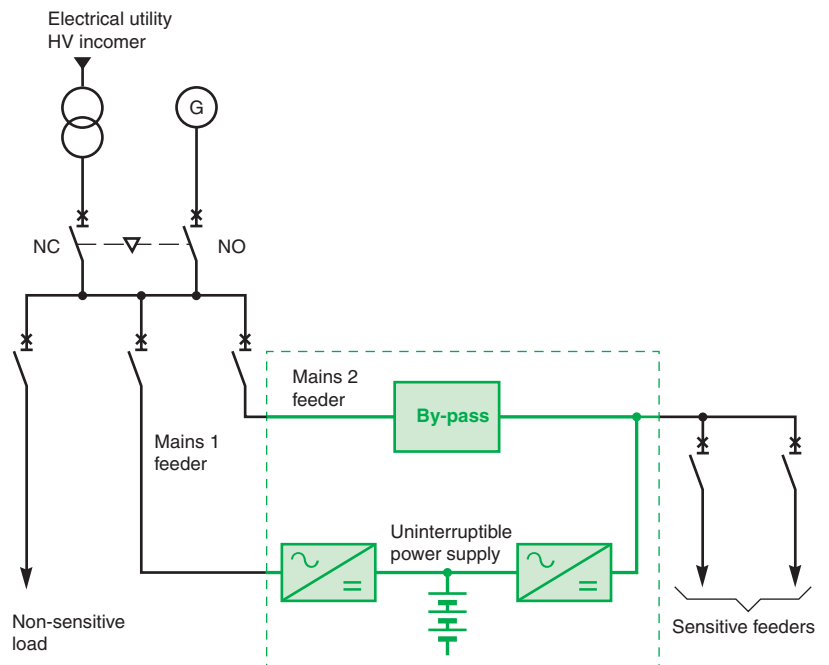


Fig N8 : Generator set- UPS combination for Quality energy

### UPS power

UPS inrush power must allow for:

- Nominal power of the downstream loads. This is the sum of the apparent powers  $P_a$  absorbed by each application. Furthermore, so as not to oversize the installation, the overload capacities at UPS level must be considered (for example: 1.5  $I_n$  for 1 minute and 1.25  $I_n$  for 10 minutes)
- The power required to recharge the battery: This current is proportional to the autonomy required for a given power. The sizing  $S_r$  of a UPS is given by:

$$S_r = 1.17 \times P_n$$

**Figure N9** next page defines the pick-up currents and protection devices for supplying the rectifier (Mains 1) and the standby mains (Mains 2).

# 1 Protection of a LV generator set and the downstream circuits

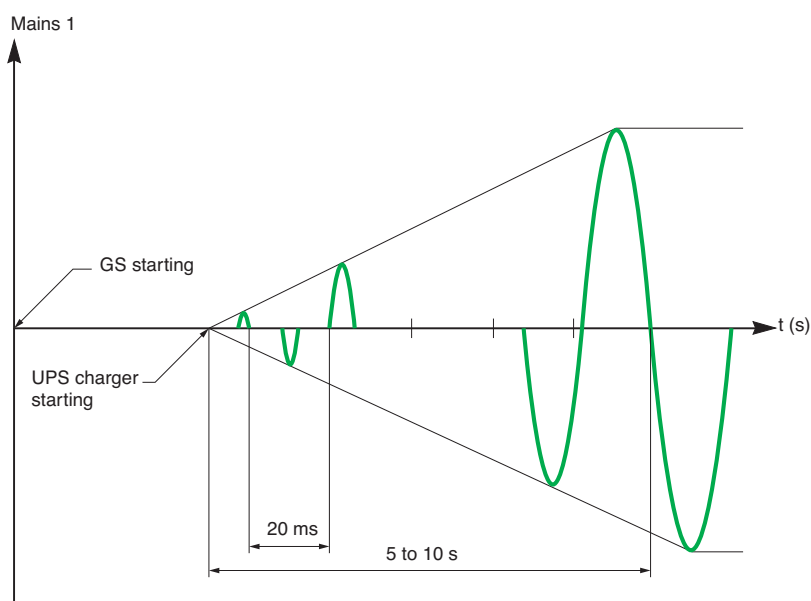
Nominal power P <sub>n</sub> (kVA)	Current value (A) Mains 1 with 3Ph battery 400 V - I <sub>1</sub>	Mains 2 or 3Ph application 400 V - I <sub>u</sub>
40	86	60.5
60	123	91
80	158	121
100	198	151
120	240	182
160	317	243
200	395	304
250	493	360
300	590	456
400	793	608
500	990	760
600	1,180	912
800	1,648	1,215

**Fig N9** : Pick-up current for supplying the rectifier and standby mains

## Generator Set/UPS combination

### ■ Restarting the Rectifier on a Generator Set

The UPS rectifier can be equipped with a progressive starting of the charger to prevent harmful pick-up currents when installation supply switches to the Generator Set (see **Fig. N10**).



**Fig N10** : Progressive starting of a type 2 UPS rectifier

### ■ Harmonics and voltage distortion

Total voltage distortion  $\tau$  is defined by:

$$\tau(\%) = \frac{\sqrt{\sum U_h^2}}{U_1}$$

where  $U_h$  is the harmonic voltage of order  $h$ .

This value depends on:

- The harmonic currents generated by the rectifier (proportional to the power  $S_r$  of the rectifier)
- The longitudinal subtransient reactance  $X''_d$  of the generator
- The power  $S_g$  of the generator

We define  $U'R_{cc}(\%) = X''_d \frac{S_r}{S_g}$  the generator relative short-circuit voltage, brought to rectifier power, i.e.  $t = f(U'R_{cc})$ .

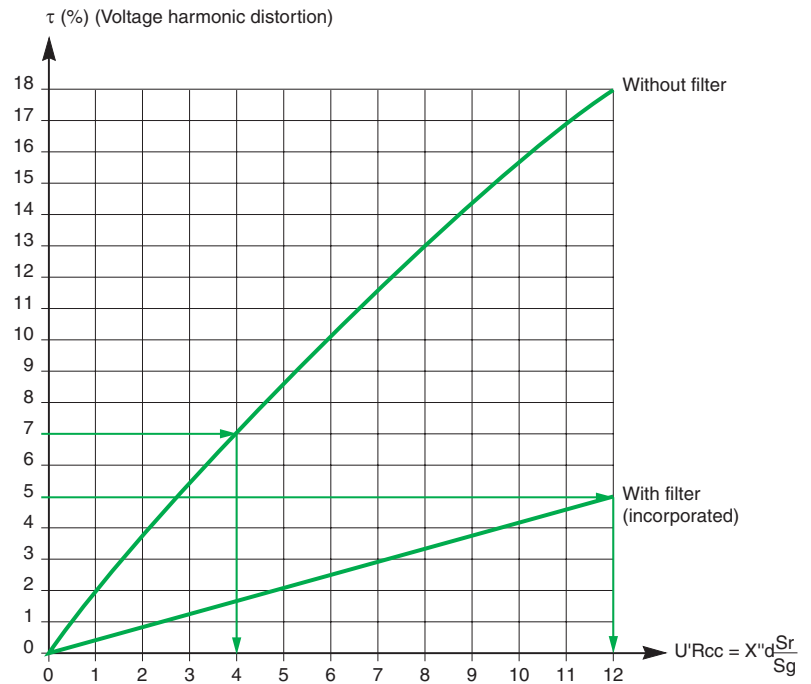
# 1 Protection of a LV generator set and the downstream circuits

**Note 1:** As subtransient reactance is great, harmonic distortion is normally too high compared with the tolerated value (7 to 8%) for reasonable economic sizing of the generator: use of a suitable filter is an appropriate and cost-effective solution.

**Note 2:** Harmonic distortion is not harmful for the rectifier but may be harmful for the other loads supplied in parallel with the rectifier.

## Application

A chart is used to find the distortion  $\tau$  as a function of  $U'R_{cc}$  (see **Fig. N11**).



**Fig N11** : Chart for calculating harmonic distortion

The chart gives:

- Either  $\tau$  as a function of  $U'R_{cc}$
- Or  $U'R_{cc}$  as a function of  $\tau$

From which generator set sizing,  $S_g$ , is determined.

## Example: Generator sizing

- 300 kVA UPS without filter, subtransient reactance of 15%

The power  $S_r$  of the rectifier is  $S_r = 1.17 \times 300 \text{ kVA} = 351 \text{ kVA}$

For a  $\tau < 7\%$ , the chart gives  $U'R_{cc} = 4\%$ , power  $S_g$  is:

$$S_g = 351 \times \frac{15}{4} \approx 1,400 \text{ kVA}$$

- 300 kVA UPS with filter, subtransient reactance of 15%

For  $\tau = 5\%$ , the calculation gives  $U'R_{cc} = 12\%$ , power  $S_g$  is:

$$S_g = 351 \times \frac{15}{12} \approx 500 \text{ kVA}$$

**Note:** With an upstream transformer of 630 kVA on the 300 kVA UPS without filter, the 5% ratio would be obtained.

The result is that operation on generator set must be continually monitored for harmonic currents.

If voltage harmonic distortion is too great, use of a filter on the network is the most effective solution to bring it back to values that can be tolerated by sensitive loads.

# 1 Protection of a LV generator set and the downstream circuits

## 1.4 Generator Set parallel-connection

Parallel-connection of the generator set irrespective of the application type - Safety source, Replacement source or Production source - requires finer management of connection, i.e. additional monitoring functions.

### Parallel operation

As generator sets generate energy in parallel on the same load, they must be synchronised properly (voltage, frequency) and load distribution must be balanced properly. This function is performed by the regulator of each Generator Set (thermal and excitation regulation). The parameters (frequency, voltage) are monitored before connection: if the values of these parameters are correct, connection can take place.

### Insulation faults (see Fig. N12)

An insulation fault inside the metal casing of a generator set may seriously damage the generator of this set if the latter resembles a phase-to-neutral short-circuit. The fault must be detected and eliminated quickly, else the other generators will generate energy in the fault and trip on overload: installation continuity of supply will no longer be guaranteed. Ground Fault Protection (GFP) built into the generator circuit is used to:

- Quickly disconnect the faulty generator and preserve continuity of supply
- Act at the faulty generator control circuits to stop it and reduce the risk of damage

This GFP is of the "Residual Sensing" type and must be installed as close as possible to the protection device as per a TN-C/TN-S<sup>(1)</sup> system at each generator set with grounding of frames by a separate PE. This kind of protection is usually called "Restricted Earth Fault".

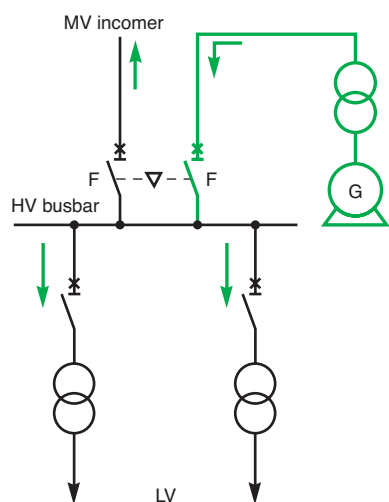


Fig N13 : Energy transfer direction – Generator Set as a generator

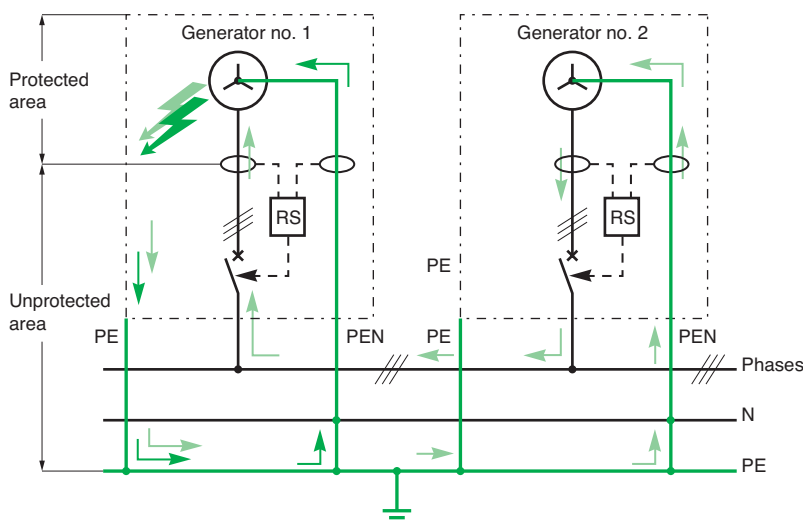


Fig N12 : Insulation fault inside a generator

### Generator Set operating as a load (see Fig. N13 and Fig. N14)

One of the parallel-connected generator sets may no longer operate as a generator but as a motor (by loss of its excitation for example). This may generate overloading of the other generator set(s) and thus place the electrical installation out of operation.

To check that the generator set really is supplying the installation with power (operation as a generator), the proper flow direction of energy on the coupling busbar must be checked using a specific "reverse power" check. Should a fault occur, i.e. the set operates as a motor, this function will eliminate the faulty set.

### Grounding parallel-connected Generator Sets

Grounding of connected generator sets may lead to circulation of earth fault currents (triplen harmonics) by connection of neutrals for common grounding (grounding system of the TN or TT type). Consequently, to prevent these currents from flowing between the generator sets, we recommend the installation of a decoupling resistance in the grounding circuit.

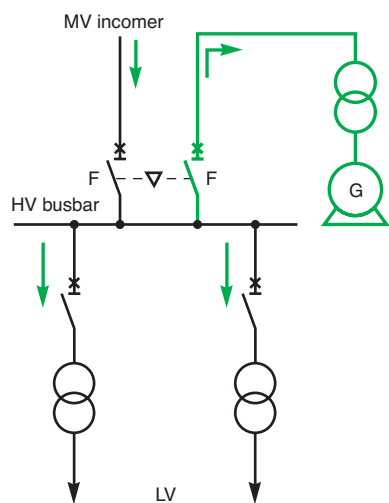


Fig N14 : Energy transfer direction – Generator Set as a load

(1) The system is in TN-C for sets seen as the "generator" and in TN-S for sets seen as "loads"



## 2 Uninterruptible Power Supply units (UPS)

### 2.1 Availability and quality of electrical power

The disturbances presented above may affect:

- Safety of human life
- Safety of property
- The economic viability of a company or production process

Disturbances must therefore be eliminated.

A number of technical solutions contribute to this goal, with varying degrees of effectiveness. These solutions may be compared on the basis of two criteria:

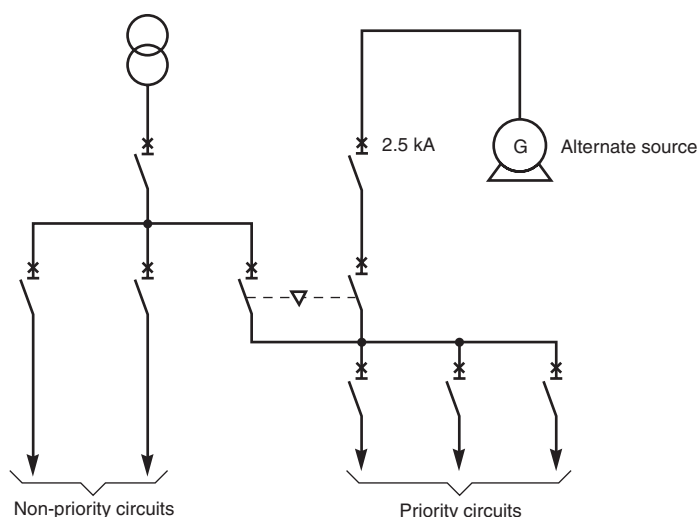
- Availability of the power supplied
- Quality of the power supplied

The availability of electrical power can be thought of as the time per year that power is present at the load terminals. Availability is mainly affected by power interruptions due to utility outages or electrical faults.

A number of solutions exist to limit the risk:

- Division of the installation so as to use a number of different sources rather than just one
- Subdivision of the installation into priority and non-priority circuits, where the supply of power to priority circuits can be picked up if necessary by another available source
- Load shedding, as required, so that a reduced available power rating can be used to supply standby power
- Selection of a system earthing arrangement suited to service-continuity goals, e.g. IT system
- Discrimination of protection devices (selective tripping) to limit the consequences of a fault to a part of the installation

Note that the only way of ensuring availability of power with respect to utility outages is to provide, in addition to the above measures, an autonomous alternate source, at least for priority loads (see **Fig. N15**).



**Fig. N15** : Availability of electrical power

This source takes over from the utility in the event of a problem, but two factors must be taken into account:

- The transfer time (time required to take over from the utility) which must be acceptable to the load
- The operating time during which it can supply the load

The quality of electrical power is determined by the elimination of the disturbances at the load terminals.

An alternate source is a means to ensure the availability of power at the load terminals, however, it does not guarantee, in many cases, the quality of the power supplied with respect to the above disturbances.

## 2 Uninterruptible Power Supply units (UPS)

Today, many sensitive electronic applications require an electrical power supply which is virtually free of these disturbances, to say nothing of outages, with tolerances that are stricter than those of the utility.

This is the case, for example, for computer centers, telephone exchanges and many industrial-process control and monitoring systems.

These applications require solutions that ensure both the availability and quality of electrical power.

### The UPS solution

The solution for sensitive applications is to provide a power interface between the utility and the sensitive loads, providing voltage that is:

- Free of all disturbances present in utility power and in compliance with the strict tolerances required by loads

- Available in the event of a utility outage, within specified tolerances

UPSs (Uninterruptible Power Supplies) satisfy these requirements in terms of power availability and quality by:

- Supplying loads with voltage complying with strict tolerances, through use of an inverter

- Providing an autonomous alternate source, through use of a battery

- Stepping in to replace utility power with no transfer time, i.e. without any interruption in the supply of power to the load, through use of a static switch

These characteristics make UPSs the ideal power supply for all sensitive applications because they ensure power quality and availability, whatever the state of utility power.

A UPS comprises the following main components:

- Rectifier/charger, which produces DC power to charge a battery and supply an inverter

- Inverter, which produces quality electrical power, i.e.

- Free of all utility-power disturbances, notably micro-outages

- Within tolerances compatible with the requirements of sensitive electronic devices (e.g. for Galaxy, tolerances in amplitude  $\pm 0.5\%$  and frequency  $\pm 1\%$ , compared to  $\pm 10\%$  and  $\pm 5\%$  in utility power systems, which correspond to improvement factors of 20 and 5, respectively)

- Battery, which provides sufficient backup time (8 minutes to 1 hour or more) to ensure the safety of life and property by replacing the utility as required

- Static switch, a semi-conductor based device which transfers the load from the inverter to the utility and back, without any interruption in the supply of power

### 2.2 Types of static UPSs

Types of static UPSs are defined by standard IEC 62040.

The standard distinguishes three operating modes:

- Passive standby (also called off-line)

- Line interactive

- Double conversion (also called on-line)

These definitions concern UPS operation with respect to the power source including the distribution system upstream of the UPS.

Standard IEC 62040 defines the following terms:

- Primary power: power normally continuously available which is usually supplied by an electrical utility company, but sometimes by the user's own generation

- Standby power: power intended to replace the primary power in the event of primary-power failure

- Bypass power: power supplied via the bypass

Practically speaking, a UPS is equipped with two AC inputs, which are called the normal AC input and bypass AC input in this guide.

- The normal AC input, noted as mains input 1, is supplied by the primary power, i.e. by a cable connected to a feeder on the upstream utility or private distribution system

- The bypass AC input, noted as mains input 2, is generally supplied by standby power, i.e. by a cable connected to an upstream feeder other than the one supplying the normal AC input, backed up by an alternate source (e.g. by an engine-generator set or another UPS, etc.)

When standby power is not available, the bypass AC input is supplied with primary power (second cable parallel to the one connected to the normal AC input).

The bypass AC input is used to supply the bypass line(s) of the UPS, if they exist. Consequently, the bypass line(s) is supplied with primary or standby power, depending on the availability of a standby-power source.

## UPS operating in passive-standby (off-line) mode

### Operating principle

The inverter is connected in parallel with the AC input in a standby (see Fig. N16).

#### ■ Normal mode

The load is supplied by utility power via a filter which eliminates certain disturbances and provides some degree of voltage regulation (the standard speaks of "additional devices...to provide power conditioning"). The inverter operates in passive standby mode.

#### ■ Battery backup mode

When the AC input voltage is outside specified tolerances for the UPS or the utility power fails, the inverter and the battery step in to ensure a continuous supply of power to the load following a very short (<10 ms) transfer time.

The UPS continues to operate on battery power until the end of battery backup time or the utility power returns to normal, which provokes transfer of the load back to the AC input (normal mode).

### Usage

This configuration is in fact a compromise between an acceptable level of protection against disturbances and cost. It can be used only with low power ratings (< 2 kVA). It operates without a real static switch, so a certain time is required to transfer the load to the inverter. This time is acceptable for certain individual applications, but incompatible with the performance required by more sophisticated, sensitive systems (large computer centers, telephone exchanges, etc.).

What is more, the frequency is not regulated and there is no bypass.

**Note:** In normal mode, the power supplying the load does not flow through the inverter, which explains why this type of UPS is sometimes called "Off-line". This term is misleading, however, because it also suggests "not supplied by utility power", when in fact the load is supplied by the utility via the AC input during normal operation. That is why standard IEC 62040 recommends the term "passive standby".

## UPS operating in line-interactive mode

### Operating principle

The inverter is connected in parallel with the AC input in a standby configuration, but also charges the battery. It thus interacts (reversible operation) with the AC input source (see Fig. N17).

#### ■ Normal mode

The load is supplied with conditioned power via a parallel connection of the AC input and the inverter. The inverter operates to provide output-voltage conditioning and/or charge the battery. The output frequency depends on the AC-input frequency.

#### ■ Battery backup mode

When the AC input voltage is outside specified tolerances for the UPS or the utility power fails, the inverter and the battery step in to ensure a continuous supply of power to the load following a transfer without interruption using a static switch which also disconnects the AC input to prevent power from the inverter from flowing upstream. The UPS continues to operate on battery power until the end of battery backup time or the utility power returns to normal, which provokes transfer of the load back to the AC input (normal mode).

#### ■ Bypass mode

This type of UPS may be equipped with a bypass. If one of the UPS functions fails, the load can be transferred to the bypass AC input (supplied with utility or standby power, depending on the installation).

### Usage

This configuration is not well suited to regulation of sensitive loads in the medium to high-power range because frequency regulation is not possible. For this reason, it is rarely used other than for low power ratings.

## UPS operating in double-conversion (on-line) mode

### Operating principle

The inverter is connected in series between the AC input and the application.

#### ■ Normal mode

During normal operation, all the power supplied to the load passes through the rectifier/charger and inverter which together perform a double conversion (AC-DC-AC), hence the name.

#### ■ Battery backup mode

When the AC input voltage is outside specified tolerances for the UPS or the utility power fails, the inverter and the battery step in to ensure a continuous supply of power to the load following a transfer without interruption using a static switch. The UPS continues to operate on battery power until the end of battery backup time or utility power returns to normal, which provokes transfer of the load back to the AC input (normal mode).

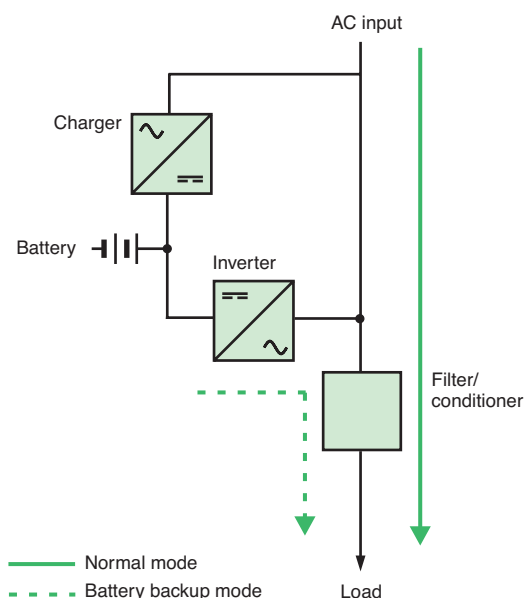


Fig. N16 : UPS operating in passive standby mode

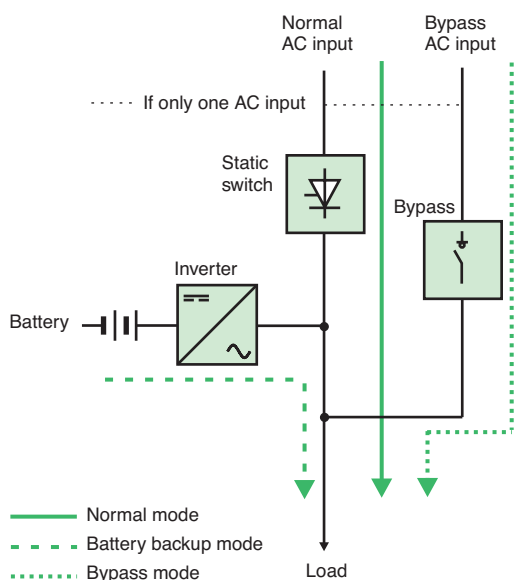


Fig. N17 : UPS operating in line-interactive mode

## 2 Uninterruptible Power Supply units (UPS)

### ■ Bypass mode

This type of UPS is generally equipped with a static bypass, sometimes referred to as a static switch (see **Fig. N18**).

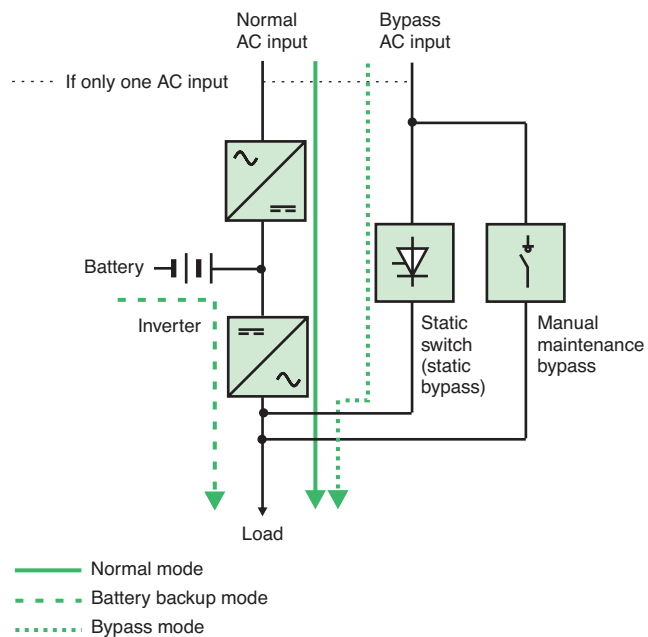
The load can be transferred without interruption to the bypass AC input (supplied with utility or standby power, depending on the installation), in the event of the following:

- UPS failure
- Load-current transients (inrush or fault currents)
- Load peaks

However, the presence of a bypass assumes that the input and output frequencies are identical and if the voltage levels are not the same, a bypass transformer is required.

For certain loads, the UPS must be synchronized with the bypass power to ensure load-supply continuity. What is more, when the UPS is in bypass mode, a disturbance on the AC input source may be transmitted directly to the load because the inverter no longer steps in.

**Note:** Another bypass line, often called the maintenance bypass, is available for maintenance purposes. It is closed by a manual switch.



**Fig. N18 :** UPS operating in double-conversion (on-line) mode

### Usage

In this configuration, the time required to transfer the load to the inverter is negligible due to the static switch.

Also, the output voltage and frequency do not depend on the input voltage and frequency conditions. This means that the UPS, when designed for this purpose, can operate as a frequency converter.

Practically speaking, this is the main configuration used for medium and high power ratings (from 10 kVA upwards). The rest of this chapter will consider only this configuration.

**Note:** This type of UPS is often called “on-line”, meaning that the load is continuously supplied by the inverter, regardless of the conditions on the AC input source. This term is misleading, however, because it also suggests “supplied by utility power”, when in fact the load is supplied by power that has been reconstituted by the double-conversion system. That is why standard IEC 62040 recommends the term “double conversion”.

## 2.3 Batteries

### Selection of battery type

A battery is made up of interconnected cells which may be vented or of the recombination type.

There are two main families of batteries:

- Nickel-cadmium batteries
- Lead-acid batteries
  - Vented cells (lead-antimony): They are equipped with ports to release to the atmosphere the oxygen and hydrogen produced during the different chemical reactions
  - Top off the electrolyte by adding distilled or demineralized water
  - Recombination cells (lead, pure lead, lead-tin batteries): The gas recombination rate is at least 95% and they therefore do not require water to be added during service life

By extension, reference will be made to vented or recombination batteries (recombination batteries are also often called “sealed” batteries).

The main types of batteries used in conjunction with UPSs are:

- Sealed lead-acid batteries, used 95% of the time because they are easy to maintain and do not require a special room
- Vented lead-acid batteries
- Vented nickel-cadmium batteries

The above three types of batteries may be proposed, depending on economic factors and the operating requirements of the installation, with all the available service-life durations.

Capacity levels and backup times may be adapted to suit the user's needs.

The proposed batteries are also perfectly suited to UPS applications in that they are the result of collaboration with leading battery manufacturers.

### Selection of back up time

Selection depends on:

- The average duration of power-system failures
- Any available long-lasting standby power (engine-generator set, etc.)
- The type of application

The typical range generally proposed is:

- Standard backup times of 10, 15 or 30 minutes
- Custom backup times

The following general rules apply:

- Computer applications

Battery backup time must be sufficient to cover file-saving and system-shutdown procedures required to ensure a controlled shutdown of the computer system.

Generally speaking, the computer department determines the necessary backup time, depending on its specific requirements.

- Industrial processes

The backup time calculation should take into account the economic cost incurred by an interruption in the process and the time required to restart.

### Selection table

**Figure N19** next page sums up the main characteristics of the various types of batteries.

Increasingly, recombination batteries would seem to be the market choice for the following reasons:

- No maintenance
- Easy implementation
- Installation in all types of rooms (computer rooms, technical rooms not specifically intended for batteries, etc.)

In certain cases, however, vented batteries are preferred, notably for:

- Long service life
- Long backup times
- High power ratings

Vented batteries must be installed in special rooms complying with precise regulations and require appropriate maintenance.

	Service life	Compact	Operating-temperature tolerances	Frequency of maintenance	Special room	Cost
Sealed lead-acid	5 or 10 years	+	+	Low	No	Low medium
Vented lead-acid	5 or 10 years	+	++	Medium	Yes	Low
Nickel-cadmium	5 or 10 years	++	+++	High	no	High

Fig. N19 : Main characteristics of the various types of batteries

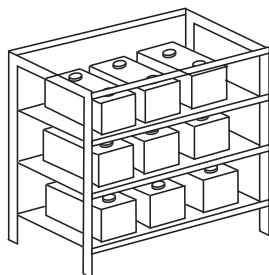


Fig. N20 : Shelf mounting

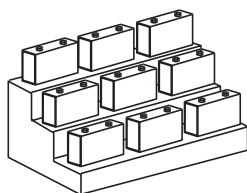


Fig. N21 : Tier mounting

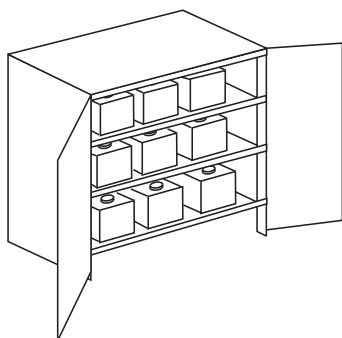


Fig. N22 : Cabinet mounting

## Installation methods

Depending on the UPS range, the battery capacity and backup time, the battery is:

- Sealed type and housed in the UPS cabinet
- Sealed type and housed in one to three cabinets
- Vented or sealed type and rack-mounted. In this case the installation method may be
  - On shelves (see Fig. N20)

This installation method is possible for sealed batteries or maintenance-free vented batteries which do not require topping up of their electrolyte.

- Tier mounting (see Fig. N21)

This installation method is suitable for all types of batteries and for vented batteries in particular, as level checking and filling are made easy.

- In cabinets (see Fig. N22)

This installation method is suitable for sealed batteries. It is easy to implement and offers maximum safety.

## 2.4 System earthing arrangements for installations comprising UPSs

Application of protection systems, stipulated by the standards, in installations comprising a UPS, requires a number of precautions for the following reasons:

- The UPS plays two roles
  - A load for the upstream system
  - A power source for downstream system
- When the battery is not installed in a cabinet, an insulation fault on the DC system can lead to the flow of a residual DC component

This component can disturb the operation of certain protection devices, notably RCDs used for the protection of persons.

### Protection against direct contact (see Fig. N23)

All installations satisfy the applicable requirements because the equipment is housed in cabinets providing a degree of protection IP 20. This is true even for the battery when it is housed in a cabinet.

When batteries are not installed in a cabinet, i.e. generally in a special room, the measures presented at the end of this chapter should be implemented.

**Note:** The TN system (version TN-S or TN-C) is the most commonly recommended system for the supply of computer systems.

N16

Type of arrangement	IT system	TT system	TN system
Operation	<ul style="list-style-type: none"> <li>■ Signaling of first insulation fault</li> <li>■ Locating and elimination of first fault</li> <li>■ Disconnection for second insulation fault</li> </ul>	<ul style="list-style-type: none"> <li>■ Disconnection for first insulation fault</li> </ul>	<ul style="list-style-type: none"> <li>■ Disconnection for first insulation fault</li> </ul>
Techniques for protection of persons	<ul style="list-style-type: none"> <li>■ Interconnection and earthing of conductive parts</li> <li>■ Surveillance of first fault using an insulation monitoring device (IMD)</li> <li>■ Second fault results in circuit interruption (circuit-breaker or fuse)</li> </ul>	<ul style="list-style-type: none"> <li>■ Earthing of conductive parts combined with use of RCDs</li> <li>■ First insulation fault results in interruption by detecting leakage currents</li> </ul>	<ul style="list-style-type: none"> <li>■ Interconnection and earthing of conductive parts and neutral imperative</li> <li>■ First insulation fault results in interruption by detecting overcurrents (circuit-breaker or fuse)</li> </ul>
Advantages and disadvantages	<ul style="list-style-type: none"> <li>■ Solution offering the best continuity of service (first fault is signalled)</li> <li>■ Requires competent surveillance personnel (location of first fault)</li> </ul>	<ul style="list-style-type: none"> <li>■ Easiest solution in terms of design and installation</li> <li>■ No insulation monitoring device (IMD) required</li> <li>■ However, each fault results in interruption of the concerned circuit</li> </ul>	<ul style="list-style-type: none"> <li>■ Low-cost solution in terms of installation</li> <li>■ Difficult design (calculation of loop impedances)</li> <li>■ Qualified operating personnel required</li> <li>■ Flow of high fault currents</li> </ul>

Fig. N23 : Main characteristics of system earthing arrangements

## 2 Uninterruptible Power Supply units (UPS)

### Essential points to be checked for UPSs

Figure N24 shows all the essential points that must be interconnected as well as the devices to be installed (transformers, RCDs, etc.) to ensure installation conformity with safety standards.

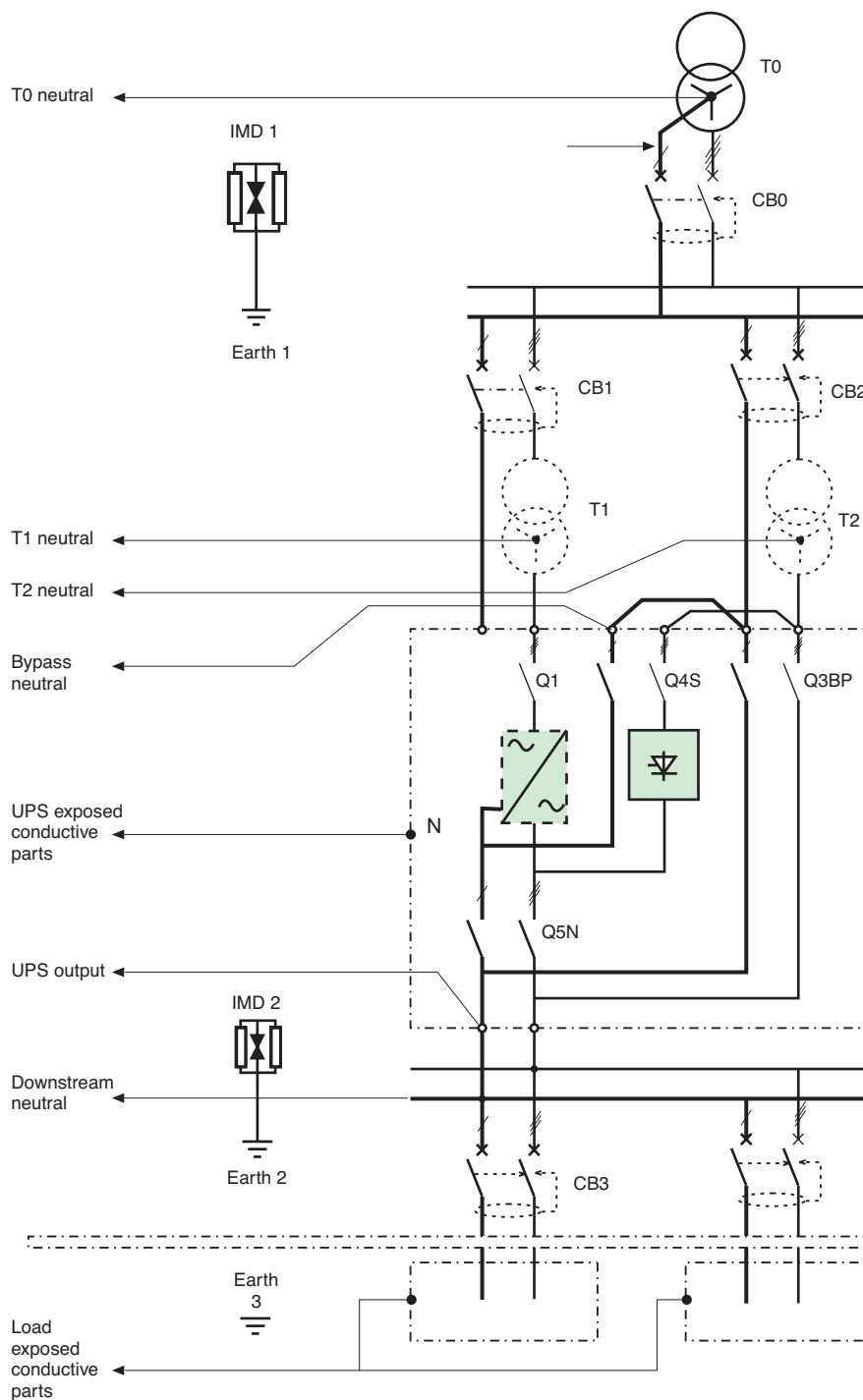


Fig. N24 : The essential points that must be connected in system earthing arrangements



## 2.5 Choice of protection schemes

The circuit-breakers have a major role in an installation but their importance often appears at the time of accidental events which are not frequent. The best sizing of UPS and the best choice of configuration can be compromised by a wrong choice of only one circuit-breaker.

### Circuit-breaker selection

Figure N25 shows how to select the circuit-breakers.

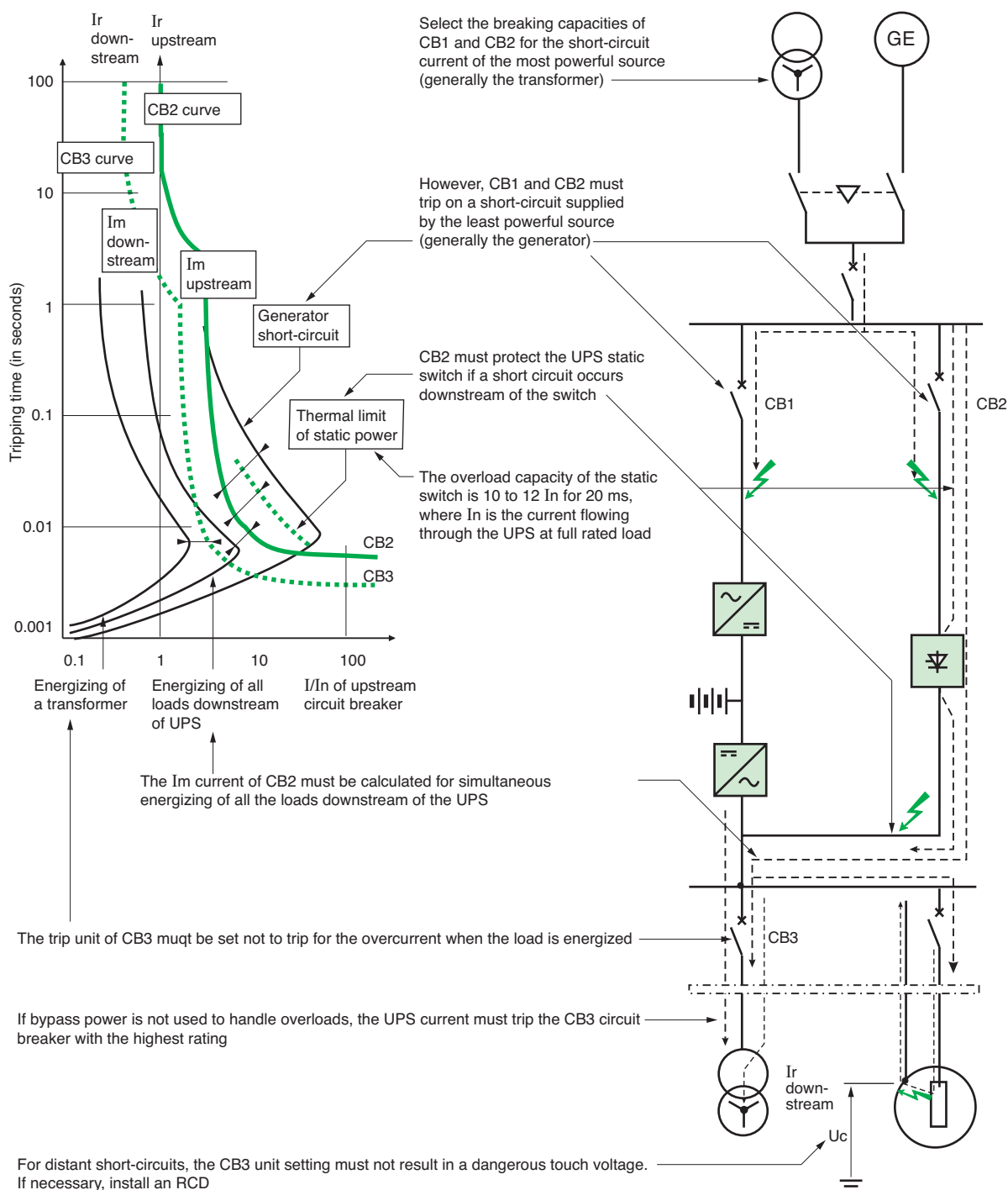


Fig. N25 : Circuit-breakers are submitted to a variety of situations



## 2 Uninterruptible Power Supply units (UPS)

### Rating

The selected rating (rated current) for the circuit-breaker must be the one just above the rated current of the protected downstream cable.

### Breaking capacity

The breaking capacity must be selected just above the short-circuit current that can occur at the point of installation.

### Ir and Im thresholds

The table below indicates how to determine the Ir (overload ; thermal or longtime) and Im (short-circuit ; magnetic or short time) thresholds to ensure discrimination, depending on the upstream and downstream trip units.

**Remark** (see Fig. N26)

- Time discrimination must be implemented by qualified personnel because time delays before tripping increase the thermal stress ( $I^2t$ ) downstream (cables, semi-conductors, etc.). Caution is required if tripping of CB2 is delayed using the Im threshold time delay
- Energy discrimination does not depend on the trip unit, only on the circuit-breaker

Type of downstream circuit	Ir upstream / Ir downstream ratio	Im upstream / Im downstream ratio	Im upstream / Im downstream ratio
Downstream trip unit	All types	Magnetic	Electronic
Distribution	> 1.6	>2	>1.5
Asynchronous motor	>3	>2	>1.5

Fig. N26 : Ir and Im thresholds depending on the upstream and downstream trip units

### Special case of generator short-circuits

Figure N27 shows the reaction of a generator to a short-circuit.

To avoid any uncertainty concerning the type of excitation, we will trip at the first peak (3 to 5  $I_n$  as per X"d) using the Im protection setting without a time delay.

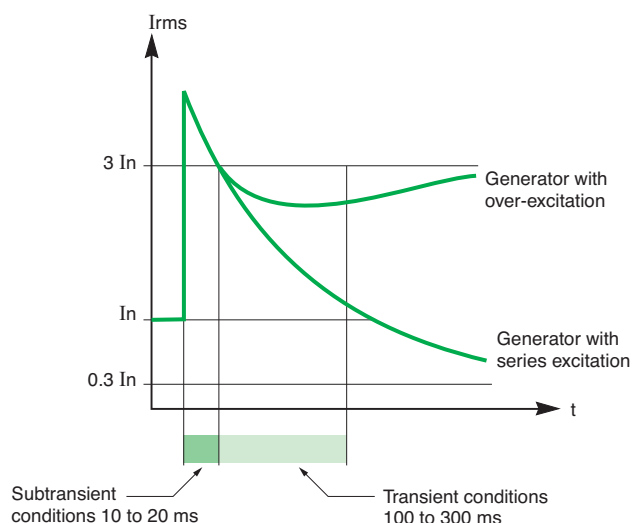


Fig. N27 : Generator during short-circuit

## 2.6 Installation, connection and sizing of cables

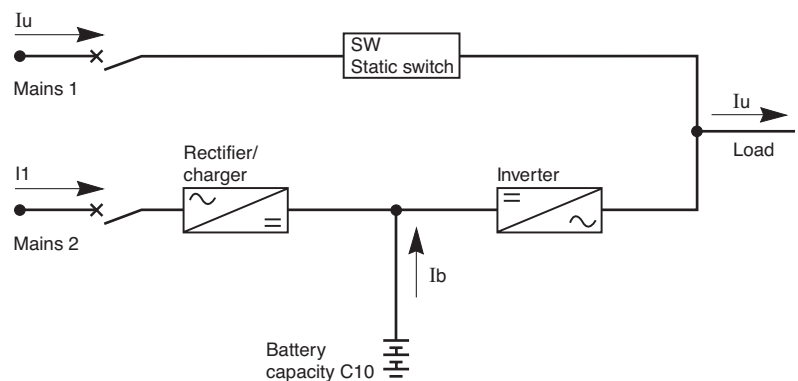
### Ready-to-use UPS units

The low power UPSs, for micro computer systems for example, are compact ready-to-use equipment. The internal wiring is built in the factory and adapted to the characteristics of the devices.

### Not ready-to-use UPS units

For the other UPSs, the wire connections to the power supply system, to the battery and to the load are not included.

Wiring connections depend on the current level as indicated in **Figure N28** below.



**Fig.N28** : Current to be taken into account for the selection of the wire connections

### Calculation of currents $I_1$ , $I_u$

- The input current  $I_u$  from the power network is the load current
- The input current  $I_1$  of the charger/rectifier depends on:
  - The capacity of the battery ( $C_{10}$ ) and the charging mode ( $I_b$ )
  - The characteristics of the charger
  - The efficiency of the inverter
- The current  $I_b$  is the current in the connection of the battery

These currents are given by the manufacturers.

### Cable temperature rise and voltage drops

The cross section of cables depends on:

- Permissible temperature rise
- Permissible voltage drop

For a given load, each of these parameters results in a minimum permissible cross section. The larger of the two must be used.

When routing cables, care must be taken to maintain the required distances between control circuits and power circuits, to avoid any disturbances caused by HF currents.

### Temperature rise

Permissible temperature rise in cables is limited by the withstand capacity of cable insulation.

Temperature rise in cables depends on:

- The type of core (Cu or Al)
- The installation method
- The number of touching cables

Standards stipulate, for each type of cable, the maximum permissible current.

### Voltage drops

The maximum permissible voltage drops are:

- 3% for AC circuits (50 or 60 Hz)
- 1% for DC circuits

## 2 Uninterruptible Power Supply units (UPS)

### Selection tables

**Figure N29** indicates the voltage drop in percent for a circuit made up of 100 meters of cable. To calculate the voltage drop in a circuit with a length L, multiply the value in the table by L/100.

■ Sph: Cross section of conductors

■  $I_n$ : Rated current of protection devices on circuit

### Three-phase circuit

If the voltage drop exceeds 3% (50-60 Hz), increase the cross section of conductors.

### DC circuit

If the voltage drop exceeds 1%, increase the cross section of conductors.

#### a - Three-phase circuits (copper conductors)

50-60 Hz - 380 V / 400 V / 415 V three-phase,  $\cos \varphi = 0.8$ , balanced system three-phase + N

$I_n$ (A)	Sph (mm <sup>2</sup> )											
	10	16	25	35	50	70	95	120	150	185	240	300
10	0.9											
15	1.2											
20	1.6	1.1										
25	2.0	1.3	0.9									
32	2.6	1.7	1.1									
40	3.3	2.1	1.4	1.0								
50	4.1	2.6	1.7	1.3	1.0							
63	5.1	3.3	2.2	1.6	1.2	0.9						
70	5.7	3.7	2.4	1.7	1.3	1.0	0.8					
80	6.5	4.2	2.7	2.1	1.5	1.2	0.9	0.7				
100	8.2	5.3	3.4	2.6	2.0	2.0	1.1	0.9	0.8			
125		6.6	4.3	3.2	2.4	2.4	1.4	1.1	1.0	0.8		
160			5.5	4.3	3.2	3.2	1.8	1.5	1.2	1.1	0.9	
200				5.3	3.9	3.9	2.2	1.8	1.6	1.3	1.2	0.9
250					4.9	4.9	2.8	2.3	1.9	1.7	1.4	1.2
320							3.5	2.9	2.5	2.1	1.9	1.5
400							4.4	3.6	3.1	2.7	2.3	1.9
500								4.5	3.9	3.4	2.9	2.4
600									4.9	4.2	3.6	3.0
800										5.3	4.4	3.8
1,000											6.5	4.7

For a three-phase 230 V circuit, multiply the result by e

For a single-phase 208/230 V circuit, multiply the result by 2

#### b - DC circuits (copper conductors)

$I_n$ (A)	Sph (mm <sup>2</sup> )											
	-	-	25	35	50	70	95	120	150	185	240	300
100			5.1	3.6	2.6	1.9	1.3	1.0	0.8	0.7	0.5	0.4
125				4.5	3.2	2.3	1.6	1.3	1.0	0.8	0.6	0.5
160					4.0	2.9	2.2	1.6	1.2	1.1	0.6	0.7
200						3.6	2.7	2.2	1.6	1.3	1.0	0.8
250							3.3	2.7	2.2	1.7	1.3	1.0
320								3.4	2.7	2.1	1.6	1.3
400									3.4	2.8	2.1	1.6
500										3.4	2.6	2.1
600										4.3	3.3	2.7
800											4.2	3.4
1,000											5.3	4.2
1,250												5.3

**Fig. N29** : Voltage drop in percent for [a] three-phase circuits and [b] DC circuits

### Special case for neutral conductors

In three-phase systems, the third-order harmonics (and their multiples) of single-phase loads add up in the neutral conductor (sum of the currents on the three phases).

For this reason, the following rule may be applied:

neutral cross section = 1.5 x phase cross section

### Example

Consider a 70-meter 400 V three-phase circuit, with copper conductors and a rated current of 600 A.

Standard IEC 60364 indicates, depending on the installation method and the load, a minimum cross section.

We shall assume that the minimum cross section is 95 mm<sup>2</sup>.

It is first necessary to check that the voltage drop does not exceed 3%.

The table for three-phase circuits on the previous page indicates, for a 600 A current flowing in a 300 mm<sup>2</sup> cable, a voltage drop of 3% for 100 meters of cable, i.e. for 70 meters:

$$3 \times \frac{70}{100} = 2.1 \%$$

Therefore less than 3%

A identical calculation can be run for a DC current of 1,000 A.

In a ten-meter cable, the voltage drop for 100 meters of 240 mm<sup>2</sup> cable is 5.3%, i.e. for ten meters:

$$5.3 \times \frac{10}{100} = 0.53 \%$$

Therefore less than 3%

## 2.7 The UPSs and their environment

The UPSs can communicate with electrical and computing environment. They can receive some data and provide information on their operation in order:

- To optimize the protection

For example, the UPS provides essential information on operating status to the computer system (load on inverter, load on static bypass, load on battery, low battery warning)

- To remotely control

The UPS provides measurement and operating status information to inform and allow operators to take specific actions

- To manage the installation

The operator has a building and energy management system which allow to obtain and save information from UPSs, to provide alarms and events and to take actions.

This evolution towards compatibility between computer equipment and UPSs has the effect to incorporate new built-in UPS functions.

## 2.8 Complementary equipment

### Transformers

A two-winding transformer included on the upstream side of the static contactor of circuit 2 allows:

- A change of voltage level when the power network voltage is different to that of the load

- A change of system of earthing between the networks

Moreover, such a transformer :

- Reduces the short-circuit current level on the secondary, (i.e load) side compared with that on the power network side

- Prevents third harmonic currents which may be present on the secondary side from passing into the power-system network, providing that the primary winding is connected in delta.

### Anti-harmonic filter

The UPS system includes a battery charger which is controlled by thyristors or transistors. The resulting regularly-chopped current cycles "generate" harmonic components in the power-supply network.

These undesirable components are filtered at the input of the rectifier and for most cases this reduces the harmonic current level sufficiently for all practical purposes.

## 2 Uninterruptible Power Supply units (UPS)

In certain specific cases however, notably in very large installations, an additional filter circuit may be necessary.

For example when :

- The power rating of the UPS system is large relative to the MV/LV transformer supplying it
- The LV busbars supply loads which are particularly sensitive to harmonics
- A diesel (or gas-turbine, etc.) driven alternator is provided as a standby power supply

In such cases, the manufacturer of the UPS system should be consulted

### Communication equipment

Communication with equipment associated with computer systems may entail the need for suitable facilities within the UPS system. Such facilities may be incorporated in an original design (see **Fig. N30a** ), or added to existing systems on request (see **Fig. N30b** ).



**Fig. N30a** : Ready-to-use UPS unit (with DIN module)



**Fig. N30b** : UPS unit achieving disponibility and quality of computer system power supply

These transformers are generally in the range of several hundreds of VA to some hundreds of kVA and are frequently used for:

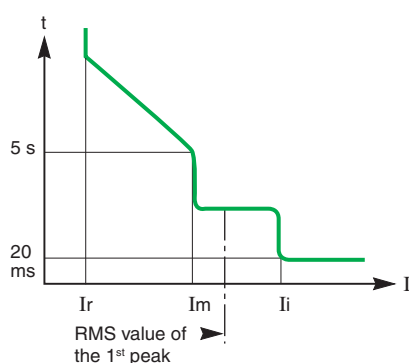
- Changing the low voltage level for:
  - Auxiliary supplies to control and indication circuits
  - Lighting circuits (230 V created when the primary system is 400 V 3-phase 3-wires)
- Changing the method of earthing for certain loads having a relatively high capacitive current to earth (computer equipment) or resistive leakage current (electric ovens, industrial-heating processes, mass-cooking installations, etc.)

LV/LV transformers are generally supplied with protective systems incorporated, and the manufacturers must be consulted for details. Overcurrent protection must, in any case, be provided on the primary side. The exploitation of these transformers requires a knowledge of their particular function, together with a number of points described below.

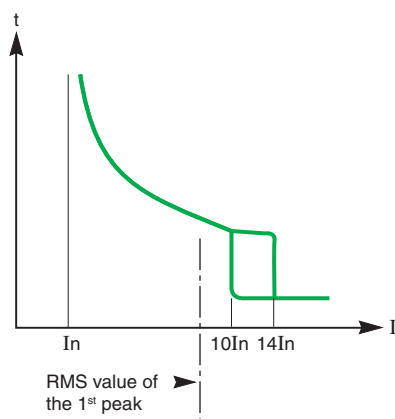
**Note:** In the particular cases of LV/LV safety isolating transformers at extra-low voltage, an earthed metal screen between the primary and secondary windings is frequently required, according to circumstances, as recommended in European Standard EN 60742.

### 3.1 Transformer-energizing inrush current

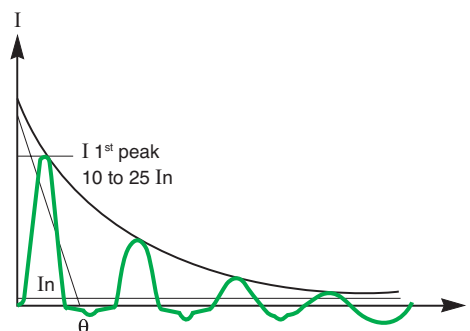
At the moment of energizing a transformer, high values of transient current (which includes a significant DC component) occur, and must be taken into account when considering protection schemes (see Fig. N31).



**Fig N32 :** Tripping characteristic of a Compact NS type STR (electronic)



**Fig N33 :** Tripping characteristic of a Multi 9 curve D



**Fig N31 :** Transformer-energizing inrush current

The magnitude of the current peak depends on:

- The value of voltage at the instant of energization
- The magnitude and polarity of the residual flux existing in the core of the transformer
- Characteristics of the load connected to the transformer

The first current peak can reach a value equal to 10 to 15 times the full-load r.m.s. current, but for small transformers (< 50 kVA) may reach values of 20 to 25 times the nominal full-load current. This transient current decreases rapidly, with a time constant  $\theta$  of the order of several ms to several tens of ms.

### 3.2 Protection for the supply circuit of a LV/LV transformer

The protective device on the supply circuit for a LV/LV transformer must avoid the possibility of incorrect operation due to the magnetizing inrush current surge, noted above. It is necessary to use therefore:

- Selective (i.e. slightly time-delayed) circuit-breakers of the type Compact NS STR (see Fig. N32) or
- Circuit-breakers having a very high magnetic-trip setting, of the types Compact NS or Multi 9 curve D (see Fig. N33)

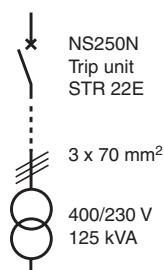


Fig N34 : Example

**Example**

A 400 V 3-phase circuit is supplying a 125 kVA 400/230 V transformer ( $I_n = 180$  A) for which the first inrush current peak can reach  $12 I_n$ , i.e.  $12 \times 180 = 2,160$  A. This current peak corresponds to a rms value of 1,530 A.

A compact NS 250N circuit-breaker with  $I_r$  setting of 200 A and  $I_m$  setting at  $8 \times I_r$  would therefore be a suitable protective device.

**A particular case: Overload protection installed at the secondary side of the transformer (see Fig. N34)**

An advantage of overload protection located on the secondary side is that the short-circuit protection on the primary side can be set at a high value, or alternatively a circuit-breaker type MA (magnetic only) can be used. The primary side short-circuit protection setting must, however, be sufficiently sensitive to ensure its operation in the event of a short-circuit occurring on the secondary side of the transformer.

**Note:** The primary protection is sometimes provided by fuses, type aM. This practice has two disadvantages:

- The fuses must be largely oversized (at least 4 times the nominal full-load rated current of the transformer)
- In order to provide isolating facilities on the primary side, either a load-break switch or a contactor must be associated with the fuses.

**3.3 Typical electrical characteristics of LV/LV 50 Hz transformers****3-phase**

kVA rating	5	6.3	8	10	12.5	16	20	25	31.5	40	50	63	80	100	125	160	200	250	315	400	500	630	800
No-load losses (W)	100	110	130	150	160	170	270	310	350	350	410	460	520	570	680	680	790	950	1160	1240	1485	1855	2160
Full-load losses (W)	250	320	390	500	600	840	800	1180	1240	1530	1650	2150	2540	3700	3700	5900	5900	6500	7400	9300	9400	11400	13400
Short-circuit voltage (%)	4.5	4.5	4.5	5.5	5.5	5.5	5.5	5.5	5	5	4.5	5	5	5.5	4.5	5.5	5	5	4.5	6	6	5.5	5.5

**1-phase**

kVA rating	8	10	12.5	16	20	25	31.5	40	50	63	80	100	125	160
No-load losses (W)	105	115	120	140	150	175	200	215	265	305	450	450	525	635
Full-load losses (W)	400	530	635	730	865	1065	1200	1400	1900	2000	2450	3950	3950	4335
Short-circuit voltage (%)	5	5	5	4.5	4.5	4.5	4	4	5	5	4.5	5.5	5	5

**3.4 Protection of LV/LV transformers, using Merlin Gerin circuit-breakers****Multi 9 circuit-breaker**

Transformer power rating (kVA)			Circuit breaker curve D or K	Size (A)
230/240 V 1-ph	230/240 V 3-ph 400/415 V 1-ph	400/415 V 3-ph		
0.05	0.09	0.16	C60, NG125	0.5
0.11	0.18	0.32	C60, NG125	1
0.21	0.36	0.63	C60, NG125	2
0.33	0.58	1.0	C60, NG125	3
0.67	1.2	2.0	C60, NG125	6
1.1	1.8	3.2	C60, C120, NG125	10
1.7	2.9	5.0	C60, C120, NG125	16
2.1	3.6	6.3	C60, C120, NG125	20
2.7	4.6	8.0	C60, C120, NG125	25
3.3	5.8	10	C60, C120, NG125	32
4.2	7.2	13	C60, C120, NG125	40
5.3	9.2	16	C60, C120, NC100, NG125	50
6.7	12	20	C60, C120, NC100, NG125	63
8.3	14	25	C120, NC100, NG125	80
11	18	32	C120, NC100, NG125	100
13	23	40	C120, NG125	125

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## Compact NSX100 to NSX250 circuit-breakers with TM-D trip units

Transformer power rating (kVA)			Circuit-breaker	Trip unit
230/240 V 1-ph	230/240 V 3-ph 400/415 V 1-ph	400/415 V 3-ph		
3	5...6	9...12	NSX100B/F/N/H/S/L	TM16D
5	8...9	14...16	NSX100B/F/N/H/S/L	TM25D
7...9	13...16	22...28	NSX100B/F/N/H/S/L	TM40D
12...15	20...25	35...44	NSX100B/F/N/H/S/L	TM63D
16...19	26...32	45...56	NSX100B/F/N/H/S/L	TM80D
18...23	32...40	55...69	NSX160B/F/N/H/S/L	TM100D
23...29	40...50	69...87	NSX160B/F/N/H/S/L	TM125D
29...37	51...64	89...111	NSX250B/F/N/H/S/L	TM160D
37...46	64...80	111...139	NSX250B/F/N/H/S/L	TM200D

## Compact NSX100 to NS1600 / Masterpact circuit-breakers with Micrologic trip units

Transformer power rating (kVA)			Circuit-breaker	Trip unit	Setting Ir max
230/240 V 1-ph	230/240 V 3-ph 400/415 V 1-ph	400/415 V 3-ph			
4...7	6...13	11...22	NSX100B/F/N/H/S/L	Micrologic 2.2 or 6.2 40	0.8
9...19	16...30	27...56	NSX100B/F/N/H/S/L	Micrologic 2.2 or 6.2 100	0.8
15...30	5...50	44...90	NSX160B/F/N/H/S/L	Micrologic 2.2 or 6.2 160	0.8
23...46	40...80	70...139	NSX250B/F/N/H/S/L	Micrologic 2.2 or 6.2 250	0.8
37...65	64...112	111...195	NSX400F/N/H/S	Micrologic 2.3 or 6.3 400	0.7
37...55	64...95	111...166	NSX400L	Micrologic 2.3 or 6.3 400	0.6
58...83	100...144	175...250	NSX630F/N/H/S/L	Micrologic 2.3 or 6.3 630	0.6
58...150	100...250	175...436	NS630bN/bH NT06H1	Micrologic 5.0/6.0/7.0	1
74...184	107...319	222...554	NS800N/H - NT08H1 - NW08N1/H1	Micrologic 5.0/6.0/7.0	1
90...230	159...398	277...693	NS1000N/H - NT10H1 - NW10N1/H1	Micrologic 5.0/6.0/7.0	1
115...288	200...498	346...866	NS1250N/H - NT12H1 - NW12N1/H1	Micrologic 5.0/6.0/7.0	1
147...368	256...640	443...1,108	NS1600N/H - NT16H1 - NW16N1/H1	Micrologic 5.0/6.0/7.0	1
184...460	320...800	554...1,385	NW20N1/H1	Micrologic 5.0/6.0/7.0	1
230...575	400...1,000	690...1,730	NW25H2/H3	Micrologic 5.0/6.0/7.0	1
294...736	510...1,280	886...2,217	NW32H2/H3	Micrologic 5.0/6.0/7.0	1



A source of comfort and productivity, lighting represents 15% of the quantity of electricity consumed in industry and 40% in buildings. The quality of lighting (light stability and continuity of service) depends on the quality of the electrical energy thus consumed. The supply of electrical power to lighting networks has therefore assumed great importance.

To help with their design and simplify the selection of appropriate protection devices, an analysis of the different lamp technologies is presented. The distinctive features of lighting circuits and their impact on control and protection devices are discussed. Recommendations relative to the difficulties of lighting circuit implementation are given.

## 4.1 The different lamp technologies

Artificial luminous radiation can be produced from electrical energy according to two principles: incandescence and electroluminescence.

**Incandescence** is the production of light via temperature elevation. The most common example is a filament heated to white state by the circulation of an electrical current. The energy supplied is transformed into heat by the Joule effect and into luminous flux.

**Luminescence** is the phenomenon of emission by a material of visible or almost visible luminous radiation. A gas (or vapors) subjected to an electrical discharge emits luminous radiation (Electroluminescence of gases).

Since this gas does not conduct at normal temperature and pressure, the discharge is produced by generating charged particles which permit ionization of the gas. The nature, pressure and temperature of the gas determine the light spectrum.

Photoluminescence is the luminescence of a material exposed to visible or almost visible radiation (ultraviolet, infrared).

When the substance absorbs ultraviolet radiation and emits visible radiation which stops a short time after energization, this is fluorescence.

### Incandescent lamps

Incandescent lamps are historically the oldest and the most often found in common use.

They are based on the principle of a filament rendered incandescent in a vacuum or neutral atmosphere which prevents combustion.

A distinction is made between:

#### ■ Standard bulbs

These contain a tungsten filament and are filled with an inert gas (nitrogen and argon or krypton).

#### ■ Halogen bulbs

These also contain a tungsten filament, but are filled with a halogen compound and an inert gas (krypton or xenon). This halogen compound is responsible for the phenomenon of filament regeneration, which increases the service life of the lamps and avoids them blackening. It also enables a higher filament temperature and therefore greater luminosity in smaller-size bulbs.

The main disadvantage of incandescent lamps is their significant heat dissipation, resulting in poor luminous efficiency.

### Fluorescent lamps

This family covers fluorescent tubes and compact fluorescent lamps. Their technology is usually known as "low-pressure mercury".

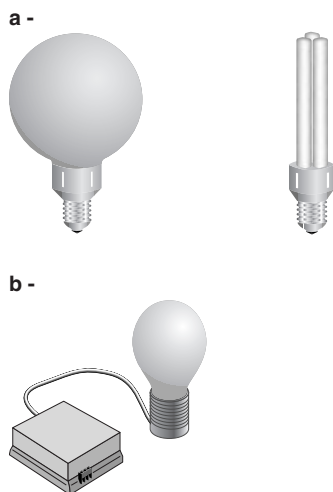
In fluorescent tubes, an electrical discharge causes electrons to collide with ions of mercury vapor, resulting in ultraviolet radiation due to energization of the mercury atoms. The fluorescent material, which covers the inside of the tubes, then transforms this radiation into visible light.

Fluorescent tubes dissipate less heat and have a longer service life than incandescent lamps, but they do need an ignition device called a "starter" and a device to limit the current in the arc after ignition. This device called "ballast" is usually a choke placed in series with the arc.

Compact fluorescent lamps are based on the same principle as a fluorescent tube. The starter and ballast functions are provided by an electronic circuit (integrated in the lamp) which enables the use of smaller tubes folded back on themselves.

Compact fluorescent lamps (see **Fig. N35**) were developed to replace incandescent lamps: They offer significant energy savings (15 W against 75 W for the same level of brightness) and an increased service life.

Lamps known as "induction" type or "without electrodes" operate on the principle of ionization of the gas present in the tube by a very high frequency electromagnetic field (up to 1 GHz). Their service life can be as long as 100,000 hrs.



**Fig. N35** : Compact fluorescent lamps [a] standard, [b] induction

N27

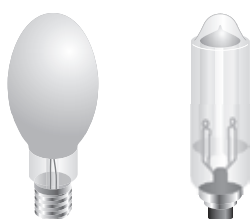


Fig. N36 : Discharge lamps

**Discharge lamps (see Fig. N36)**

The light is produced by an electrical discharge created between two electrodes within a gas in a quartz bulb. All these lamps therefore require a ballast to limit the current in the arc. A number of technologies have been developed for different applications.

Low-pressure sodium vapor lamps have the best light output, however the color rendering is very poor since they only have a monochromatic orange radiation.

High-pressure sodium vapor lamps produce a white light with an orange tinge.

In high-pressure mercury vapor lamps, the discharge is produced in a quartz or ceramic bulb at high pressure. These lamps are called "fluorescent mercury discharge lamps". They produce a characteristically bluish white light.

Metal halide lamps are the latest technology. They produce a color with a broad color spectrum. The use of a ceramic tube offers better luminous efficiency and better color stability.

**Light Emitting Diodes (LED)**

The principle of light emitting diodes is the emission of light by a semi-conductor as an electrical current passes through it. LEDs are commonly found in numerous applications, but the recent development of white or blue diodes with a high light output opens new perspectives, especially for signaling (traffic lights, exit signs or emergency lighting).

LEDs are low-voltage and low-current devices, thus suitable for battery-supply.

A converter is required for a line power supply.

The advantage of LEDs is their low energy consumption. As a result, they operate at a very low temperature, giving them a very long service life. Conversely, a simple diode has a weak light intensity. A high-power lighting installation therefore requires connection of a large number of units in series and parallel.

Technology	Application	Advantages	Disadvantages
Standard incandescent	- Domestic use - Localized decorative lighting	- Direct connection without intermediate switchgear - Reasonable purchase price - Compact size - Instantaneous lighting - Good color rendering	- Low luminous efficiency and high electricity consumption - Significant heat dissipation - Short service life
Halogen incandescent	- Spot lighting - Intense lighting	- Direct connection - Instantaneous efficiency - Excellent color rendering	- Average luminous efficiency
Fluorescent tube	- Shops, offices, workshops - Outdoors	- High luminous efficiency - Average color rendering	- Low light intensity of single unit - Sensitive to extreme temperatures
Compact fluorescent lamp	- Domestic use - Offices - Replacement of incandescent lamps	- Good luminous efficiency - Good color rendering	- High initial investment compared to incandescent lamps
HP mercury vapor	- Workshops, halls, hangars - Factory floors	- Good luminous efficiency - Acceptable color rendering - Compact size - Long service life	- Lighting and relighting time of a few minutes
High-pressure sodium	- Outdoors - Large halls	- Very good luminous efficiency	- Lighting and relighting time of a few minutes
Low-pressure sodium	- Outdoors - Emergency lighting	- Good visibility in foggy weather - Economical to use	- Long lighting time (5 min.) - Mediocre color rendering
Metal halide	- Large areas - Halls with high ceilings	- Good luminous efficiency - Good color rendering - Long service life	- Lighting and relighting time of a few minutes
LED	- Signaling (3-color traffic lights, "exit" signs and emergency lighting)	- Insensitive to the number of switching operations - Low energy consumption - Low temperature	- Limited number of colors - Low brightness of single unit

Technology	Power (watt)	Efficiency (lumen/watt)	Service life (hours)
Standard incandescent	3 – 1,000	10 – 15	1,000 – 2,000
Halogen incandescent	5 – 500	15 – 25	2,000 – 4,000
Fluorescent tube	4 – 56	50 – 100	7,500 – 24,000
Compact fluorescent lamp	5 – 40	50 – 80	10,000 – 20,000
HP mercury vapor	40 – 1,000	25 – 55	16,000 – 24,000
High-pressure sodium	35 – 1,000	40 – 140	16,000 – 24,000
Low-pressure sodium	35 – 180	100 – 185	14,000 – 18,000
Metal halide	30 – 2,000	50 – 115	6,000 – 20,000
LED	0.05 – 0.1	10 – 30	40,000 – 100,000

Fig. N37 : Usage and technical characteristics of lighting devices

## 4.2 Electrical characteristics of lamps

### Incandescent lamps with direct power supply

Due to the very high temperature of the filament during operation (up to 2,500 °C), its resistance varies greatly depending on whether the lamp is on or off. As the cold resistance is low, a current peak occurs on ignition that can reach 10 to 15 times the nominal current for a few milliseconds or even several milliseconds.

This constraint affects both ordinary lamps and halogen lamps: it imposes a reduction in the maximum number of lamps that can be powered by devices such as remote-control switches, modular contactors and relays for busbar trunking.

### Extra Low Voltage (ELV) halogen lamps

■ Some low-power halogen lamps are supplied with ELV 12 or 24 V, via a transformer or an electronic converter. With a transformer, the magnetization phenomenon combines with the filament resistance variation phenomenon at switch-on. The inrush current can reach 50 to 75 times the nominal current for a few milliseconds. The use of dimmer switches placed upstream significantly reduces this constraint.

■ Electronic converters, with the same power rating, are more expensive than solutions with a transformer. This commercial handicap is compensated by a greater ease of installation since their low heat dissipation means they can be fixed on a flammable support. Moreover, they usually have built-in thermal protection.

New ELV halogen lamps are now available with a transformer integrated in their base. They can be supplied directly from the LV line supply and can replace normal lamps without any special adaptation.

### Dimming for incandescent lamps

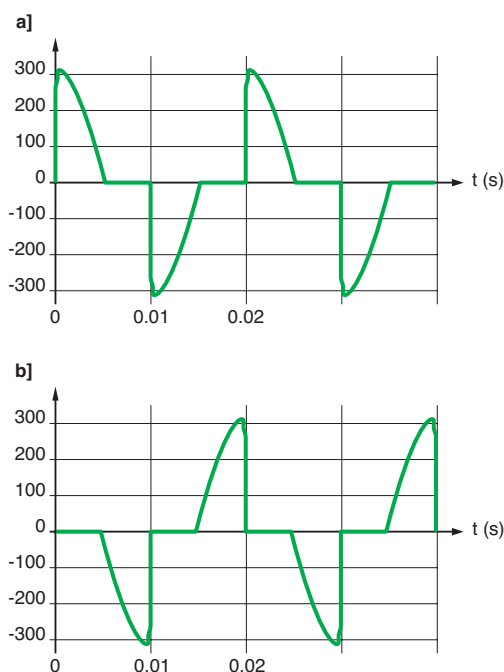
This can be obtained by varying the voltage applied to the lampere

This voltage variation is usually performed by a device such as a Triac dimmer switch, by varying its firing angle in the line voltage period. The wave form of the voltage applied to the lamp is illustrated in **Figure N38a**. This technique known as “cut-on control” is suitable for supplying power to resistive or inductive circuits. Another technique suitable for supplying power to capacitive circuits has been developed with MOS or IGBT electronic components. This techniques varies the voltage by blocking the current before the end of the half-period (see **Fig. N38b**) and is known as “cut-off control”.

Switching on the lamp gradually can also reduce, or even eliminate, the current peak on ignition.

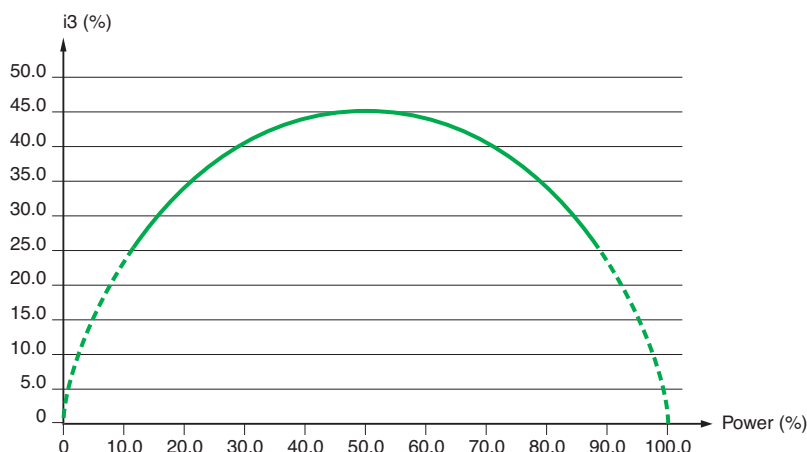
As the lamp current is distorted by the electronic switching, harmonic currents are produced. The 3<sup>rd</sup> harmonic order is predominant, and the percentage of 3<sup>rd</sup> harmonic current related to the maximum fundamental current (at maximum power) is represented on **Figure N39**.

Note that in practice, the power applied to the lamp by a dimmer switch can only vary in the range between 15 and 85% of the maximum power of the lampere



**Fig. N38** : Shape of the voltage supplied by a light dimmer at 50% of maximum voltage with the following techniques:

a) “cut-on control”  
b) “cut-off control”



**Fig. N39** : Percentage of 3<sup>rd</sup> harmonic current as a function of the power applied to an incandescent lamp using an electronic dimmer switch

According to IEC standard 61000-3-2 setting harmonic emission limits for electric or electronic systems with current  $\leq 16\text{ A}$ , the following arrangements apply:

- Independent dimmers for incandescent lamps with a rated power less than or equal to 1 kW have no limits applied
- Otherwise, or for incandescent lighting equipment with built-in dimmer or dimmer built in an enclosure, the maximum permissible 3<sup>rd</sup> harmonic current is equal to 2.30 A

Fluorescent lamps with magnetic ballast

Fluorescent tubes and discharge lamps require the intensity of the arc to be limited, and this function is fulfilled by a choke (or magnetic ballast) placed in series with the bulb itself (see Fig. N40).

This arrangement is most commonly used in domestic applications with a limited number of tubes. No particular constraint applies to the switches.

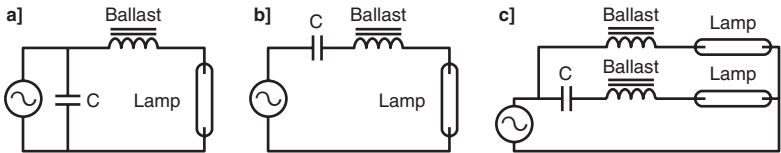
Dimmer switches are not compatible with magnetic ballasts: the cancellation of the voltage for a fraction of the period interrupts the discharge and totally extinguishes the lampere

The starter has a dual function: preheating the tube electrodes, and then generating an overvoltage to ignite the tube. This overvoltage is generated by the opening of a contact (controlled by a thermal switch) which interrupts the current circulating in the magnetic ballast.

During operation of the starter (approx. 1 s), the current drawn by the luminaire is approximately twice the nominal current.

Since the current drawn by the tube and ballast assembly is essentially inductive, the power factor is very low (on average between 0.4 and 0.5). In installations consisting of a large number of tubes, it is necessary to provide compensation to improve the power factor.

For large lighting installations, centralized compensation with capacitor banks is a possible solution, but more often this compensation is included at the level of each luminaire in a variety of different layouts (see Fig. N41).



Compensation layout	Application	Comments
Without compensation	Domestic	Single connection
Parallel [a]	Offices, workshops, superstores	Risk of overcurrents for control devices
Series [b]		Choose capacitors with high operating voltage (450 to 480 V)
Duo [c]		Avoids flicker

Fig. N41 : The various compensation layouts: a) parallel; b) series; c) dual series also called "duo" and their fields of application

The compensation capacitors are therefore sized so that the global power factor is greater than 0.85. In the most common case of parallel compensation, its capacity is on average 1  $\mu\text{F}$  for 10 W of active power, for any type of lampere However, this compensation is incompatible with dimmer switches.

Constraints affecting compensation

The layout for parallel compensation creates constraints on ignition of the lampere Since the capacitor is initially discharged, switch-on produces an overcurrent. An overvoltage also appears, due to the oscillations in the circuit made up of the capacitor and the power supply inductance.

The following example can be used to determine the orders of magnitude.

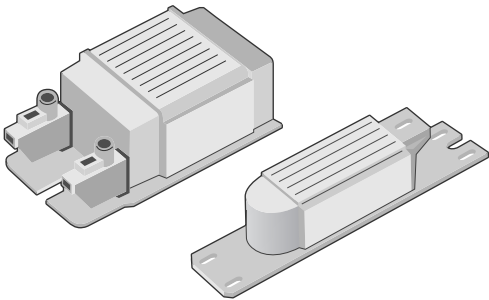


Fig. N40 : Magnetic ballasts

N30

Assuming an assembly of 50 fluorescent tubes of 36 W each:

- Total active power: 1,800 W
- Apparent power: 2 kVA
- Total rms current: 9 A
- Peak current: 13 A

With:

- A total capacity:  $C = 175 \mu\text{F}$
- A line inductance (corresponding to a short-circuit current of 5 kA):  $L = 150 \mu\text{H}$

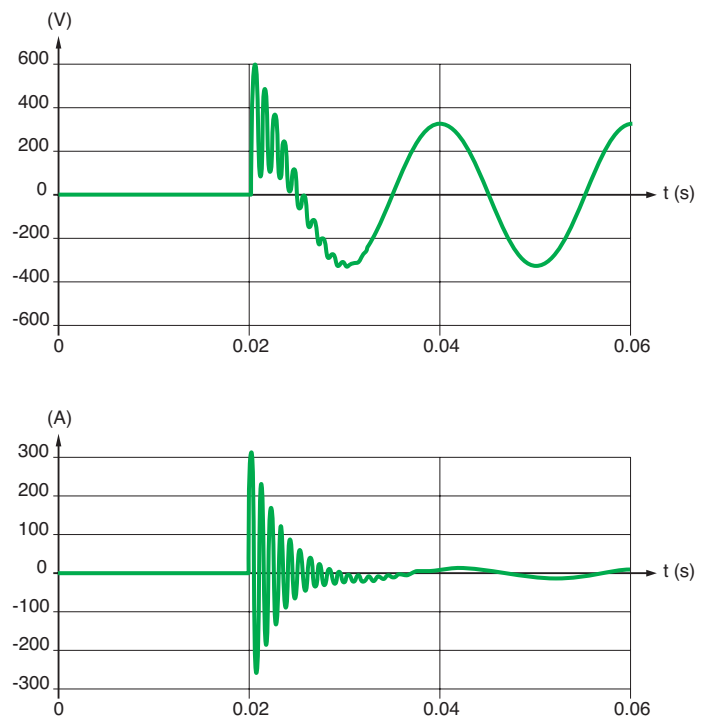
The maximum peak current at switch-on equals:

$$I_c = V_{\max} \sqrt{\frac{C}{L}} = 230\sqrt{2} \sqrt{\frac{175 \times 10^{-6}}{150 \times 10^{-6}}} = 350 \text{ A}$$

The theoretical peak current at switch-on can therefore reach **27 times** the peak current during normal operation.

The shape of the voltage and current at ignition is given in **Figure N42** for switch closing at the line supply voltage peak.

There is therefore a risk of contact welding in electromechanical control devices (remote-control switch, contactor, circuit-breaker) or destruction of solid state switches with semi-conductors.



**Fig. N42** : Power supply voltage at switch-on and inrush current

In reality, the constraints are usually less severe, due to the impedance of the cables. Ignition of fluorescent tubes in groups implies one specific constraint. When a group of tubes is already switched on, the compensation capacitors in these tubes which are already energized participate in the inrush current at the moment of ignition of a second group of tubes: they “amplify” the current peak in the control switch at the moment of ignition of the second group.

The table in **Figure N43**, resulting from measurements, specifies the magnitude of the first current peak, for different values of prospective short-circuit current  $I_{sc}$ . It is seen that the current peak can be multiplied by 2 or 3, depending on the number of tubes already in use at the moment of connection of the last group of tubes.

Number of tubes already in use	Number of tubes connected	Inrush current peak (A)		
		$I_{sc} = 1,500\text{ A}$	$I_{sc} = 3,000\text{ A}$	$I_{sc} = 6,000\text{ A}$
0	14	233	250	320
14	14	558	556	575
28	14	608	607	624
42	14	618	616	632

**Fig. N43** : Magnitude of the current peak in the control switch of the moment of ignition of a second group of tubes

Nonetheless, sequential ignition of each group of tubes is recommended so as to reduce the current peak in the main switch.

The most recent magnetic ballasts are known as “low-loss”. The magnetic circuit has been optimized, but the operating principle remains the same. This new generation of ballasts is coming into widespread use, under the influence of new regulations (European Directive, Energy Policy Act - USA).

In these conditions, the use of electronic ballasts is likely to increase, to the detriment of magnetic ballasts.

Fluorescent lamps with electronic ballast

Electronic ballasts are used as a replacement for magnetic ballasts to supply power to fluorescent tubes (including compact fluorescent lamps) and discharge lamps. They also provide the “starter” function and do not need any compensation capacity.

The principle of the electronic ballast (see **Fig. N44**) consists of supplying the lamp arc via an electronic device that generates a rectangular form AC voltage with a frequency between 20 and 60 kHz.

Supplying the arc with a high-frequency voltage can totally eliminate the flicker phenomenon and strobe effects. The electronic ballast is totally silent.

During the preheating period of a discharge lamp, this ballast supplies the lamp with increasing voltage, imposing an almost constant current. In steady state, it regulates the voltage applied to the lamp independently of any fluctuations in the line voltage.

Since the arc is supplied in optimum voltage conditions, this results in energy savings of 5 to 10% and increased lamp service life. Moreover, the efficiency of the electronic ballast can exceed 93%, whereas the average efficiency of a magnetic device is only 85%.

The power factor is high (> 0.9).

The electronic ballast is also used to provide the light dimming function. Varying the frequency in fact varies the current magnitude in the arc and hence the luminous intensity.

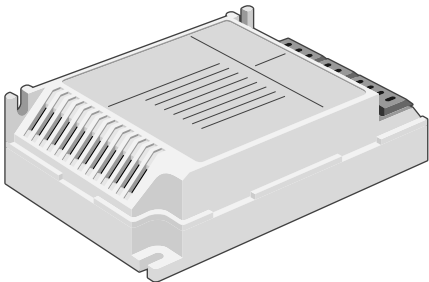
Inrush current

The main constraint that electronic ballasts bring to line supplies is the high inrush current on switch-on linked to the initial load of the smoothing capacitors (see **Fig. N45**).

Technology	Max. inrush current	Duration
Rectifier with PFC	30 to 100 In	≤ 1 ms
Rectifier with choke	10 to 30 In	≤ 5 ms
Magnetic ballast	≤ 13 In	5 to 10 ms

**Fig. N45** : Orders of magnitude of the inrush current maximum values, depending on the technologies used

N32

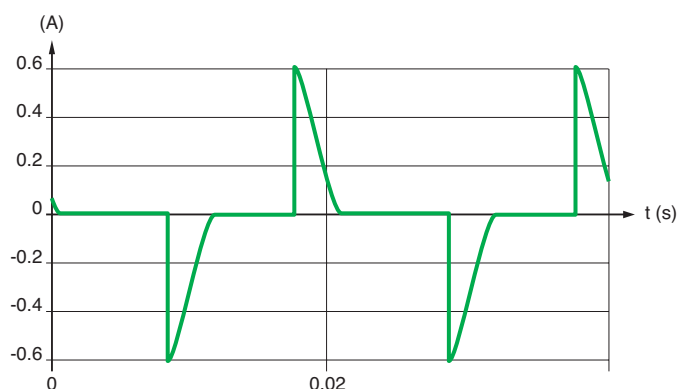


**Fig. N44** : Electronic ballast

In reality, due to the wiring impedances, the inrush currents for an assembly of lamps is much lower than these values, in the order of 5 to 10  $I_n$  for less than 5 ms. Unlike magnetic ballasts, this inrush current is not accompanied by an overvoltage.

### Harmonic currents

For ballasts associated with high-power discharge lamps, the current drawn from the line supply has a low total harmonic distortion (< 20% in general and < 10% for the most sophisticated devices). Conversely, devices associated with low-power lamps, in particular compact fluorescent lamps, draw a very distorted current (see **Fig. N46**). The total harmonic distortion can be as high as 150%. In these conditions, the rms current drawn from the line supply equals 1.8 times the current corresponding to the lamp active power, which corresponds to a power factor of 0.55.



**Fig. N46** : Shape of the current drawn by a compact fluorescent lamp

In order to balance the load between the different phases, lighting circuits are usually connected between phases and neutral in a balanced way. In these conditions, the high level of third harmonic and harmonics that are multiple of 3 can cause an overload of the neutral conductor. The least favorable situation leads to a neutral current which may reach  $\sqrt{3}$  times the current in each phase.

Harmonic emission limits for electric or electronic systems are set by IEC standard 61000-3-2. For simplification, the limits for lighting equipment are given here only for harmonic orders 3 and 5 which are the most relevant (see **Fig. N47**).

Harmonic order	Active input power > 25W	Active input power ≤ 25W one of the 2 sets of limits apply:	
	% of fundamental current	% of fundamental current	Harmonic current relative to active power
3	30	86	3.4 mA/W
5	10	61	1.9 mA/W

**Fig. N47** : Maximum permissible harmonic current

### Leakage currents

Electronic ballasts usually have capacitors placed between the power supply conductors and the earth. These interference-suppressing capacitors are responsible for the circulation of a permanent leakage current in the order of 0.5 to 1 mA per ballast. This therefore results in a limit being placed on the number of ballasts that can be supplied by a Residual Current Differential Safety Device (RCD).

At switch-on, the initial load of these capacitors can also cause the circulation of a current peak whose magnitude can reach several amps for 10  $\mu$ s. This current peak may cause unwanted tripping of unsuitable devices.



### High-frequency emissions

Electronic ballasts are responsible for high-frequency conducted and radiated emissions.

The very steep rising edges applied to the ballast output conductors cause current pulses circulating in the stray capacities to earth. As a result, stray currents circulate in the earth conductor and the power supply conductors. Due to the high frequency of these currents, there is also electromagnetic radiation. To limit these HF emissions, the lamp should be placed in the immediate proximity of the ballast, thus reducing the length of the most strongly radiating conductors.

**The different power supply modes** (see Fig. N48)

Technology	Power supply mode	Other device
Standard incandescent	Direct power supply	Dimmer switch
Halogen incandescent		
ELV halogen incandescent	Transformer	Electronic converter
Fluorescent tube	Magnetic ballast and starter	Electronic ballast
Compact fluorescent lamp		Electronic dimmer + ballast
Mercury vapor	Built-in electronic ballast	
High-pressure sodium	Magnetic ballast	Electronic ballast
Low-pressure sodium		
Metal halide		

*Fig. N48 : Different power supply modes*

## 4.3 Constraints related to lighting devices and recommendations

### The current actually drawn by luminaires

#### The risk

This characteristic is the first one that should be defined when creating an installation, otherwise it is highly probable that overload protection devices will trip and users may often find themselves in the dark.

It is evident that their determination should take into account the consumption of all components, especially for fluorescent lighting installations, since the power consumed by the ballasts has to be added to that of the tubes and bulbs.

#### The solution

For incandescent lighting, it should be remembered that the line voltage can be more than 10% of its nominal value, which would then cause an increase in the current drawn.

For fluorescent lighting, unless otherwise specified, the power of the magnetic ballasts can be assessed at 25% of that of the bulbs. For electronic ballasts, this power is lower, in the order of 5 to 10%.

The thresholds for the overcurrent protection devices should therefore be calculated as a function of the total power and the power factor, calculated for each circuit.

### Overcurrents at switch-on

#### The risk

The devices used for control and protection of lighting circuits are those such as relays, triac, remote-control switches, contactors or circuit-breakers.

The main constraint applied to these devices is the current peak on energization. This current peak depends on the technology of the lamps used, but also on the installation characteristics (supply transformer power, length of cables, number of lamps) and the moment of energization in the line voltage period. A high current peak, however fleeting, can cause the contacts on an electromechanical control device to weld together or the destruction of a solid state device with semi-conductors.



Two solutions

Because of the inrush current, the majority of ordinary relays are incompatible with lighting device power supply. The following recommendations are therefore usually made:

- Limit the number of lamps to be connected to a single device so that their total power is less than the maximum permissible power for the device
- Check with the manufacturers what operating limits they suggest for the devices. This precaution is particularly important when replacing incandescent lamps with compact fluorescent lamps

By way of example, the table in **Figure N49** indicates the maximum number of compensated fluorescent tubes that can be controlled by different devices with 16 A rating. Note that the number of controlled tubes is well below the number corresponding to the maximum power for the devices.

Tube unit power requirement (W)	Number of tubes corresponding to the power 16 A x 230 V	Maximum number of tubes that can be controlled by		
		Contactors GC16 A CT16 A	Remote control switches TL16 A	Circuit-breakers C60-16 A
18	204	15	50	112
36	102	15	25	56
58	63	10	16	34

Fig. N49 : The number of controlled tubes is well below the number corresponding to the maximum power for the devices

But a technique exists to limit the current peak on energization of circuits with capacitive behavior (magnetic ballasts with parallel compensation and electronic ballasts). It consists of ensuring that activation occurs at the moment when the line voltage passes through zero. Only solid state switches with semi-conductors offer this possibility (see **Fig. N50a**). This technique has proved to be particularly useful when designing new lighting circuits.

More recently, hybrid technology devices have been developed that combine a solid state switch (activation on voltage passage through zero) and an electromechanical contactor short-circuiting the solid state switch (reduction of losses in the semi-conductors) (see **Fig. N50b**).

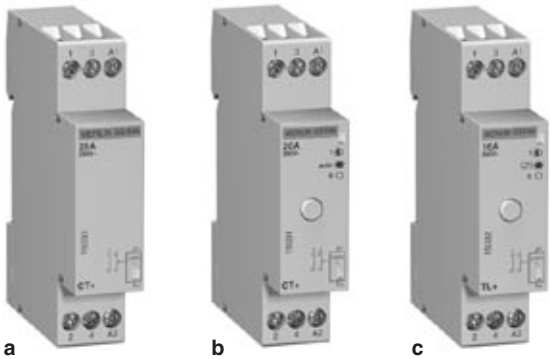


Fig. N50 : “Standard” CT+ contactor [a], CT+ contactor with manual override, pushbutton for selection of operating mode and indicator lamp showing the active operating mode [b], and TL + remote-control switch [c] (Merlin Gerin brand)

Modular contactors and impulse relays do not use the same technologies. Their rating is determined according to different standards. For example, for a given rating, an impulse relay is more efficient than a modular contactor for the control of light fittings with a strong inrush current, or with a low power factor (non-compensated inductive circuit).

### Choice of relay rating according to lamp type

■ **Figure 51** below shows the maximum number of light fittings for each relay, according to the type, power and configuration of a given lamp. As an indication, the total acceptable power is also mentioned.

■ These values are given for a 230 V circuit with 2 active conductors (single-phase phase/neutral or two-phase phase/phase). For 110 V circuits, divide the values in the table by 2.

■ To obtain the equivalent values for the whole of a 230 V three-phase circuit, multiply the number of lamps and the total acceptable power:

- by  $\sqrt{3}$  (1.73) for circuits without neutral;
- by 3 for circuits with neutral.

**Note:** The power ratings of the lamps most commonly used are shown in bold.

Type of lamp	Unit power and capacitance of power factor correction capacitor	Maximum number of light fittings for a single-phase circuit and maximum power output per circuit											
		TL impulse relay				CT contactor							
		16 A	32 A	16 A	25 A	40 A	63 A						
<b>Basic incandescent lamps</b>													
<b>LV halogen lamps</b>													
<b>Replacement mercury vapour lamps (without ballast)</b>													
	<b>40 W</b>	40	1500 W	106	4000 W	38	1550 W	57	2300 W	115	4600 W	172	6900 W
	<b>60 W</b>	25	to	66	to	30	to	45	to	85	to	125	to
	<b>75 W</b>	20	1600 W	53	4200 W	25	2000 W	38	2850 W	70	5250 W	100	7500 W
	<b>100 W</b>	16		42		19		28		50		73	
	150 W	10		28		12		18		35		50	
	200 W	8		21		10		14		26		37	
	300 W	5	1500 W	13	4000 W	7	2100 W	10	3000 W	18	5500 W	25	7500 W
	500 W	3		8		4		6		10	to	15	to
	1000 W	1		4		2		3		6	6000 W	8	8000 W
	1500 W	1		2		1		2		4		5	
<b>ELV 12 or 24 V halogen lamps</b>													
With ferromagnetic transformer	<b>20 W</b>	70	1350 W	180	3600 W	15	300 W	23	450 W	42	850 W	63	1250 W
	<b>50 W</b>	28	to	74	to	10	to	15	to	27	to	42	to
	75 W	19	1450 W	50	3750 W	8	600 W	12	900 W	23	1950 W	35	2850 W
	100 W	14		37		6		8		18		27	
With electronic transformer	<b>20 W</b>	60	1200 W	160	3200 W	62	1250 W	90	1850 W	182	3650 W	275	5500 W
	<b>50 W</b>	25	to	65	to	25	to	39	to	76	to	114	to
	75 W	18	1400 W	44	3350 W	20	1600 W	28	2250 W	53	4200 W	78	6000 W
	100 W	14		33		16		22		42		60	
<b>Fluorescent tubes with starter and ferromagnetic ballast</b>													
1 tube without compensation (1)	15 W	83	1250 W	213	3200 W	22	330 W	30	450 W	70	1050 W	100	1500 W
	<b>18 W</b>	70	to	186	to	22	to	30	to	70	to	100	to
	20 W	62	1300 W	160	3350 W	22	850 W	30	1200 W	70	2400 W	100	3850 W
	<b>36 W</b>	35		93		20		28		60		90	
	40 W	31		81		20		28		60		90	
	<b>58 W</b>	21		55		13		17		35		56	
	65 W	20		50		13		17		35		56	
	80 W	16		41		10		15		30		48	
	115 W	11		29		7		10		20		32	
	15 W	60	900 W	160	2400 W	15	200 W	20	300 W	40	600 W	60	900 W
1 tube with parallel compensation (2)	<b>18 W</b>	50		133		15	to	20	to	40	to	60	to
	20 W	45		120		15	800 W	20	1200 W	40	2400 W	60	3500 W
	<b>36 W</b>	25		66		15		20		40		60	
	40 W	22		60		15		20		40		60	
	<b>58 W</b>	16		42		10		15		30		43	
	65 W	13		37		10		15		30		43	
	80 W	11		30		10		15		30		43	
	115 W	7		20		5		7		14		20	
	2 x <b>18 W</b>	56	2000 W	148	5300 W	30	1100 W	46	1650 W	80	2900 W	123	4450 W
	4 x <b>18 W</b>	28		74		16	to	24	to	44	to	68	to
2 or 4 tubes with series compensation	2 x <b>36 W</b>	28		74		16	1500 W	24	2400 W	44	3800 W	68	5900 W
	2 x <b>58 W</b>	17		45		10		16		27		42	
	2 x 65 W	15		40		10		16		27		42	
	2 x 80 W	12		33		9		13		22		34	
	2 x 115 W	8		23		6		10		16		25	
	2 x <b>58 W</b>	13		34		12		19		38		57	
<b>Fluorescent tubes with electronic ballast</b>													
1 or 2 tubes	<b>18 W</b>	80	1450 W	212	3800 W	74	1300 W	111	2000 W	222	4000 W	333	6000 W
	<b>36 W</b>	40	to	106	to	38	to	58	to	117	to	176	to
	<b>58 W</b>	26	1550 W	69	4000 W	25	1400 W	37	2200 W	74	4400 W	111	6600 W
	2 x <b>18 W</b>	40		106		36		55		111		166	
	2 x <b>36 W</b>	20		53		20		30		60		90	
	2 x <b>58 W</b>	13		34		12		19		38		57	

**Fig. N51** : Maximum number of light fittings for each relay, according to the type, power and configuration of a given lamp (Continued on opposite page)

Type of lamp	Unit power and capacitance of power factor correction capacitor	Maximum number of light fittings for a single-phase circuit and maximum power output per circuit												
		TL impulse relay				CT contactor								
		16 A		32 A		16 A		25 A		40 A		63 A		
Compact fluorescent lamps														
With external electronic ballast	5 W	240	1200 W	630	3150 W	210	1050 W	330	1650 W	670	3350 W	not tested		
	7 W	171	to	457	to	150	to	222	to	478	to			
	9 W	138	1450 W	366	3800 W	122	1300 W	194	2000 W	383	4000 W			
	11 W	118		318		104		163		327				
	18 W	77		202		66		105		216				
	26 W	55		146		50		76		153				
With integral electronic ballast (replacement for incandescent lamps)	5 W	170	850 W	390	1950 W	160	800 W	230	1150 W	470	2350 W	710	3550 W	
	7 W	121	to	285	to	114	to	164	to	335	to	514	to	
	9 W	100	1050 W	233	2400 W	94	900 W	133	1300 W	266	2600 W	411	3950 W	
	11 W	86		200		78		109		222		340		
	18 W	55		127		48		69		138		213		
	26 W	40		92		34		50		100		151		
High-pressure mercury vapour lamps with ferromagnetic ballast without ignitor														
Replacement high-pressure sodium vapour lamps with ferromagnetic ballast with integral ignitor (3)														
Without compensation (1)	50 W		not tested, infrequent use				15	750 W	20	1000 W	34	1700 W	53	2650 W
	80 W						10	to	15	to	27	to	40	to
	125 / 110 W (3)						8	1000 W	10	1600 W	20	2800 W	28	4200 W
	250 / 220 W (3)						4		6		10		15	
	400 / 350 W (3)						2		4		6		10	
	700 W						1		2		4		6	
With parallel compensation (2)	50 W	7 µF					10	500 W	15	750 W	28	1400 W	43	2150 W
	80 W	8 µF					9	to	13	to	25	to	38	to
	125 / 110 W (3)	10 µF					9	1400 W	10	1600 W	20	3500 W	30	5000 W
	250 / 220 W (3)	18 µF					4		6		11		17	
	400 / 350 W (3)	25 µF					3		4		8		12	
	700 W	40 µF					2		2		5		7	
	1000 W	60 µF					0		1		3		5	
Low-pressure sodium vapour lamps with ferromagnetic ballast with external ignitor														
Without compensation (1)	35 W		not tested, infrequent use				5	270 W	9	320 W	14	500 W	24	850 W
	55 W						5	to	9	to	14	to	24	to
	90 W						3	360 W	6	720 W	9	1100 W	19	1800 W
	135 W						2		4		6		10	
	180 W						2		4		6		10	
With parallel compensation (2)	35 W	20 µF	38	1350 W	102	3600 W	3	100 W	5	175 W	10	350 W	15	550 W
	55 W	20 µF	24		63		3	to	5	to	10	to	15	to
	90 W	26 µF	15		40		2	180 W	4	360 W	8	720 W	11	1100 W
	135 W	40 µF	10		26		1		2		5		7	
	180 W	45 µF	7		18		1		2		4		6	
High-pressure sodium vapour lamps														
Metal-iodide lamps														
With ferromagnetic ballast with external ignitor, without compensation (1)	35 W		not tested, infrequent use				16	600 W	24	850 W	42	1450 W	64	2250 W
	70 W						8		12		20	to	32	to
	150 W						4		7	1200 W	13	2000 W	18	3200 W
	250 W						2		4		8		11	
	400 W						1		3		5		8	
	1000 W						0		1		2		3	
With ferromagnetic ballast with external ignitor and parallel compensation (2)	35 W	6 µF	34	1200 W	88	3100 W	12	450 W	18	650 W	31	1100 W	50	1750 W
	70 W	12 µF	17	to	45	to	6	to	9	to	16	to	25	to
	150 W	20 µF	8	1350 W	22	3400 W	4	1000 W	6	2000 W	10	4000 W	15	6000 W
	250 W	32 µF	5		13		3		4		7		10	
	400 W	45 µF	3		8		2		3		5		7	
	1000 W	60 µF	1		3		1		2		3		5	
	2000 W	85 µF	0		1		0		1		2		3	
With electronic ballast	35 W		38	1350 W	87	3100 W	24	850 W	38	1350 W	68	2400 W	102	3600 W
	70 W		29	to	77	to	18	to	29	to	51	to	76	to
	150 W		14	2200 W	33	5000 W	9	1350 W	14	2200 W	26	4000 W	40	6000 W

(1) Circuits with non-compensated ferromagnetic ballasts consume twice as much current for a given lamp power output. This explains the small number of lamps in this configuration.

(2) The total capacitance of the power factor correction capacitors in parallel in a circuit limits the number of lamps that can be controlled by a contactor. The total downstream capacitance of a modular contactor of rating 16, 25, 40 or 63 A should not exceed 75, 100, 200 or 300 µF respectively. Allow for these limits to calculate the maximum acceptable number of lamps if the capacitance values are different from those in the table.

(3) High-pressure mercury vapour lamps without ignitor, of power 125, 250 and 400 W, are gradually being replaced by high-pressure sodium vapour lamps with integral ignitor, and respective power of 110, 220 and 350 W.

**Fig. N51** : Maximum number of light fittings for each relay, according to the type, power and configuration of a given lamp (Concluded)

**Protection of lamp circuits: Maximum number of lamps and MCB rating versus lamp type, unit power and MCB tripping curve**

During start up of discharge lamps (with their ballast), the inrush current drawn by each lamp may be in the order of:

- 25 x circuit start current for the first 3 ms
- 7 x circuit start current for the following 2 s

For fluorescent lamps with High Frequency Electronic control ballast, the protective device ratings must cope with 25 x inrush for 250 to 350  $\mu$ s.

However due to the circuit resistance the total inrush current seen by the MCB is lower than the summation of all individual lamp inrush current if directly connected to the MCB.

The tables below (see **Fig. N52 to NXX**) take into account:

- Circuits cables have a length of 20 meters from distribution board to the first lamp and 7 meters between each additional fittings.
- MCB rating is given to protect the lamp circuit in accordance with the cable cross section, and without unwanted tripping upon lamp starting.
- MCB tripping curve (C = instantaneous trip setting 5 to 10 In, D = instantaneous trip setting 10 to 14 In).

Lamp power (W)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
	Number of lamps per circuit																			
	MCB rating C & D tripping curve																			
14/18	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6
14 x2	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6
14 x3	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	10	10	10
14 x4	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	10	10	10	10
18 x2	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6
18 x4	6	6	6	6	6	6	6	6	6	6	6	6	6	10	10	10	10	10	10	10
21/24	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6
21/24 x2	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6
28	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6
28 x2	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	10	10	10
35/36/39	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6
35/36 x2	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	10	10	10	10	10
38/39 x2	6	6	6	6	6	6	6	6	6	6	6	6	10	10	10	10	10	10	10	10
40/42	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6
40/42 x2	6	6	6	6	6	6	6	6	6	6	6	6	10	10	10	10	10	10	10	16
49/50	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6
49/50 x2	6	6	6	6	6	6	6	6	6	6	10	10	10	10	10	10	16	16	16	16
54/55	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	10	10
54/55 x2	6	6	6	6	6	6	6	6	10	10	10	10	10	10	16	16	16	16	16	16
60	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	10	10	10	10

N38

Fig. N52 : Fluorescent tubes with electronic ballast - Vac = 230 V

Lamp power (W)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
	Number of lamps per circuit																			
	MCB rating C & D tripping curve																			
6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6
9	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6
11	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6
13	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6
14	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6
15	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6
16	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6
17	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6
18	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6
20	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6
21	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6
23	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6
25	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	10

Fig. N53 : Compact fluorescent lamps - Vac = 230 V

Lamp power (W)	Number of lamps per circuit																			
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
MCB rating C tripping curve																				
50	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	10	10	10	10
80	6	6	6	6	6	6	6	6	6	6	10	10	10	10	10	10	10	16	16	16
125	6	6	6	10	10	10	10	10	10	10	10	16	16	16	16	16	16	16	20	20
250	6	10	10	16	16	16	16	16	16	20	20	25	25	25	32	32	32	32	40	40
400	6	16	20	25	25	32	32	32	32	32	32	40	40	40	50	50	50	50	63	63
1000	16	32	40	50	50	50	50	63	63	-	-	-	-	-	-	-	-	-	-	-
MCB rating D tripping curve																				
50	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	10	10	10	10
80	6	6	6	6	6	6	6	6	6	6	10	10	10	10	10	10	10	16	16	16
125	6	6	6	6	6	6	10	10	10	10	10	16	16	16	16	16	16	16	20	20
250	6	6	10	10	10	10	16	16	16	20	20	25	25	25	32	32	32	32	40	40
400	6	10	16	16	20	20	25	25	25	32	32	40	40	40	50	50	50	50	63	63
1000	10	20	25	32	40	40	50	63	63	-	-	-	-	-	-	-	-	-	-	-

Fig. N54 : High pressure mercury vapour (with ferromagnetic ballast and PF correction) - Vac = 230 V

Lamp power (W)	Number of lamps per circuit																			
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
MCB rating C tripping curve																				
Ferromagnetic ballast																				
18	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6
26	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6
35/36	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6
55	6	6	6	6	6	6	6	6	6	6	6	6	6	10	10	10	10	10	10	10
91	6	6	6	6	6	6	6	6	6	10	10	10	10	10	10	10	16	16	16	16
131	6	6	6	10	10	10	10	10	10	10	10	10	16	16	16	16	16	16	16	20
135	6	6	6	10	10	10	10	10	10	10	10	16	16	16	16	16	16	20	20	20
180	6	6	10	10	10	10	10	10	16	16	16	16	20	20	20	20	25	25	25	25
Electronic ballast																				
36	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6
55	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6
66	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	10	10	10
91	6	6	6	6	6	10	10	10	10	10	10	10	10	10	10	10	16	16	16	16
MCB rating D tripping curve																				
Ferromagnetic ballast																				
18	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6
26	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6
35/36	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6
55	6	6	6	6	6	6	6	6	6	6	6	6	6	6	10	10	10	10	10	10
91	6	6	6	6	6	6	6	6	6	6	10	10	10	10	10	10	16	16	16	16
131	6	6	6	6	6	6	6	10	10	10	10	10	16	16	16	16	16	16	16	20
135	6	6	6	6	6	6	10	10	10	10	10	16	16	16	16	16	16	20	20	20
180	6	6	6	6	10	10	10	10	16	16	16	16	20	20	20	20	25	25	25	25
Electronic ballast																				
36	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6
55	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6
66	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	10	10	10
91	6	6	6	6	6	6	6	6	6	10	10	10	10	10	10	10	16	16	16	16

Fig. N55 : Low pressure sodium (with PF correction) - Vac = 230 V

Lamp power (W)	1	2	3	4	5	6	7	8	Number of lamps per circuit													
	9	10	11	12	13	14	15	16	17	18	19	20	MCB rating C tripping curve									
Ferromagnetic ballast																						
50	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	10	10	10	10		
70	6	6	6	6	6	6	6	6	6	6	10	10	10	10	10	10	10	16	16	16		
100	6	6	6	6	6	6	6	6	10	10	10	10	10	16	16	16	16	16	16	16		
150	6	6	10	10	10	10	10	10	6	16	16	16	16	16	16	20	20	20	25	25		
250	6	10	16	16	16	20	20	20	20	20	20	25	25	25	32	32	32	32	40	40		
400	10	16	20	25	32	32	32	32	32	32	32	40	40	40	50	50	50	50	63	63		
1000	16	32	40	50	50	50	50	63	63	-	-	-	-	-	-	-	-	-	-	-		
Electronic ballast																						
35	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6		
50	6	6	6	6	6	6	6	6	6	6	6	6	6	10	10	10	10	10	10	10		
100	6	6	6	6	6	6	6	6	10	10	10	10	10	10	16	16	16	16	16	16		
MCB rating D tripping curve																						
Ferromagnetic ballast																						
50	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	10	10	10	10		
70	6	6	6	6	6	6	6	6	6	6	10	10	10	10	10	10	10	16	16	16		
100	6	6	6	6	6	6	6	6	10	10	10	10	10	16	16	16	16	16	16	16		
150	6	6	6	6	6	10	10	10	10	16	16	16	16	16	16	20	20	20	25	25		
250	6	6	10	10	16	16	16	16	16	20	20	25	25	25	32	32	32	32	40	40		
400	6	10	16	16	20	20	25	25	25	32	32	40	40	40	50	50	50	50	63	63		
1000	10	20	32	32	40	40	50	63	63	-	-	-	-	-	-	-	-	-	-	-		
Electronic ballast																						
35	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6		
50	6	6	6	6	6	6	6	6	6	6	6	6	6	10	10	10	10	10	10	10		
100	6	6	6	6	6	6	6	6	10	10	10	10	10	10	16	16	16	16	16	16		

Fig. N56 : High pressure sodium (with PF correction) - Vac = 230 V

Lamp power (W)	1	2	3	4	5	6	7	8	Number of lamps per circuit													
	9	10	11	12	13	14	15	16	17	18	19	20	MCB rating C tripping curve									
Ferromagnetic ballast																						
35	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6		
70	6	6	6	6	6	6	6	6	6	6	10	10	10	10	10	10	10	16	16	16		
150	6	6	10	10	10	10	10	10	10	16	16	16	16	16	16	20	20	20	25	25		
250	6	10	16	16	16	20	20	20	20	20	25	25	25	32	32	32	32	40	40	40		
400	6	16	20	25	25	32	32	32	32	32	40	40	40	50	50	50	50	63	63	63		
1000	16	32	40	50	50	50	50	63	63	63	63	63	63	63	63	63	63	63	63	63		
1800/2000	25	50	63	63	63	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-		
Electronic ballast																						
35	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6		
70	6	6	6	6	6	6	6	6	6	6	6	6	10	10	10	10	10	10	10	10		
150	6	6	6	10	10	10	10	10	10	16	16	16	16	16	16	16	16	20	20	20		
MCB rating D tripping curve																						
Ferromagnetic ballast																						
35	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6		
70	6	6	6	6	6	6	6	6	6	6	6	10	10	10	10	10	10	16	16	16		
150	6	6	6	6	6	10	10	10	10	16	16	16	16	16	16	20	20	20	25	25		
250	6	6	10	10	16	16	16	16	16	20	20	25	25	25	32	32	32	32	40	40		
400	6	10	16	16	20	20	25	25	25	32	32	40	40	40	50	50	50	50	63	63		
1000	16	20	32	32	40	50	50	63	63	-	-	-	-	-	-	-	-	-	-	-		
1800	16	32	40	50	63	63	-	-	-	-	-	-	-	-	-	-	-	-	-	-		
2000	20	32	40	50	63	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-		
Electronic ballast																						
35	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6		
70	6	6	6	6	6	6	6	6	6	6	6	6	10	10	10	10	10	10	10	10		
150	6	6	6	6	6	6	6	10	10	10	16	16	16	16	16	16	16	20	20	20		

Fig. N57 : Metal halide (with PF correction) - Vac = 230 V

Lamp power (W)									Number of lamps per circuit											
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
MCB rating C tripping curve																				
1800	16	32	40	50	50	50	50	63	63	-	-	-	-	-	-	-	-	-	-	-
2000	16	32	40	50	50	50	50	63	63	-	-	-	-	-	-	-	-	-	-	-
MCB rating D tripping curve																				
1800	16	20	32	32	32	32	50	63	63	-	-	-	-	-	-	-	-	-	-	-
2000	16	25	32	32	32	32	50	63	-	-	-	-	-	-	-	-	-	-	-	-

Fig. N58 : Metal halide (with ferromagnetic ballast and PF correction) - Vac = 400 V

Overload of the neutral conductor

The risk

In an installation including, for example, numerous fluorescent tubes with electronic ballasts supplied between phases and neutral, a high percentage of 3<sup>rd</sup> harmonic current can cause an overload of the neutral conductor. **Figure N59** below gives an overview of typical H3 level created by lighting.

Lamp type	Typical power	Setting mode	Typical H3 level
Incandescend lamp with dimmer	100 W	Light dimmer	5 to 45 %
ELV halogen lamp	25 W	Electronic ELV transformer	5 %
Fluorescent tube	100 W	Magnetic ballast	10 %
	< 25 W	Electronic ballast	85 %
	> 25 W	+ PFC	30 %
Discharge lamp	100 W	Magnetic ballast	10 %
		Electrical ballast	30 %

Fig. N59 : Overview of typical H3 level created by lighting

The solution

Firstly, the use of a neutral conductor with a small cross-section (half) should be prohibited, as requested by Installation standard IEC 60364, section 523–5–3.

As far as overcurrent protection devices are concerned, it is necessary to provide 4-pole circuit-breakers with protected neutral (except with the TN-C system for which the PEN, a combined neutral and protection conductor, should not be cut).

This type of device can also be used for the breaking of all poles necessary to supply luminaires at the phase-to-phase voltage in the event of a fault.

A breaking device should therefore interrupt the phase and Neutral circuit simultaneously.

Leakage currents to earth

The risk

At switch-on, the earth capacitances of the electronic ballasts are responsible for residual current peaks that are likely to cause unintentional tripping of protection devices.

Two solutions

The use of Residual Current Devices providing immunity against this type of impulse current is recommended, even essential, when equipping an existing installation (see **Fig. N60**).

For a new installation, it is sensible to provide solid state or hybrid control devices (contactors and remote-control switches) that reduce these impulse currents (activation on voltage passage through zero).

Overvoltages

The risk

As illustrated in earlier sections, switching on a lighting circuit causes a transient state which is manifested by a significant overcurrent. This overcurrent is accompanied by a strong voltage fluctuation applied to the load terminals connected to the same circuit. These voltage fluctuations can be detrimental to correct operation of sensitive loads (micro-computers, temperature controllers, etc.)

The Solution

It is advisable to separate the power supply for these sensitive loads from the lighting circuit power supply.

Sensitivity of lighting devices to line voltage disturbances

Short interruptions

■ The risk

Discharge lamps require a relighting time of a few minutes after their power supply has been switched off.

■ The solution

Partial lighting with instantaneous relighting (incandescent lamps or fluorescent tubes, or "hot restrike" discharge lamps) should be provided if safety requirements so dictate. Its power supply circuit is, depending on current regulations, usually distinct from the main lighting circuit.

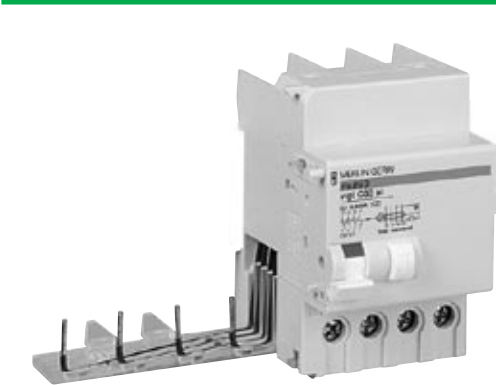


Fig. N60 : s.i. residual current devices with immunity against impulse currents (Merlin Gerin brand)



**Voltage fluctuations**

## ■ The risk

The majority of lighting devices (with the exception of lamps supplied by electronic ballasts) are sensitive to rapid fluctuations in the supply voltage. These fluctuations cause a flicker phenomenon which is unpleasant for users and may even cause significant problems. These problems depend on both the frequency of variations and their magnitude.

Standard IEC 61000-2-2 ("compatibility levels for low-frequency conducted disturbances") specifies the maximum permissible magnitude of voltage variations as a function of the number of variations per second or per minute.

These voltage fluctuations are caused mainly by high-power fluctuating loads (arc furnaces, welding machines, starting motors).

## ■ The solution

Special methods can be used to reduce voltage fluctuations. Nonetheless, it is advisable, wherever possible, to supply lighting circuits via a separate line supply. The use of electronic ballasts is recommended for demanding applications (hospitals, clean rooms, inspection rooms, computer rooms, etc).

**Developments in control and protection equipment**

The use of light dimmers is more and more common. The constraints on ignition are therefore reduced and derating of control and protection equipment is less important. New protection devices adapted to the constraints on lighting circuits are being introduced, for example Merlin Gerin brand circuit-breakers and modular residual current circuit-breakers with special immunity, such as s.i. type ID switches and Vigi circuit-breakers. As control and protection equipment evolves, some now offer remote control, 24-hour management, lighting control, reduced consumption, etc.

**4.4 Lighting of public areas****Normal lighting**

Regulations governing the minimum requirements for buildings receiving the public in most European countries are as follows:

- Installations which illuminates areas accessible to the public must be controlled and protected independently from installations providing illumination to other areas
- Loss of supply on a final lighting circuit (i.e. fuse blown or CB tripped) must not result in total loss of illumination in an area which is capable of accommodating more than 50 persons
- Protection by Residual Current Devices (RCD) must be divided amongst several devices (i.e. more than on device must be used)

**Emergency lighting and other systems**

When we refer to emergency lighting, we mean the auxiliary lighting that is triggered when the standard lighting fails.

**Emergency lighting is subdivided as follows (EN-1838):**

**Safety lighting**

It originates from the emergency lighting and is intended to provide lighting for people to evacuate an area safely or for those who try to finish a potentially dangerous operation before leaving the area. It is intended to illuminate the means of evacuation and ensure continuous visibility and ready usage in safety when standard or emergency lighting is needed. Safety lighting may be further subdivided as follows:

**Safety lighting for escape routes**

It originates from the safety lighting, and is intended to ensure that the escape means can be clearly identified and used safely when the area is busy.

**Anti-panic lighting in extended areas**

It originates from the safety lighting, and is intended to avoid panic and to provide the necessary lighting to allow people to reach a possible escape route area.

**Emergency lighting and safety signs for escape routes**

The emergency lighting and safety signs for escape routes are very important for all those who design emergency systems. Their suitable choice helps improve safety levels and allows emergency situations to be handled better.



Standard EN 1838 ("Lighting applications. Emergency lighting") gives some fundamental concepts concerning what is meant by emergency lighting for escape routes:

"The intention behind lighting escape routes is to allow safe exit by the occupants, providing them with sufficient visibility and directions on the escape route ..."

The concept referred to above is very simple:

The safety signs and escape route lighting must be two separate things.

### Functions and operation of the luminaires

The manufacturing specifications are covered by standard EN 60598-2-22, "Particular Requirements - Luminaires for Emergency Lighting", which must be read with EN 60598-1, "Luminaires – Part 1: General Requirements and Tests".

#### Duration

A basic requirement is to determine the duration required for the emergency lighting. Generally it is 1 hour but some countries may have different duration requirements according to statutory technical standards.

#### Operation

We should clarify the different types of emergency luminaires:

##### ■ Non-maintained luminaires

□ The lamp will only switch on if there is a fault in the standard lighting

□ The lamp will be powered by the battery during failure

□ The battery will be automatically recharged when the mains power supply is restored

##### ■ Maintained luminaires

□ The lamp can be switched on in continuous mode

□ A power supply unit is required with the mains, especially for powering the lamp, which can be disconnected when the area is not busy

□ The lamp will be powered by the battery during failure.

### Design

The integration of emergency lighting with standard lighting must comply strictly with electrical system standards in the design of a building or particular place.

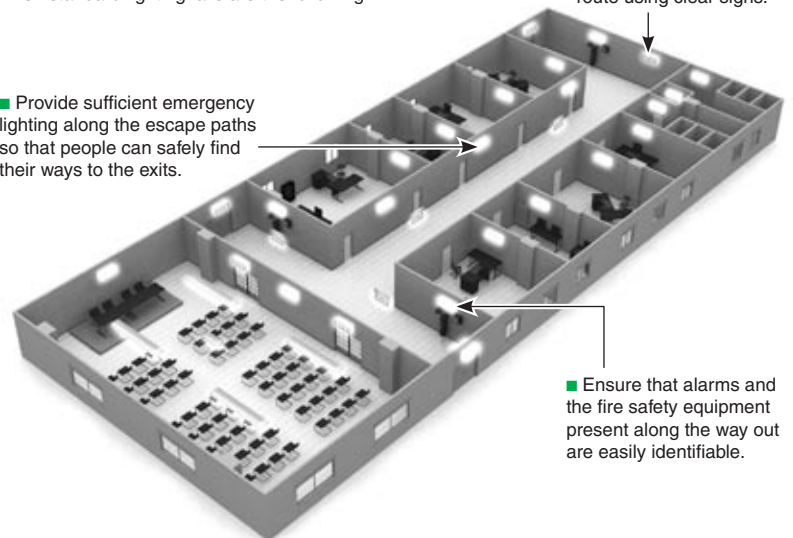
All regulations and laws must be complied with in order to design a system which is up to standard (see **Fig. N61**).

The main functions of an emergency lighting system when standard lighting fails are the following:

■ Provide sufficient emergency lighting along the escape paths so that people can safely find their ways to the exits.

■ Clearly show the escape route using clear signs.

■ Ensure that alarms and the fire safety equipment present along the way out are easily identifiable.



**Fig. N61** : The main functions of an emergency lighting system

### European standards

The design of emergency lighting systems is regulated by a number of legislative provisions that are updated and implemented from time to time by new documentation published on request by the authorities that deal with European and international technical standards and regulations.

Each country has its own laws and regulations, in addition to technical standards

which govern different sectors. Basically they describe the places that must be provided with emergency lighting as well as its technical specifications. The designer's job is to ensure that the design project complies with these standards.

### EN 1838

A very important document on a European level regarding emergency lighting is the Standard EN 1838, "Lighting applications. Emergency lighting".

This standard presents specific requirements and constraints regarding the operation and the function of emergency lighting systems.

### CEN and CENELEC standards

With the CEN (Comité Européen de Normalisation) and CENELEC standards (Comité Européen de Normalisation Electrotechnique), we are in a standardised environment of particular interest to the technician and the designer. A number of sections deal with emergencies. An initial distinction should be made between luminaire standards and installation standards.

### EN 60598-2-22 and EN-60598-1

Emergency lighting luminaires are subject to European standard EN 60598-2-22, "Particular Requirements - Luminaires for Emergency Lighting", which is an integrative text (of specifications and analysis) of the Standard EN-60598-1, Luminaires – "Part 1: General Requirements and Tests".

*The asynchronous (i.e. induction) motor is robust and reliable, and very widely used. 95% of motors installed around the world are asynchronous. The protection of these motors is consequently a matter of great importance in numerous applications.*

The consequence of an incorrectly protected motor can include the following:

- For persons:
  - Asphyxiation due to the blockage of motor ventilation
  - Electrocution due to insulation failure in the motor
  - Accident due to non stopping of the motor following the failure of the control circuit in case of incorrect overcurrent protection
- For the driven machine and the process
  - Shaft couplings and axles, etc, damaged due to a stalled rotor
  - Loss of production
  - Manufacturing time delayed
- For the motor
  - Motor windings burnt out due to stalled rotor
  - Cost of dismantling and reinstalling or replacement of motor
  - Cost of repairs to the motor

Therefore, the safety of persons and goods, and reliability and availability levels are highly dependant on the choice of protective equipment.

In economic terms, the overall cost of failure must be considered. This cost is increasing with the size of the motor and with the difficulties of access and replacement. Loss of production is a further, and evidently important factor.

Specific features of motor performance influence the power supply circuits required for satisfactory operation

A motor power-supply circuit presents certain constraints not normally encountered in other (common) distribution circuits, owing to the particular characteristics, specific to motors, such as:

- High start-up current (see **Fig. N62**) which is mostly reactive, and can therefore be the cause of important voltage drop
- Number and frequency of start-up operations are generally high
- The high start-up current means that motor overload protective devices must have operating characteristics which avoid tripping during the starting period

## 5.1 Functions for the motor circuit

Functions generally provided are:

- Basic functions including:
  - Isolating facility
  - Motor control (local or remote)
  - Protection against short-circuits
  - Protection against overload
- Complementary protections including:
  - Thermal protection by direct winding temperature measurement
  - Thermal protection by indirect winding temperature determination
  - Permanent insulation-resistance monitoring
  - Specific motor protection functions
- Specific control equipment including:
  - Electromechanical starters
  - Control and Protective Switching devices (CPS)
  - Soft-start controllers
  - Variable speed drives

### Basic functions

#### Isolating facility

It is necessary to isolate the circuits, partially or totally, from their power supply network for safety of personnel during maintenance work. "Isolation" function is provided by disconnectors. This function can be included in other devices designed to provide isolation such as disconnector/circuit-breaker.

#### Motor control

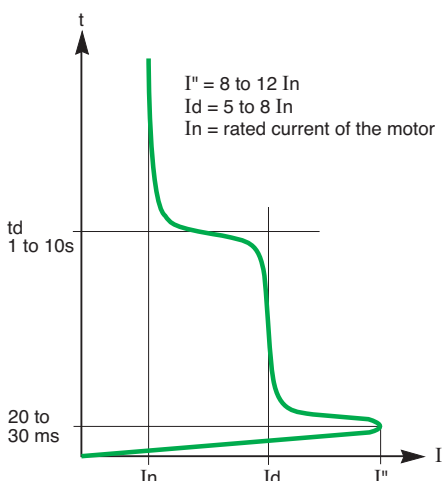
The motor control function is to make and break the motor current. In case of manual control, this function can be provided by motor-circuit-breakers or switches.

In case of remote control, this function can be provided by contactors, starters or CPS.

The control function can also be initiated by other means:

- Overload protection
- Complementary protection
- Under voltage release (needed for a lot of machines)

The control function can also be provided by specific control equipment.



**Fig. N62** : Direct on-line starting current characteristics of an induction motor

**Protection against short-circuits**

## ■ Phase-to-phase short-circuit

This type of fault inside the machine is very rare. It is generally due to mechanical incident of the power supply cable of the motor.

## ■ Phase-to-earth short-circuit

The deterioration of winding insulation is the main cause. The resulting fault current depends on the system of earthing. For the TN system, the resulting fault current is very high and in most cases the motor will be deteriorated. For the other systems of earthing, protection of the motor can be achieved by earth fault protection.

For short-circuit protection, it is recommended to pay special attention to avoid unexpected tripping during the starting period of the motor. The inrush current of a standard motor is about 6 to 8 times its rated current but during a fault the current can be as high as 15 times the rated current. So, the starting current must not be seen as a fault by the protection. In addition, a fault occurring in a motor circuit must not disturb any upstream circuit. As a consequence, discrimination/selectivity of magnetic protections must be respected with all parts of the installation.

**Protection against overload**

Mechanical overloads due to the driven machine are the main origins of the overload for a motor application. They cause overload current and motor overheating. The life of the motor can be reduced and sometimes, the motor can be deteriorated. So, it is necessary to detect motor overload. This protection can be provided by:

## ■ Specific thermal overload relay

## ■ Specific thermal-magnetic circuit-breaker commonly referred to as "motor circuit-breaker"

## ■ Complementary protection (see below) like thermal sensor or electronic multifunction relay

## ■ Electronic soft start controllers or variable speed drives (see below)

**Complementary protections**

## ■ Thermal protection by direct winding temperature measurement

Provided by thermal sensors incorporated inside the windings of the motor and associated relays.

## ■ Thermal protection by indirect winding temperature determination

Provided by multifunction relays through current measurement and taking into account the characteristics of the motors (e.g.: thermal time constant).

## ■ Permanent insulation-resistance monitoring relays or residual current differential relays

They provide detection and protection against earth leakage current and short-circuit to earth, allowing maintenance operation before destruction of the motor.

## ■ Specific motor protection functions

Such as protection against too long starting period or stalled rotor, protection against unbalanced, loss or permutation of phases, earth fault protection, no load protection, rotor blocked (during start or after)...; pre alarm overheating indication, communication, can also be provided by multifunction relays.

**Specific control equipment**

## ■ Electromechanical starters (star-delta, auto-transformer, rheostatic rotor starters,...)

They are generally used for application with no load during the starting period (pump, fan, small centrifuge, machine-tool, etc.)

## □ Advantages

Good torque/current ratio; great reduction of inrush current.

## □ Disadvantages

Low torque during the starting period; no easy adjustment; power cut off during the transition and transient phenomenon; 6 motor connection cables needed.

## ■ Control and Protective Switching devices (CPS)

They provide all the basic functions listed before within a single unit and also some complementary functions and the possibility of communication. These devices also provide continuity of service in case of short-circuit.

## ■ Soft-start controllers

Used for applications with pump, fan, compressor, conveyor.

## □ Advantages

Reduced inrush current, voltage drop and mechanical stress during the motor start; built-in thermal protection; small size device; possibility of communication

## □ Disadvantages

Low torque during the starting period; thermal dissipation.

### ■ Variable speed drives

They are used for applications with pump, fan, compressor, conveyor, machine with high load torque, machine with high inertia.

### □ Advantages

Continuous speed variation (adjustment typically from 2 to 130% of nominal speed), overspeed is possible; accurate control of acceleration and deceleration; high torque during the starting and stopping periods; low inrush current, built-in thermal protection, possibility of communication.

### □ Disadvantages

Thermal dissipation, volume, cost.

## 5.2 Standards

The motor control and protection can be achieved in different way:

■ By using an association of a SCPD (Short-Circuit-Protective-Device) and electromechanical devices such as

□ An electromechanical starters fulfilling the standard IEC 60947-4-1

□ A semiconductor starter fulfilling the standard IEC 60947-4-2

□ A variable speed drives fulfilling the standard series IEC 61800

■ By using a CPS, single device covering all the basic functions, and fulfilling the standard IEC 60947-6-2

In this document, only the motor circuits including association of electromechanical devices such as, starters and protection against short-circuit, are considered. The devices meeting the standard 60947-6-2, the semiconductor starters and the variable speed drives will be considered only for specific points.

A motor circuit will meet the rules of the IEC 60947-4-1 and mainly:

■ The co-ordination between the devices of the motor circuit

■ The tripping class of the thermal relays

■ The category of utilization of the contactors

■ The insulation co-ordination

**Note:** The first and last points are satisfied inherently by the devices meeting the IEC 60947-6-2 because they provide a continuity of service.

### Standardization of the association circuit-breaker + contactor + thermal relay

#### Control devices categories

The standards in the IEC 60947 series define the utilisation categories according to the purposes the control gear is designed for (see **Fig. N63**). Each category is characterised by one or more operating conditions such as:

■ Currents

■ Voltages

■ Power factor or time constant

■ And if necessary, other operating conditions

N47

Type of current	Operating categories	Typical uses
Alternating current	AC-1	Non inductive or slightly inductive load, resistance furnace. Power distribution (lighting, generators, etc.).
	AC-2	Brush motor: starting, breaking. Heavy duty equipment (hoisting, handling, crusher, rolling-mill train, etc.).
	AC-3	Squirrel cage motor: starting, switching off running motors. Motor control (pumps, compressors, fans, machine-tools, conveyors, presses, etc.).
	AC-4	Squirrel cage motor: starting, plugging, inching. Heavy-duty equipment (hoisting, handling, crusher, rolling-mill train, etc.).
Direct current	DC-1	Non inductive or slightly inductive load, resistance furnace.
	DC-3	Shunt wound motor: starting, reversing, counter-current breaking, inching. Dynamic breaking for direct current motors.
	DC-5	Series wound motor: starting, reversing, counter-current breaking, inching. Dynamic breaking for direct current motors.

\* Category AC-3 can be used for the inching or reversing, counter-current breaking for occasional operations of a limited length of time, such as for the assembly of a machine. The number of operations per limited length of time normally do not exceed five per minute and ten per 10 minutes.

**Fig. N63** : Contactor utilisation categories based on the purposes they are designed for, according to IEC 60947-1

The following is also taken into consideration:

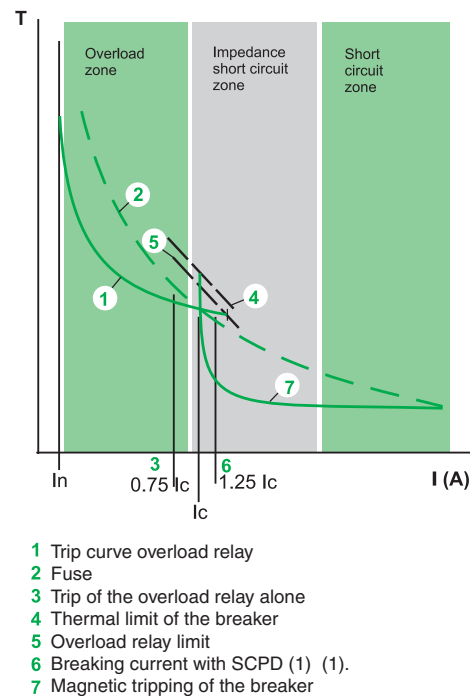
- Circuit making and breaking conditions
- Type of load (squirrel cage motor, brush motor, resistor)
- Conditions in which making and breaking take place (motor running, motor stalled, starting process, counter-current breaking, etc.)

### Coordination between protections and control

It is coordination, the most efficient combination of the different protections (against short circuits and overloads) and the control device (contactor) which make up a motor starter unit.

Studied for a given power, it provides the best possible protection of the equipment controlled by this motor starter unit (see **Fig. N64**).

It has the double advantage of reducing equipment and maintenance costs as the different protections complement each other as exactly as possible, with no useless redundancy.



**Fig. N64** : The basics of coordination

### There are different types of coordination

Two types of coordination (type 1 and type 2) are defined by IEC 60947-4-1.

#### ■ Type 1 coordination:

The commonest standard solution. It requires that in event of a short circuit, the contactor or the starter do not put people or installations in danger. It admits the necessity of repairs or part replacements before service restoration.

#### ■ Type 2 coordination:

The high performance solution. It requires that in the event of a short circuit, the contactor or the starter do not put people or installations in danger and that it is able to work afterwards. It admits the risk of contact welding. In this case, the manufacturer must specify the measures to take for equipment maintenance.

#### ■ Some manufacturers offer:

The highest performance solution, which is “**Total coordination**”.

This coordination requires that in the event of a short circuit, the contactor or the starter do not put people or installations in danger and that it is able to work afterwards. It does not admit the risk of contact welding and the starting of the motor starter unit must be immediate.

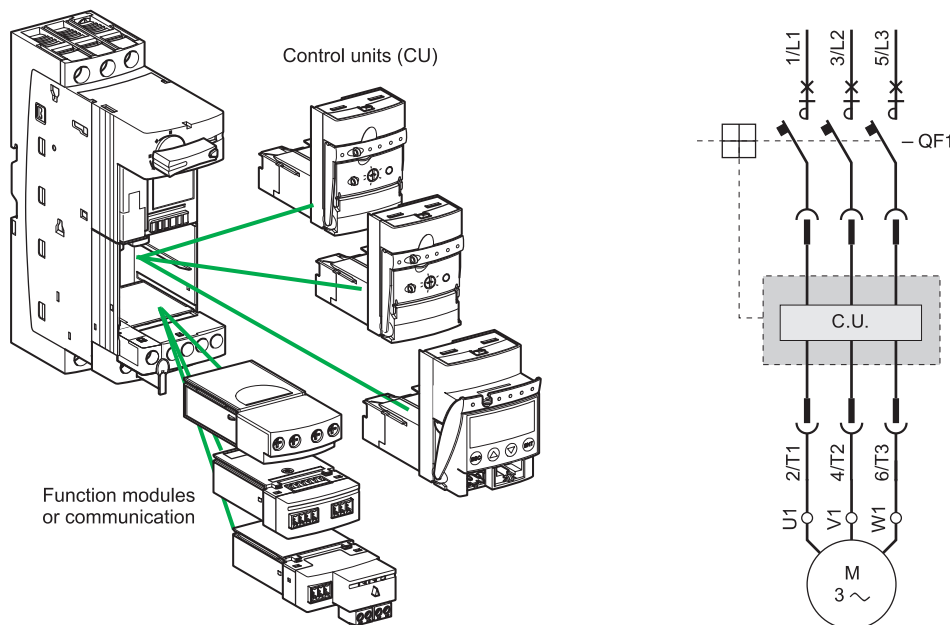
**Control and protection switching gear (CPS)**

CPS or “starter-controllers” are designed to fulfil control and protection functions simultaneously (overload and short circuit). In addition, they are designed to carry out control operations in the event of a short circuit.

They can also assure additional functions such as insulation, thereby totally fulfilling the function of “motor starter unit”. They comply with standard IEC 60947-6-2, which notably defines the assigned values and utilisation categories of a CPS, as do standards IEC 60947-1 and 60947-4-1.

The functions performed by a CPS are combined and coordinated in such a way as to allow for uptime at all currents up to the Ics working short circuit breaking capacity of the CPS. The CPS may or may not consist of one device, but its characteristics are assigned as for a single device. Furthermore, the guarantee of “total” coordination of all the functions ensures the user has a simple choice with optimal protection which is easy to implement.

Although presented as a single unit, a CPS can offer identical or greater modularity than the “three product” motor starter unit solution. This is the case with the “Tesys U” starter-controller (see **Fig. N65**).



**Fig. N65** : Example of a CPS modularity (Tesys Ustarter controller by Telemecanique)

This starter-controller can at any time bring in or change a control unit with protection and control functions for motors from 0.15A to 32A in a generic “base power” or “base unit” of a 32 A calibre.

Additional functionality's can also be installed with regard to:

- Power, reversing block, limiter
- Control
- Functions modules, alarms, motor load, automatic resetting, etc,
- Communication modules: AS-I, Modbus, Profibus, CAN-Open, etc,
- Auxiliary contact modules, added contacts.

Communications functions are possible with this system (see Fig. N66).

Available functions:	Standard	Control units: Upgradeable	Multifunction
Starter status (ready, running, with default)			
Alarms (overcurrents...)			
Thermal alarm			
Remote resetting by bus			
Indication of motor load			
Defaults differentiation			
Parameter setting and protection function reference			
"Log file" function			
"Monitoring" function			
Start and Stop controls			

Information conveyed by bus (Modbus) and functions performed

Fig. N66 : Tesys U Communication functions

What sort of coordination does one choose?

The choice of the coordination type depends on the operation parameters. It should be made to achieve the best balance of user needs and installation costs.

■ Type 1

Acceptable when uptime is not required and the system can be reactivated after replacing the faulty parts.

In this case the maintenance service must be efficient (available and competent). The advantage is reduced equipment costs.

■ Type 2

To be considered when the uptime is required.

It requires a reduced maintenance service.

When immediate motor starting is necessary, "Total coordination" must be retained.

No maintenance service is necessary.

The coordinations offered in the manufacturers' catalogues simplify the users' choice and guarantees that the motor starter unit complies with the standard.

5.3 Applications

The control and protection of a motor can consist of one, two, three or four different devices which provide one or several functions.

In the case of the combination of several devices, co-ordination between them is essential in order to provide optimized protection of the motor application.

To protect a motor circuit, many parameters must be taken into account. They depend on:

- The application (type of driven machine, safety of operation, number of operations, etc.)
- The continuity performance requested by the application
- The standards to be enforced to provide security and safety.

The electrical functions to be provided are quite different:

- Start, normal operation and stop without unexpected tripping while maintaining control requirements, number of operations, durability and safety requirements (emergency stops), as well as circuit and motor protection, disconnection (isolation) for safety of personnel during maintenance work.



Among the many possible methods of protecting a motor, the association of a circuit breaker + contactor + thermal relay<sup>(1)</sup> provides many advantages

### Basic protection schemes: circuit-breaker + contactor + thermal relay

#### Advantages

The combination of devices facilitates installation work, as well as operation and maintenance, by:

- The reduction of the maintenance work load: the circuit-breaker avoids the need to replace blown fuses and the necessity of maintaining a stock (of different sizes and types)
- Better continuity performance: the installation can be re-energized immediately following the elimination of a fault and after checking of the starter
- Additional complementary devices sometimes required on a motor circuit are easily accommodated
- Tripping of all three phases is assured (thereby avoiding the possibility of "single phasing")
- Full load current switching possibility (by circuit-breaker) in the event of contactor failure, e.g. contact welding
- Interlocking
- Diverse remote indications
- Better protection for the starter in case of overcurrent and in particular for impedant short-circuit<sup>(2)</sup> corresponding to currents up to about 30 times  $I_n$  of motor (see Fig. N67).
- Possibility of adding RCD:
  - Prevention of risk of fire (sensitivity 500 mA)
  - Protection against destruction of the motor (short-circuit of laminations) by the early detection of earth fault currents (sensitivity 300 mA to 30 A)

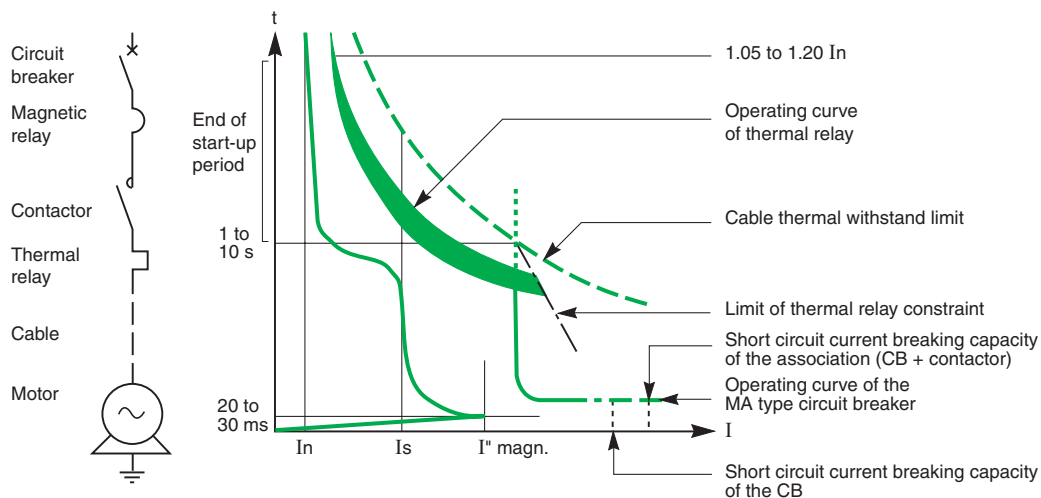


Fig. N67 : Tripping characteristics of a circuit-breaker + contactor + thermal relay<sup>(1)</sup>

#### Conclusion

The combination of a circuit-breaker + contactor + thermal relay for the control and protection of motor circuits is eminently appropriate when:

- The maintenance service for an installation is reduced, which is generally the case in tertiary and small and medium sized industrial sites
- The job specification calls for complementary functions
- There is an operational requirement for a load breaking facility in the event of need of maintenance.

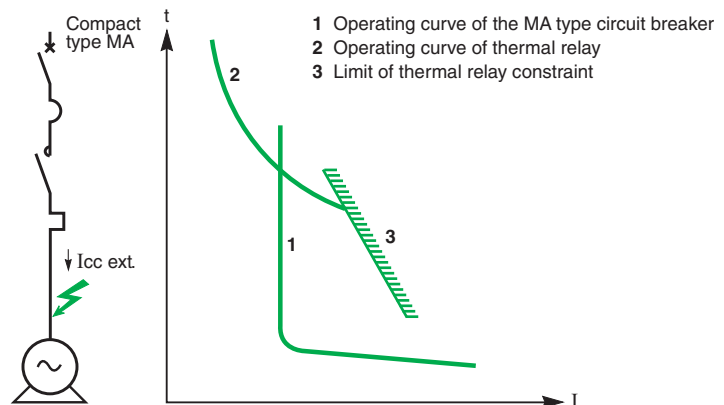
(1) The combination of a contactor with a thermal relay is commonly referred to as a "discontactor".

(2) In the majority of cases, short-circuit faults occur at the motor, so that the current is limited by the cable and the wiring of the starter and are called impedant short-circuits

### Key points in the successful combination of a circuit-breaker and a disconnector

Standards define precisely the elements which must be taken into account to achieve a correct coordination of type 2:

- Absolute compatibility between the thermal relay of the disconnector and the magnetic trip of the circuit-breaker. In **Figure N68** the thermal relay is protected if its limit boundary for thermal withstand is placed to the right of the circuit-breaker magnetic trip characteristic curve. In the case of a motor control circuit-breaker incorporating both magnetic and thermal relay devices, coordination is provided by design.
- The overcurrent breaking capability of the contactor must be greater than the current corresponding to the setting of the circuit-breaker magnetic trip relay.
- When submitted to a short-circuit current, the contactor and its thermal relay must perform in accordance with the requirements corresponding to the specified type of co-ordination.



**Fig. N68** : The thermal-withstand limit of the thermal relay must be to the right of the CB magnetic-trip characteristic

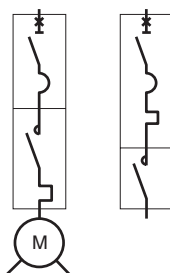
It is not possible to predict the short-circuit current-breaking capacity of a circuit-breaker + contactor combination. Only laboratory tests by manufacturers allow to do it. So, Schneider Electric can give table with combination of Multi 9 and Compact type MA circuit-breakers with different types of starters

N52

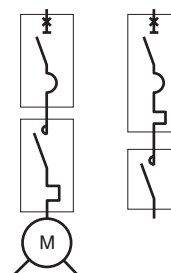
### Short-circuit current-breaking capacity of a circuit-breaker + contactor combination

At the selection stage, the short-circuit current-breaking capacity which must be compared to the prospective short-circuit current is:

- Either, that of the circuit-breaker + contactor combination if the circuit-breaker and the contactor are physically close together (see **Fig. N69**) (same drawer or compartment of a motor control cabinet). A short-circuit downstream of the combination will be limited to some extent by the impedances of the contactor and the thermal relay. The combination can therefore be used on a circuit for which the prospective short-circuit current level exceeds the rated short-circuit current-breaking capacity of the circuit-breaker. This feature very often presents a significant economic advantage
- Or that of the circuit-breaker only, for the case where the contactor is separated (see **Fig. N70**) with the risk of short-circuit between the contactor and the circuit-breaker.



**Fig. N69** : Circuit-breaker and contactor mounted side by side



**Fig. N70** : Circuit-breaker and contactor mounted separately

### Choice of instantaneous magnetic-trip relay for the circuit-breaker

The operating threshold must never be less than 12 In for this relay, in order to avoid unexpected tripping due to the first current peak during motor starting.

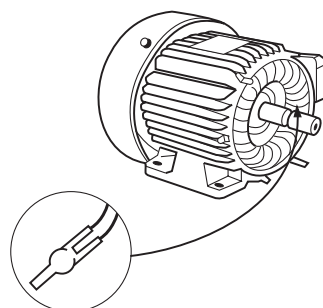
### Complementary protections

Complementary protections are:

- Thermal sensors in the motor (windings, bearings, cooling-air ducts, etc.)
- Multifunction protections (association of functions)
- Insulation-failure detection devices on running or stationary motor

#### Thermal sensors

Thermal sensors are used to detect abnormal temperature rise in the motor by direct measurement. The thermal sensors are generally embedded in the stator windings (for LV motors), the signal being processed by an associated control device acting to trip the contactor or the circuit-breaker (see **Fig. N71**).



**Fig. N71** : Overheating protection by thermal sensors

### Multifunction motor protection relay

The multifunction relay, associated with a number of sensors and indication modules, provides protection for motor and also for some functions, protection of the driven machine such as:

- Thermal overload
- Stalled rotor, or starting period too long
- Overheating
- Unbalanced phase current, loss of one phase, inverse rotation
- Earth fault (by RCD)
- Running at no-load, blocked rotor on starting

The advantages are essentially:

- A comprehensive protection, providing a reliable, high performance and permanent monitoring/control function
- Efficient monitoring of all motor-operating schedules
- Alarm and control indications
- Possibility of communication via communication buses

Example: Telemecanique LT6 relay with permanent monitoring/control function and communication by bus, or multifunction control unit LUCM and communication module for TeSys model U.

### Preventive protection of stationary motors

This protection concerns the monitoring of the insulation resistance level of a stationary motor, thereby avoiding the undesirable consequences of insulation failure during operation such as:

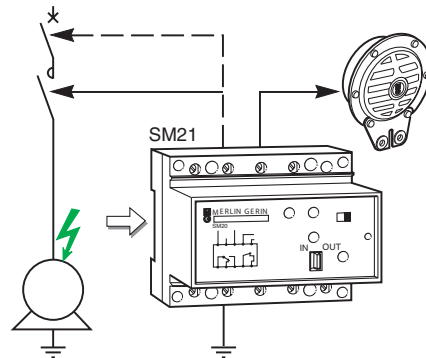
- Failure to start or to perform correctly for motor used on emergency systems
- Loss of production

This type of protection is essential for emergency systems motors, especially when installed in humid and/or dusty locations. Such protection avoids the destruction of a motor by short-circuit to earth during starting (one of the most frequently-occurring incidents) by giving a warning informing that maintenance work is necessary to restore the motor to a satisfactory operational condition.

Example of application:

Motors driving pumps for “sprinklers” fire-protection systems or irrigation pumps for seasonal operation.

A VigiloHM SN21 (Merlin Gerin) monitors the insulation of a motor, and signals audibly and visually any abnormal reduction of the insulation resistance level. Furthermore, this relay can prevent any attempt to start the motor, if necessary (see **Fig. N72**).



**Fig. N72** : Preventive protection of stationary motors

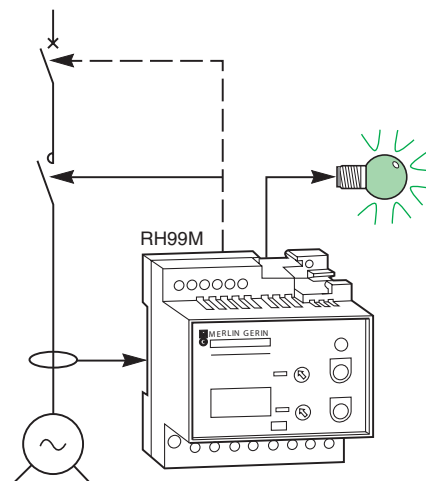
#### Limitative protections

Residual current differential protective devices (RCDs) can be very sensitive and detect low values of leakage current which occur when the insulation to earth of an installation deteriorates (by physical damage, contamination, excessive humidity, and so on). Some versions of RCDs, with dry contacts, specially designed for such applications, provide the following:

- To avoid the destruction of a motor (by perforation and short-circuiting of the laminations of the stator) caused by an eventual arcing fault to earth. This protection can detect incipient fault conditions by operating at leakage currents in the range of 300 mA to 30 A, according to the size of the motor (approx sensitivity: 5%  $I_n$ )
- To reduce the risk of fire: sensitivity  $\leq 500$  mA

For example, RH99M relay (Merlin Gerin) provides (see **Fig. N73**):

- 5 sensitivities (0.3; 1; 3; 10; 30 A)
- Possibility of discrimination or to take account of particular operation by virtue of 3 possible time delays (0, 90, 250 ms)
- Automatic breaking if the circuit from the current transformer to the relay is broken
- Protection against unwanted trippings
- Protection against DC leakage currents (type A RCD)



**Fig. N73** : Example using relay RH99M

**The importance of limiting the voltage drop at the motor terminals during start-up**

In order to have a motor starting and accelerating to its normal speed in the appropriate time, the torque of the motor must exceed the load torque by at least 70%. However, the starting current is much higher than the full-load current of the motor. As a result, if the voltage drop is very high, the motor torque will be excessively reduced (motor torque is proportional to  $U^2$ ) and it will result, for extreme case, in failure to start.

Example:

■ With 400 V maintained at the terminals of a motor, its torque would be 2.1 times that of the load torque

■ For a voltage drop of 10% during start-up, the motor torque would be  $2.1 \times 0.9^2 = 1.7$  times the load torque, and the motor would accelerate to its rated speed normally

■ For a voltage drop of 15% during start-up, the motor torque would be  $2.1 \times 0.85^2 = 1.5$  times the load torque, so that the motor starting time would be longer than normal

In general, a maximum allowable voltage drop of 10% is recommended during start-up of the motor.

**5.4 Maximum rating of motors installed for consumers supplied at LV**

The disturbances caused on LV distribution networks during the start-up of large direct-on-line AC motors can cause considerable nuisance to neighbouring consumers, so that most power-supply utilities have strict rules intended to limit such disturbances to tolerable levels. The amount of disturbance created by a given motor depends on the “strength” of the network, i.e. on the short-circuit fault level at the point concerned. The higher the fault level, the “stronger” the system and the lower the disturbance (principally voltage drop) experienced by neighbouring consumers. For distribution networks in many countries, typical values of maximum allowable starting currents and corresponding maximum power ratings for direct-on-line motors are shown in **Figures N74** and **N75** below.

Type of motor	Location	Maximum starting current (A)	
		Overhead-line network	Underground-cable network
Single phase	Dwellings	45	45
	Others	100	200
Three phase	Dwellings	60	60
	Others	125	250

**Fig. N74** : Maximum permitted values of starting current for direct-on-line LV motors (230/400 V)

Location		Type of motor		
		Single phase 230 V (kW)	Three phase 400 V Direct-on-line starting at full load (kW)	Other methods of starting (kW)
Dwellings		1.4	5.5	11
Others	Overhead line network	3	11	22
	Underground cable network	5.5	22	45

**Fig. N75** : Maximum permitted power ratings for LV direct-on-line starting motors

Since, even in areas supplied by one power utility only, “weak” areas of the network exist as well as “strong” areas, it is always advisable to secure the agreement of the power supplier before acquiring the motors for a new project.

Other (but generally more costly) alternative starting arrangements exist, which reduce the large starting currents of direct-on-line motors to acceptable levels; for example, star-delta starters, slip-ring motor, “soft start” electronic devices, etc.

**5.5 Reactive-energy compensation (power-factor correction)**

The method to correct the power factor is indicated in chapter L.

# Chapter P

## Residential and other special locations

Contents		
1	<b>Residential and similar premises</b>	<b>P2</b>
	1.1 General	P2
	1.2 Distribution boards components	P2
	1.3 Protection of people	P4
	1.4 Circuits	P6
	1.5 Protection against overvoltages and lightning	P7
2	<b>Bathrooms and showers</b>	<b>P8</b>
	2.1 Classification of zones	P8
	2.2 Equipotential bonding	P11
	2.3 Requirements prescribed for each zone	P11
3	<b>Recommendations applicable to special installations and locations</b>	<b>P12</b>

*Electrical installations for residential premises need a high standard of safety and reliability*

*The power distribution utility connects the LV neutral point to its MV/LV distribution transformer to earth.*

*All LV installations must be protected by RCDs. All exposed conductive parts must be bonded together and connected to the earth.*

*The quality of electrical equipment used in residential premises is commonly ensured by a mark of conformity situated on the front of each item*

## 1.1 General

### Related standards

Most countries have national regulations and-or standards governing the rules to be strictly observed in the design and realization of electrical installations for residential and similar premises. The relevant international standard is the publication IEC 60364.

### The power network

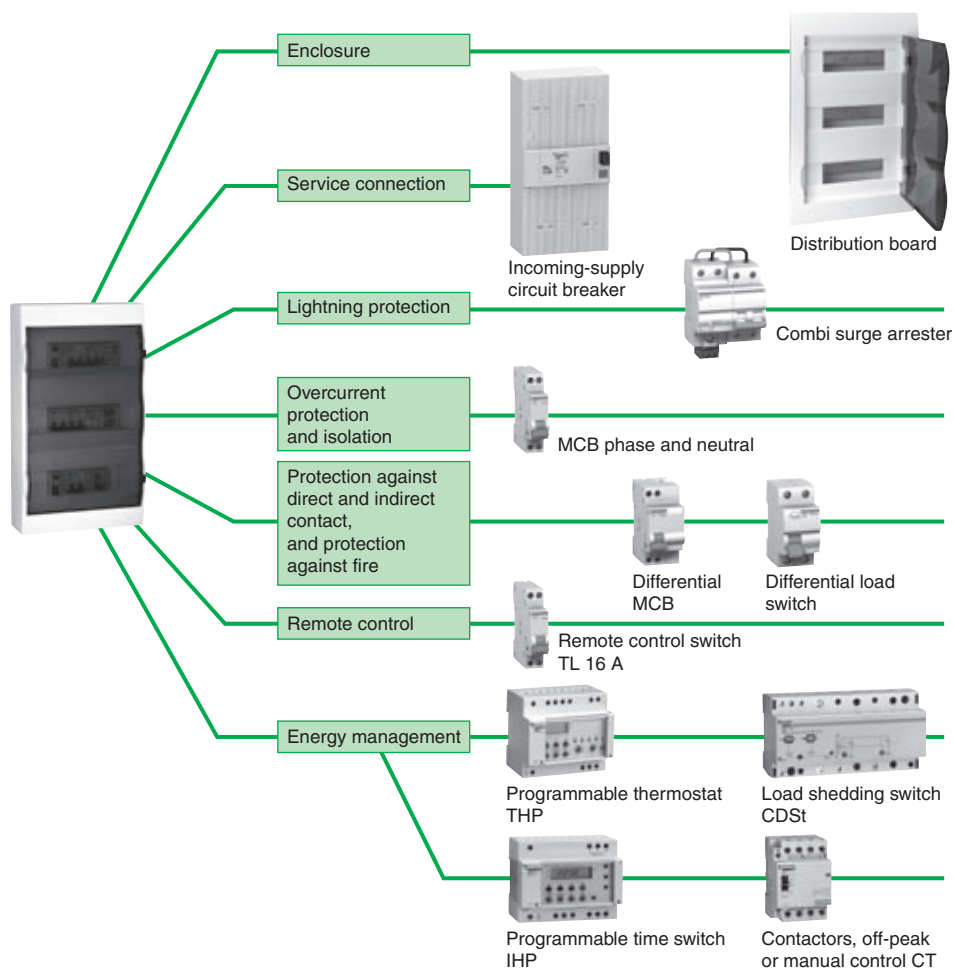
The vast majority of power distribution utilities connect the low voltage neutral point of their MV/LV distribution transformers to earth.

The protection of persons against electric shock therefore depends, in such case, on the principle discussed in chapter F. The measures required depend on whether the TT, TN or IT scheme of earthing is adopted.

RCDs are essential for TT and IT earthed installations. For TN installations, high speed overcurrent devices or RCDs may provide protection against direct contact of the electrical circuits. To extend the protection to flexible leads beyond the fixed socket outlets and to ensure protection against fires of electrical origin RCDs shall be installed.

## 1.2 Distribution boards components (see Fig. P1)

Distribution boards (generally only one in residential premises) usually include the meter(s) and in some cases (notably where the supply utilities impose a TT earthing system and/or tariff conditions which limit the maximum permitted current consumption) an incoming supply differential circuit-breaker which includes an overcurrent trip. This circuit-breaker is freely accessible to the consumer.



**Fig. P1** : Presentation of realizable functions on a consumer unit



Fig. P3 : Incoming-supply circuit-breaker



Fig. P4 : Control and distribution board

*If, in a TT scheme, the value of  $80\ \Omega$  for the resistance of the electrode can not be met then, 30 mA RCDs must be installed to take over the function of the earth leakage protection of the incoming supply circuit-breaker*

On installations which are TN earthed, the supply utilities usually protect the installation simply by means of sealed fuse cut-outs immediately upstream of the meter(s) (see Fig. P2). The consumer has no access to these fuses.

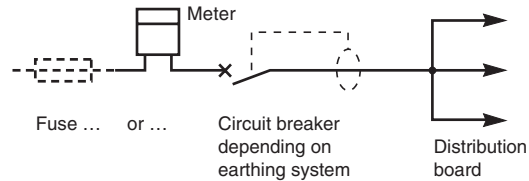


Fig. P2 : Components of a control and distribution board

### The incoming supply circuit-breaker (see Fig. P3)

The consumer is allowed to operate this CB if necessary (e.g. to reclose it if the current consumption has exceeded the authorized limit; to open it in case of emergency or for isolation purposes).

The rated residual current of the incoming circuit-breaker in the earth leakage protection shall be 300 mA.

If the installation is TT, the earth electrode resistance shall be less than

$$R = \frac{50\text{ V}}{300\text{ mA}} = 166\ \Omega. \text{ In practice, the earth electrode resistance of a new installation shall be less than } 80\ \Omega \left( \frac{R}{2} \right).$$

### The control and distribution board (consumer unit) (see Fig. P4)

This board comprises:

- A control panel for mounting (where appropriate) the incoming supply circuit-breaker and other control auxiliaries, as required
- A distribution panel for housing 1, 2 or 3 rows (of 24 multi 9 units) or similar MCBs or fuse units, etc.
- Installation accessories for fixing conductors, and rails for mounting MCBs, fuses bases, etc, neutral busbar and earthing bar, and so on
- Service cable ducts or conduits, surface mounted or in cable chases embedded in the wall

**Note:** to facilitate future modifications to the installation, it is recommended to keep all relevant documents (photos, diagrams, characteristics, etc.) in a suitable location close to the distribution board.

The board should be installed at a height such that the operating handles, indicating dials (of meters) etc., are between 1 metre and 1.80 metres from the floor (1.30 metres in situations where handicapped or elderly people are concerned).

### Lightning arresters

The installation of lightning arresters at the service position of a LV installation is strongly recommended for installations which include sensitive (e.g. electronic) equipment.

These devices must automatically disconnect themselves from the installation in case of failure or be protected by a MCB. In the case of residential installations, the use of a 300 mA differential incoming supply circuit-breaker type S (i.e. slightly time-delayed) will provide effective earth leakage protection, while, at the same time, will not trip unnecessarily each time a lightning arrester discharges the current (of an overvoltage-surge) to earth.

### Resistance value of the earth electrode

In the case where the resistance to earth exceeds  $80\ \Omega$ , one or several 30 mA RCDs should be used in place of the earth leakage protection of the incoming supply circuit-breaker.

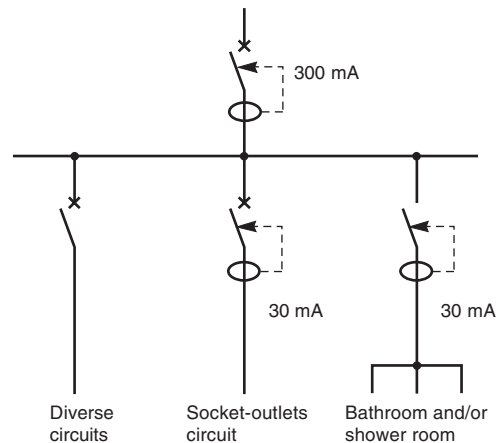


Where utility power supply systems and consumers' installations form a TT earthed system, the governing standards impose the use of RCDs to ensure the protection of persons

### 1.3 Protection of people

On TT earthed systems, the protection of persons is ensured by the following measures:

- Protection against indirect contact hazards by RCDs (see **Fig. P5**) of medium sensitivity (300 mA) at the origin of the installation (incorporated in the incoming supply circuit-breaker or, on the incoming feed to the distribution board). This measure is associated with a consumer installed earth electrode to which must be connected the protective earth conductor (PE) from the exposed conductive parts of all class I insulated appliances and equipment, as well as those from the earthing pins of all socket outlets
- When the CB at the origin of an installation has no RCD protection, the protection of persons shall be ensured by class II level of insulation on all circuits upstream of the first RCDs. In the case where the distribution board is metallic, care shall be taken that all live parts are double insulated (supplementary clearances or insulation, use of covers, etc.) and wiring reliably fixed
- Obligatory protection by 30 mA sensitive RCDs of socket outlet circuits, and circuits feeding bathroom, laundry rooms, and so on (for details of this latter obligation, refer to clause 3 of this chapter)



**Fig. P5** : Installation with incoming-supply circuit-breaker having instantaneous differential protection

#### Incoming supply circuit-breaker with instantaneous differential relay

In this case:

- An insulation fault to earth could result in a shutdown of the entire installation
- Where a lightning arrester is installed, its operation (i.e. discharging a voltage surge to earth) could appear to an RCD as an earth fault, with a consequent shutdown of the installation

#### Recommendation of suitable Merlin Gerin components

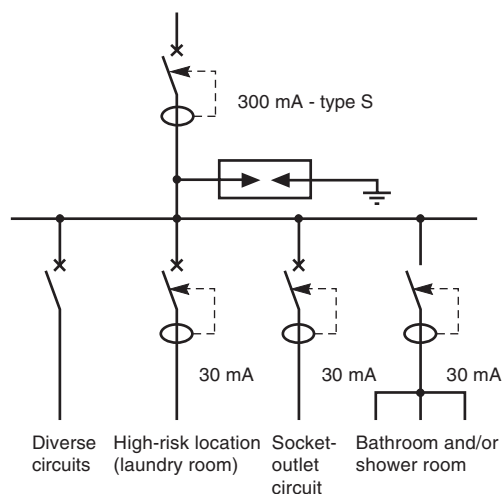
- Incoming supply circuit-breaker with 300 mA differential and
- High sensitivity 30 mA RCD (for example differential circuit-breaker 1P + N type Declic Vigi) on the circuits supplying socket outlets
- High sensitivity 30 mA RCD (for example differential load switch type ID'clac) on circuits to bathrooms, shower rooms, laundry rooms, etc. (lighting, heating, socket outlets)

#### Incoming supply circuit-breaker with type S time delayed differential relay

This type of CB affords protection against fault to earth, but by virtue of a short time delay, provides a measure of discrimination with downstream instantaneous RCDs. Tripping of the incoming supply CB and its consequences (on deep freezers, for example) is thereby made less probable in the event of lightning, or other causes of voltage surges. The discharge of voltage surge current to earth, through the surge arrester, will leave the type S circuit-breaker unaffected.

**Recommendation of suitable Merlin Gerin components (see Fig. P6)**

- Incoming supply circuit-breaker with 300 mA differential type S and
- High sensitivity 30 mA RCD (for example differential circuit-breaker 1P + N type Declic Vigi) on the circuits supplying washing machines and dish-washing machine
- High sensitivity 30 mA RCD (for example differential load switch type ID'clac) on circuits to bathrooms, shower rooms, laundry rooms, etc. (lighting, heating, socket outlets)



**Fig. P6 :** Installation with incoming-supply circuit-breaker having short time delay differential protection, type S

**Incoming supply circuit-breaker without differential protection**

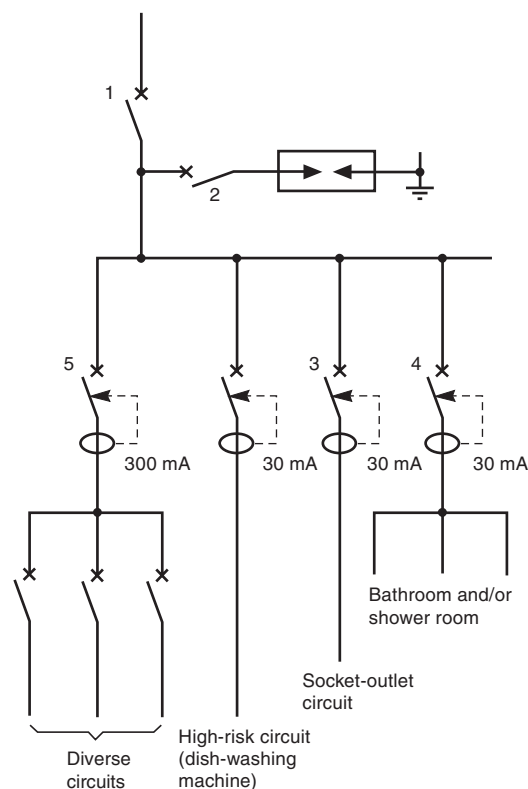
In this case the protection of persons must be ensured by:

- Class II level of insulation up to the downstream terminals of the RCDs
- All outgoing circuits from the distribution board must be protected by 30 mA or 300 mA RCDs according to the type of circuit concerned as discussed in chapter F. Where a voltage surge arrester is installed upstream of the distribution board (to protect sensitive electronic equipment such as microprocessors, video-cassette recorders, TV sets, electronic cash registers, etc.) it is imperative that the device automatically disconnects itself from the installation following a rare (but always possible) failure. Some devices employ replaceable fusing elements; the recommended method however as shown in **Figure P7**, is to use a circuit-breaker.

**Recommendation of suitable Merlin Gerin components**

Figure P7 refers:

1. Incoming-supply circuit-breaker without differential protection
2. Automatic disconnection device (if a lightning arrester is installed)
3. 30 mA RCD (for example differential circuit-breaker 1P + N type Declic Vigi) on each circuit supplying one or more socket-outlets
4. 30 mA RCD (for example differential load switch type ID'clac) on circuits to bathrooms and shower rooms (lighting, heating and socket-outlets) or a 30 mA differential circuit-breaker per circuit
5. 300 mA RCD (for example differential load switch) on all the other circuits



**Fig. P7 :** Installation with incoming-supply circuit-breaker having no differential protection

The distribution and division of circuits provides comfort and facilitates rapid location of fault

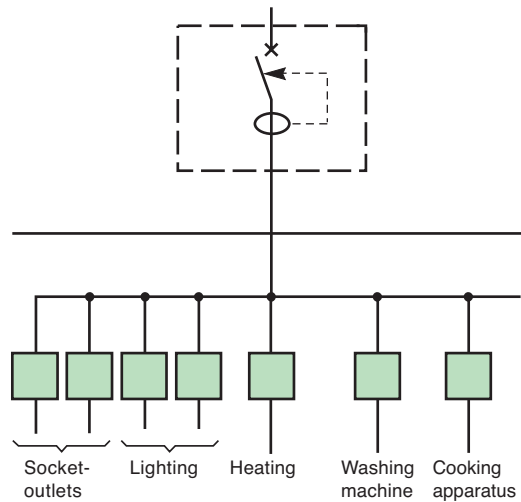


Fig. P8 : Circuit division according to utilization

The inclusion of a protective conductor in all circuits is required by IEC and most national standards

1.4 Circuits

Subdivision

National standards commonly recommend the subdivision of circuits according to the number of utilization categories in the installation concerned (see Fig. P8):

- At least 1 circuit for lighting. Each circuit supplying a maximum of 8 lighting points
- At least 1 circuit for socket-outlets rated 10/16 A, each circuit supplying a maximum of 8 sockets. These sockets may be single or double units (a double unit is made up of two 10/16 A sockets mounted on a common base in an embedded box, identical to that of a single unit)
- 1 circuit for each appliance such as water heater, washing machine, dish-washing machine, cooker, refrigerator, etc. Recommended numbers of 10/16 A (or similar) socket-outlets and fixed lighting points, according to the use for which the various rooms of a dwelling are intended, are indicated in Figure P9

Room function	Minimum number of fixed lighting points	Minimum number of 10/16 A socket-outlets
Living room	1	5
Bedroom, lounge, bureau, dining room	1	3
Kitchen	2	4 (1)
Bathroom, shower room	2	1 or 2
Entrance hall, box room	1	1
WC, storage space	1	-
Laundry room	-	1

(1) Of which 2 above the working surface and 1 for a specialized circuit: in addition an independent socket-outlet of 16 A or 20 A for a cooker and a junction box or socket-outlet for a 32 A specialized circuit

Fig P9 : Recommended minimum number of lighting and power points in residential premises

Protective conductors

IEC and most national standards require that each circuit includes a protective conductor. This practice is strongly recommended where class I insulated appliances and equipment are installed, which is the general case. The protective conductors must connect the earthing-pin contact in each socket-outlet, and the earthing terminal in class I equipment, to the main earthing terminal at the origin of the installation. Furthermore, 10/16 A (or similarly sized) socket-outlets must be provided with shuttered contact orifices.








Cross-sectional-area (c.s.a.) of conductors (see Fig. P10)

The c.s.a. of conductors and the rated current of the associated protective device depend on the current magnitude of the circuit, the ambient temperature, the kind of installation, and the influence of neighbouring circuits (refer to chapter G) Moreover, the conductors for the phase wires, the neutral and the protective conductors of a given circuit must all be of equal c.s.a. (assuming the same material for the conductors concerned, i.e. all copper or all aluminium).



Fig. P10 : Circuit-breaker 1 phase + N - 2 x 9 mm spaces

**Figure P11** indicates the c.s.a. required for commonly-used appliances. Protective devices 1 phase + N in 2 x 9 mm spaces comply with requirements for isolation, and for marking of circuit current rating and conductor sizes.

Type of circuit single-phase 230 V 1 ph + N or 1 ph + N + PE		c. s. a. of the conductors	Maximum power	Protective device	
Fixed lighting		1.5 mm <sup>2</sup> (2.5 mm <sup>2</sup> )	2,300 W	Circuit-breaker Fuse	16 A 10 A
10/16 A		2.5 mm <sup>2</sup> (4 mm <sup>2</sup> )	4,600 W	Circuit-breaker Fuse	25 A 20 A
Individual-load circuits					
Water heater		2.5 mm <sup>2</sup> (4 mm <sup>2</sup> )	4,600 W	Circuit-breaker Fuse	25 A 20 A
Dish-washing machine		2.5 mm <sup>2</sup> (4 mm <sup>2</sup> )	4,600 W	Circuit-breaker Fuse	25 A 20 A
Clothes-washing machine		2.5 mm <sup>2</sup> (4 mm <sup>2</sup> )	4,600 W	Circuit-breaker Fuse	25 A 20 A
Cooker or hotplate <sup>(1)</sup>		6 mm <sup>2</sup> (10 mm <sup>2</sup> )	7,300 W	Circuit-breaker Fuse	40 A 32 A
Electric space heater		1.5 mm <sup>2</sup> (2.5 mm <sup>2</sup> )	2,300 W	Circuit-breaker Fuse	16 A 10 A

(1) In a 230/400 V 3-phase circuit, the c. s. a. is 4 mm<sup>2</sup> for copper or 6 mm<sup>2</sup> for aluminium, and protection is provided by a 32 A circuit-breaker or by 25 A fuses.

**Fig. P11** : C. s. a. of conductors and current rating of the protective devices in residential installations (the c. s. a. of aluminium conductors are shown in brackets)

## 1.5 Protection against overvoltages and lightning

The choice of surge arrester is described in chapter J

### Installation rules

Three principal rules must be respected:

1 - It is imperative that the three lengths of cable used for the installation of the surge arrester each be less than 50 cm i.e.:

- the live conductors connected to the isolating switch
- from the isolating switch to the surge arrester
- from the surge arrester to the main distribution board (MDB) earth bar (not to be confused with the main protective-earth (PE) conductor or the main earth terminal for the installation. The MDB earth bar must evidently be located in the same cabinet as the surge arrester.

2 - It is necessary to use an isolating switch of a type recommended by the manufacturer of the surge arrester.

3 - In the interest of a good continuity of supply it is recommended that the circuit-breaker be of the time-delayed or selective type.

## 2 Bathrooms and showers

Bathrooms and showers rooms are areas of high risk, because of the very low resistance of the human body when wet or immersed in water.

Precaution to be taken are therefore correspondingly rigorous, and the regulations are more severe than those for most other locations.

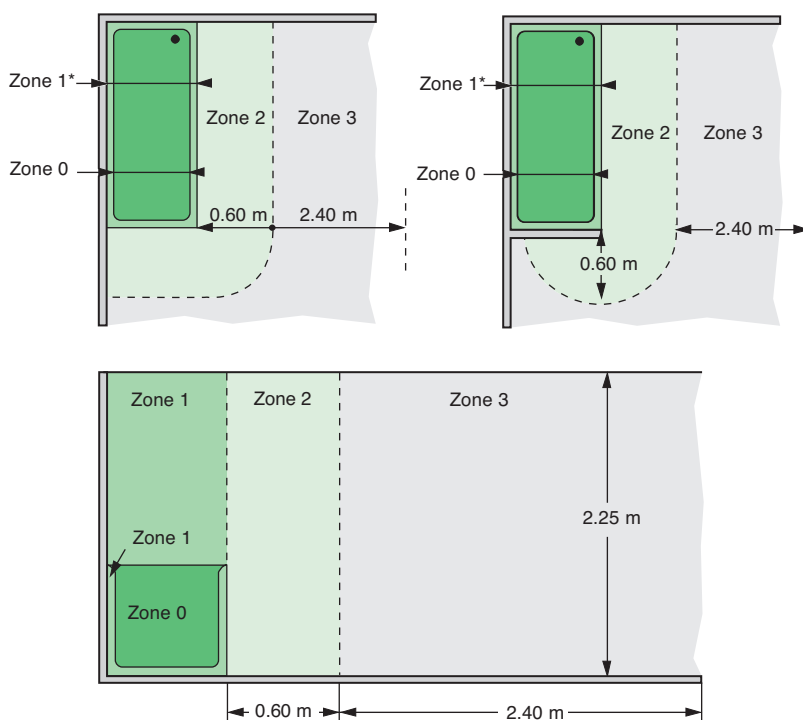
The relevant standard is IEC 60364-7-701.

Precautions to observe are based on three aspects:

- The definition of zones, numbered 0, 1, 2, 3 in which the placement (or exclusion) of any electrical device is strictly limited or forbidden and, where permitted, the electrical and mechanical protection is prescribed
- The establishment of an equipotential bond between all exposed and extraneous metal parts in the zones concerned
- The strict adherence to the requirements prescribed for each particular zones, as tabled in clause 3

### 2.1 Classification of zones

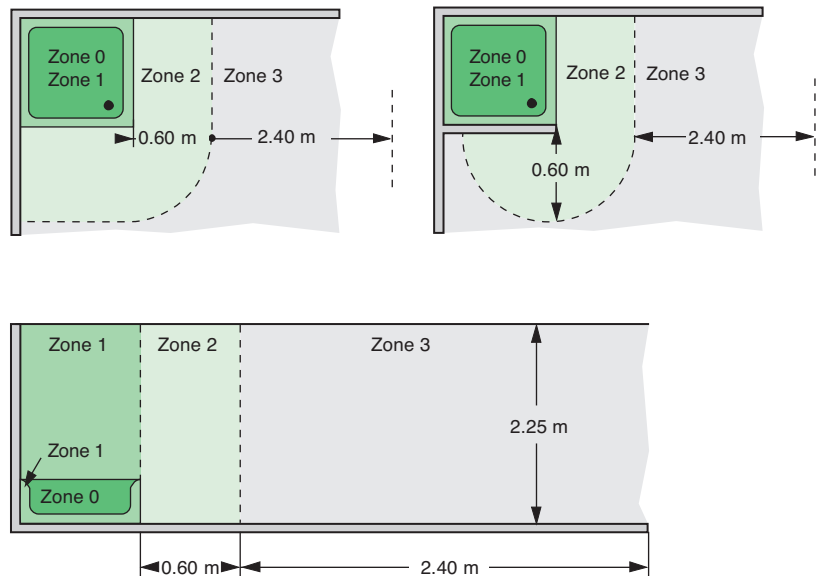
Sub-clause 701.32 of IEC 60364-7-701 defines the zones 0, 1, 2, 3 as shown in the following diagrams (see **Fig. P12** below to **Fig P18** opposite and next pages):



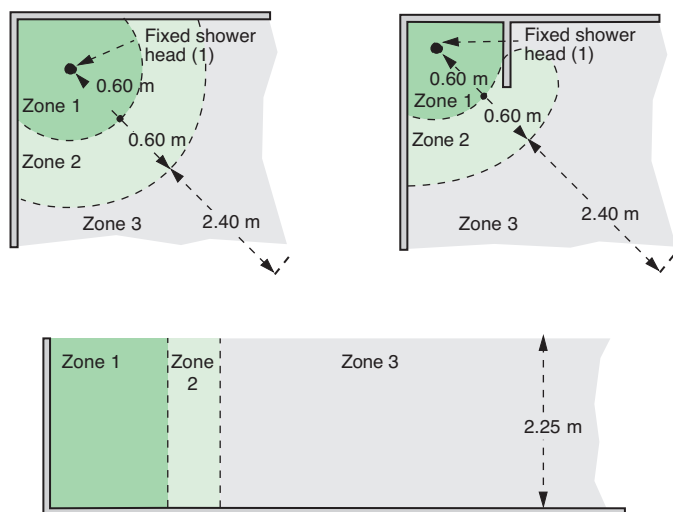
(\*) Zone 1 is above the bath as shown in the vertical cross-section

**Fig. P12** : Zones 0, 1, 2 and 3 in proximity to a bath-tub

## 2 Bathrooms and showers

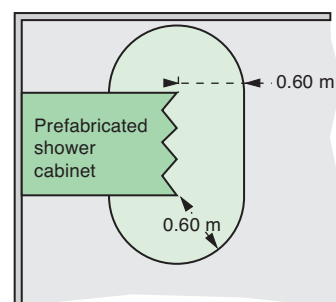


**Fig. P13 :** Zones 0, 1, 2 and 3 in proximity of a shower with basin



(1) When the shower head is at the end of a flexible tube, the vertical central axis of a zone passes through the fixed end of the flexible tube

**Fig. P14 :** Zones 0, 1, 2 and 3 in proximity of a shower without basin



**Fig. P15 :** No switch or socket-outlet is permitted within 60 cm of the door opening of a shower cabinet

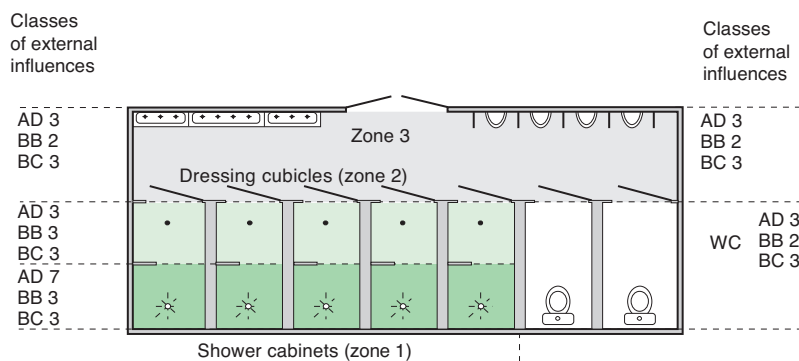


Fig. P16 : Individual showers with dressing cubicles

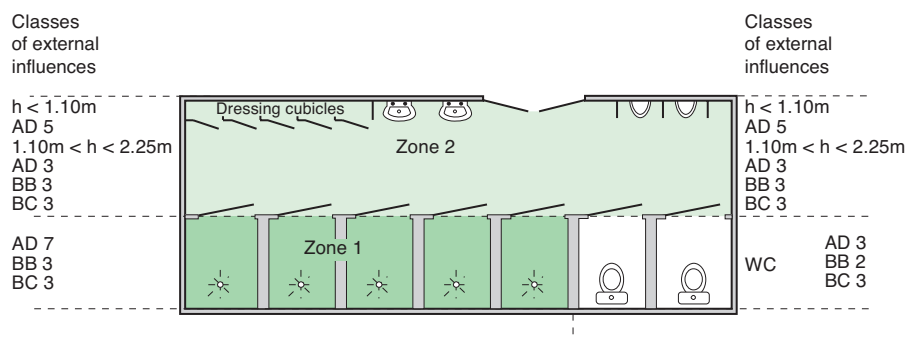


Fig. P17 : Individual showers with separate individual dressing cubicles

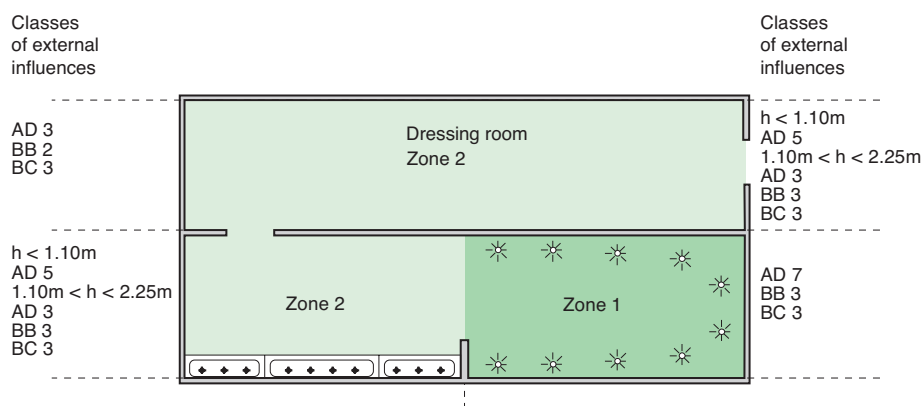
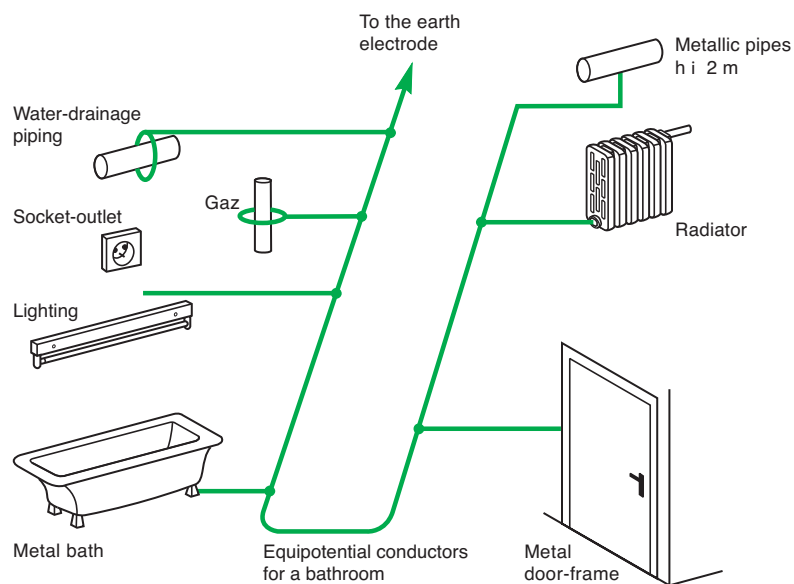


Fig. P18 : Communal showers and common dressing room

**Note:** Classes of external influences (see Fig. E46).

## 2.2 Equipotential bonding (see Fig. P19)



**Fig. P19** : Supplementary equipotential bonding in a bathroom

## 2.3 Requirements prescribed for each zone

The table of clause 3 describes the application of the principles mentioned in the foregoing text and in other similar or related cases



### 3 Recommendations applicable to special installations and locations

**Figure P20** below summarizes the main requirements prescribed in many national and international standards.

**Note:** Section in brackets refer to sections of IEC 60364-7

Locations	Protection principles	IP level	Wiring and cables	Switchgear	Socket-outlets	Installation materials
Domestic dwellings and other habitations	<ul style="list-style-type: none"> <li>■ TT or TN-S systems</li> <li>■ Differential protection</li> <li>□ 300 mA if the earth electrode resistance is <math>\leq 80</math> ohms instantaneous or short time delay (type S)</li> <li>□ 30 mA if the earth electrode resistance is <math>\geq 500</math> ohms</li> <li>■ surge arrester at the origin of the installation if</li> <li>□ supply is from overhead line with bare conductors, and if</li> <li>□ the keraunic level <math>&gt; 25</math></li> <li>■ a protective earth (PE) conductor on all circuits</li> </ul>	20		Switch operating handles and similar devices on distribution panels, to be mounted between 1 metre and 1.80 metre above the floor	Protection by 30 mA RCDs	
Bathrooms or shower rooms (section 701)	Supplementary equipotential bonding in zones 0, 1, 2 and 3					
Zone 0	SELV 12 V only	27	Class II limited to strict minimum			Special appliances
Zone 1	SELV 12 V	25	Class II limited to strict minimum			Special appliances Water heater
Zone 2	SELV 12 V or 30 mA RCD	24	Class II limited to strict minimum			Special appliances Water heater Class II luminaires
Zone 3		21		Only socket-outlets protected by : <ul style="list-style-type: none"> <li>■ 30 mA RCD or</li> <li>■ Electrical separation or</li> <li>■ SELV 50 V</li> </ul>		
Swimming baths (section 702)	Supplementary equipotential bonding in zones 0, 1, and 2					
Zone 0	SELV 12 V	28	Class II limited to strict minimum			Special appliances
Zone 1		25	Class II limited to strict minimum			Special appliances
Zone 2		22 (indoor) 24 (outdoor)		Only socket-outlets protected by : <ul style="list-style-type: none"> <li>■ 30 mA RCD or</li> <li>■ electrical separation or</li> <li>■ SELV 50 V</li> </ul>		
Saunas (section 703)		24	Class II			Adapted to temperature
Work sites (section 704)	Conventional voltage limit UL reduced to 25 V	44	Mechanically protected		Protection by 30 mA RCDs	
Agricultural and horticultural establishments (section 705)	Conventional voltage limit UL reduced to 25 V Protection against fire risks by 500 mA RCDs	35			Protection by 30 mA RCDs	
Restricted conductive locations (section 706)		2x				Protection of: <ul style="list-style-type: none"> <li>■ Portable tools by:  <ul style="list-style-type: none"> <li>□ SELV or</li> <li>□ Electrical separation</li> </ul> </li> <li>■ Hand-held lamps</li> <li>□ By SELV</li> <li>■ Fixed equipment by  <ul style="list-style-type: none"> <li>□ SELV</li> <li>□ Electrical separation</li> <li>□ 30 mA RCDs</li> </ul> </li> <li>□ Special supplementary equipotential bonding</li> </ul>

**Fig. P20** : Main requirements prescribed in many national and international standards (continued on opposite page)

### 3 Recommendations applicable to special installations and locations

Locations	Protection principles	IP level	Wiring and cables	Switchgear	Socket-outlets	Installation materials
Fountains (section 702)	Protection by 30 mA RCDs and equipotential bonding of all exposed and extraneous conductive parts					
Data processing (section 707)	TN-S system recommended TT system if leakage current is limited. Protective conductor 10 mm <sup>2</sup> minimum in aluminium. Smaller sizes (in copper) must be doubled.					
Caravan park (section 708)		55	Flexible cable of 25 metres length		Socket-outlets shall be placed at a height of 0.80 m to 1.50 m from the ground. Protection of circuits by 30 mA RCDs (one per 6 socket-outlets)	
Marinas and pleasure craft (section 709)	The cable length for connection to pleasure craft must not exceed 25 m				Protection of circuits by 30 mA RCDs (one per 6 socket-outlets)	
Medical locations Group 2 : Operating theatres and similar (section 710)	IT medical system equipotential grounding, limited to one operating theatre and not exceeding 10 kVA			Only magnetic protection for the primary of LV/LV transformer. Monitoring of secondary loads and transformer temperature	Protection of circuits by thermal-magnetic protection only. One to three per circuit.	
Medical locations Group 1 : Hospitalization and similar (section 710)	TT or TNS				Protection by 30 mA RCDs	
Exhibitions, shows and stands (section 711)	TT or TN-S systems	4x			Protection by 30 mA RCDs	
Balneotherapy (cure-centre baths)	Individual: see section 701 (volumes 0 and 1) Collective: see section 702 (volumes 0 and 1)					
Motor-fuel filling stations	Explosion risks in security zones		Limited to the necessary minimum			
Motor vehicles	Protection by RCDs or by electrical separation					
External lighting installations (section 714)		23			Protection by 30 mA RCDs	
Mobile or transportable units (section 717)	The use of TN-C system is not permitted inside any unit				30 mA RCDs must be used for all socket-outlets supplying equipment outside the unit	

Fig. P20 : Main requirements prescribed in many national and international standards (concluded)

# Chapter Q

## EMC guidelines

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<b>4</b>	<b>Coupling mechanisms and counter-measures</b>	<b>Q16</b>
	4.1 General	Q16
	4.2 Common-mode impedance coupling	Q17
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<b>5</b>	<b>Wiring recommendations</b>	<b>Q22</b>
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# 1 Electrical distribution

The system earthing arrangement must be properly selected to ensure the safety of life and property. The behaviour of the different systems with respect to EMC considerations must be taken into account. **Figure Q1** below presents a summary of their main characteristics.

European standards (see EN 50174-2 § 6.4 and EN 50310 § 6.3) recommend the TN-S system which causes the fewest EMC problems for installations comprising information-technology equipment (including telecom equipment).

	TT	TN-S	IT	TN-C
Safety of persons	Good RCD mandatory	Good Continuity of the PE conductor must be ensured throughout the installation		
Safety of property	Good Medium fault current (< a few dozen amperes)	Poor High fault current (around 1 kA)	Good Low current for first fault (< a few dozen mA), but high for second fault	Poor High fault current (around 1 kA)
Availability of energy	Good	Good	Excellent	Good
EMC behaviour	Good - Risk of overvoltages - Equipotential problems - Need to manage devices with high leakage currents	Excellent - Few equipotential problems - Need to manage devices with high leakage currents - High fault currents (transient disturbances)	Poor (to be avoided) - Risk of overvoltages - Common-mode filters and surge arrestors must handle the phase-to-phase voltages - RCDs subject to nuisance tripping if common-mode capacitors are present - Equivalent to TN system for second fault	Poor (should never be used) - Neutral and PE are the same - Circulation of disturbed currents in exposed conductive parts (high magnetic-field radiation) - High fault currents (transient disturbances)

Fig. Q1 : Main characteristics of system earthing

When an installation includes high-power equipment (motors, air-conditioning, lifts, power electronics, etc.), it is advised to install one or more transformers specifically for these systems. Electrical distribution must be organised in a star system and all outgoing circuits must exit the main low-voltage switchboard (MLVS).

Electronic systems (control/monitoring, regulation, measurement instruments, etc.) must be supplied by a dedicated transformer in a TN-S system.

**Figure Q2** below illustrate these recommendations.

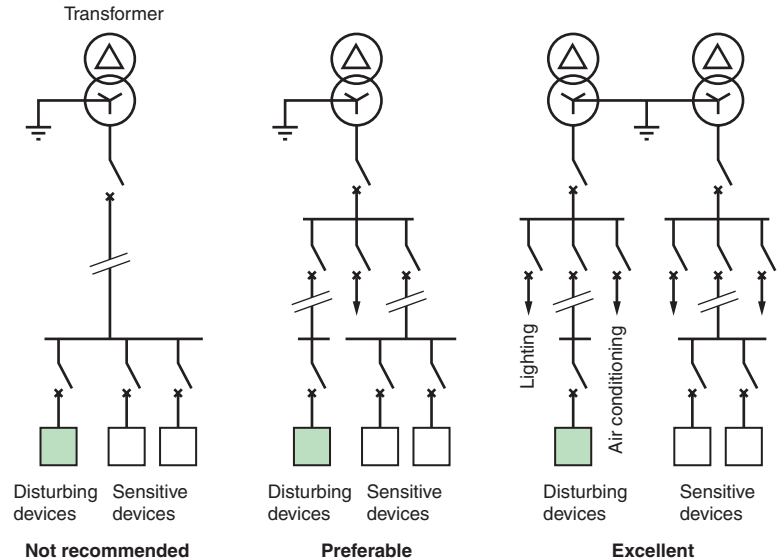


Fig. Q2 : Recommendations of separated distributions

Q2

## 2 Earthing principles and structures

This section deals with the earthing and equipotential bonding of information-technology devices and other similar devices requiring interconnections for signalling purposes.

Earthing networks are designed to fulfil a number of functions. They can be independent or operate together to provide one or more of the following:

- Safety of persons with respect to electrical hazards
- Protection of equipment with respect to electrical hazards
- A reference value for reliable, high-quality signals
- Satisfactory EMC performance

The system earthing arrangement is generally designed and installed in view of obtaining a low impedance capable of diverting fault currents and HF currents away from electronic devices and systems. There are different types of system earthing arrangements and some require that specific conditions be met. These conditions are not always met in typical installations. The recommendations presented in this section are intended for such installations.

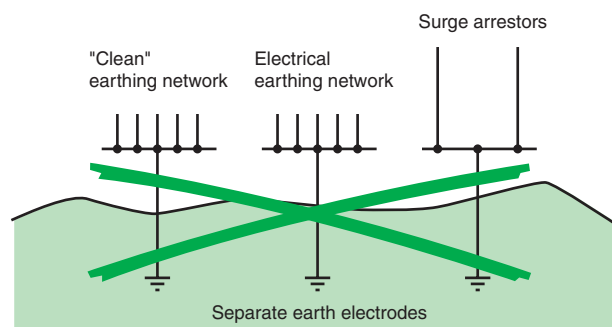
For professional and industrial installations, a common bonding network (CBN) may be useful to ensure better EMC performance with respect to the following points:

- Digital systems and new technologies
- Compliance with the EMC requirements of EEC 89/336 (emission and immunity)
- The wide number of electrical applications
- A high level of system safety and security, as well as reliability and/or availability

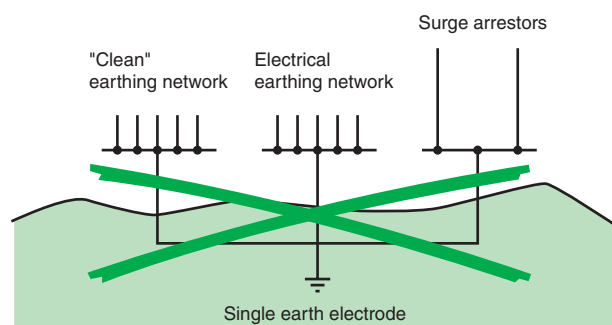
For residential premises, however, where the use of electrical devices is limited, an isolated bonding network (IBN) or, even better, a mesh IBN may be a solution.

It is now recognised that independent, dedicated earth electrodes, each serving a separate earthing network, are a solution that is not acceptable in terms of EMC, but also represent a serious safety hazard. In certain countries, the national building codes forbid such systems.

Use of a separate "clean" earthing network for electronics and a "dirty" earthing network for energy is not recommended in view of obtaining correct EMC, even when a single electrode is used (see **Fig. Q3** and **Fig. Q4**). In the event of a lightning strike, a fault current or HF disturbances as well as transient currents will flow in the installation. Consequently, transient voltages will be created and result in failures or damage to the installation. If installation and maintenance are carried out properly, this approach may be dependable (at power frequencies), but it is generally not suitable for EMC purposes and is not recommended for general use.



**Fig. Q3** : Independent earth electrodes, a solution generally not acceptable for safety and EMC reasons

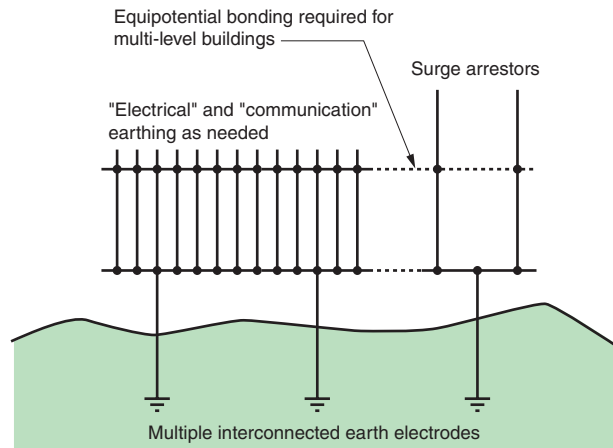


**Fig. Q4** : Installation with a single earth electrode

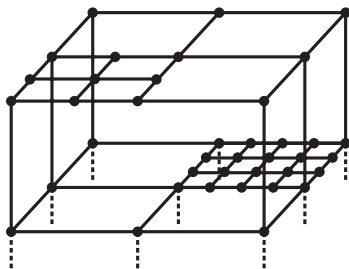
**Q3**

## 2 Earthing principles and structures

The recommended configuration for the earthing network and electrodes is two or three dimensional (see **Fig. Q5**). This approach is advised for general use, both in terms of safety and EMC. This recommendation does not exclude other special configurations that, when correctly maintained, are also suitable.



**Fig. Q5 :** Installation with multiple earth electrodes



**Fig. Q6 :** Each level has a mesh and the meshes are interconnected at several points between levels. Certain ground-floor meshes are reinforced to meet the needs of certain areas

In a typical installation for a multi-level building, each level should have its own earthing network (generally a mesh) and all the networks must be both interconnected and connected to the earth electrode. At least two connections are required (built in redundancy) to ensure that, if one conductor breaks, no section of the earthing network is isolated.

Practically speaking, more than two connections are made to obtain better symmetry in current flow, thus reducing differences in voltage and the overall impedance between the various levels in the building.

The many parallel paths have different resonance frequencies. If one path has a high impedance, it is most probably shunted by another path with a different resonance frequency. On the whole, over a wide frequency spectrum (dozens of Hz and MHz), a large number of paths results in a low-impedance system (see **Fig. Q6**).

Each room in the building should have earthing-network conductors for equipotential bonding of devices and systems, cableways, trunking systems and structures. This system can be reinforced by connecting metal pipes, gutters, supports, frames, etc. In certain special cases, such as control rooms or computers installed on false floors, ground reference plane or earthing strips in areas for electronic systems can be used to improve earthing of sensitive devices and protection interconnection cables.

## 3.1 Equipotential bonding inside and outside buildings

The fundamental goals of earthing and bonding are the following:

- Safety

By limiting the touch voltage and the return path of fault currents

- EMC

By avoiding differences in potential and providing a screening effect.

Stray currents are inevitably propagated in an earthing network. It is impossible to eliminate all the sources of disturbances for a site. Earth loops are also inevitable. When a magnetic field affects a site, e.g. the field created by lightning, differences in potential are created in the loops formed by the various conductors and the currents flowing in the earthing system. Consequently, the earthing network is directly affected by any counter-measures taken outside the building.

As long as the currents flow in the earthing system and not in the electronic circuits, they do no damage. However, when earthing networks are not equipotential, e.g. when they are star connected to the earth electrode, the HF stray currents will flow wherever they can, including in control wires. Equipment can be disturbed, damaged or even destroyed.

The only inexpensive means to divide the currents in an earthing system and maintain satisfactory equipotential characteristics is to interconnect the earthing networks. This contributes to better equipotential bonding within the earthing system, but does not remove the need for protective conductors. To meet legal requirements in terms of the safety of persons, sufficiently sized and identified protective conductors must remain in place between each piece of equipment and the earthing terminal. What is more, with the possible exception of a building with a steel structure, a large number of conductors for the surge-arrestor or the lightning-protection network must be directly connected to the earth electrode.

The fundamental difference between a protective conductor (PE) and a surge-arrestor down-lead is that the first conducts internal currents to the neutral of the MV/LV transformer whereas the second carries external current (from outside the installation) to the earth electrode.

In a building, it is advised to connect an earthing network to all accessible conducting structures, namely metal beams and door frames, pipes, etc. It is generally sufficient to connect metal trunking, cable trays and lintels, pipes, ventilation ducts, etc. at as many points as possible. In places where there is a large amount of equipment and the size of the mesh in the bonding network is greater than four metres, an equipotential conductor should be added. The size and type of conductor are not of critical importance.

It is imperative to interconnect the earthing networks of buildings that have shared cable connections. Interconnection of the earthing networks must take place via a number of conductors and all the internal metal structures of the buildings or linking the buildings (on the condition that they are not interrupted).

In a given building, the various earthing networks (electronics, computing, telecom, etc.) must be interconnected to form a single equipotential bonding network.

This earthing-network must be as meshed as possible. If the earthing network is equipotential, the differences in potential between communicating devices will be low and a large number of EMC problems disappear. Differences in potential are also reduced in the event of insulation faults or lightning strikes.

If equipotential conditions between buildings cannot be achieved or if the distance between buildings is greater than ten metres, it is highly recommended to use optical fibre for communication links and galvanic insulators for measurement and communication systems.

These measures are mandatory if the electrical supply system uses the IT or TN-C system.

Q5

## 3.2 Improving equipotential conditions

### Bonding networks

Even though the ideal bonding network would be made of sheet metal or a fine mesh, experience has shown that for most disturbances, a three-metre mesh size is sufficient to create a mesh bonding network.

Examples of different bonding networks are shown in **Figure Q7** next page. The minimum recommended structure comprises a conductor (e.g. copper cable or strip) surrounding the room.

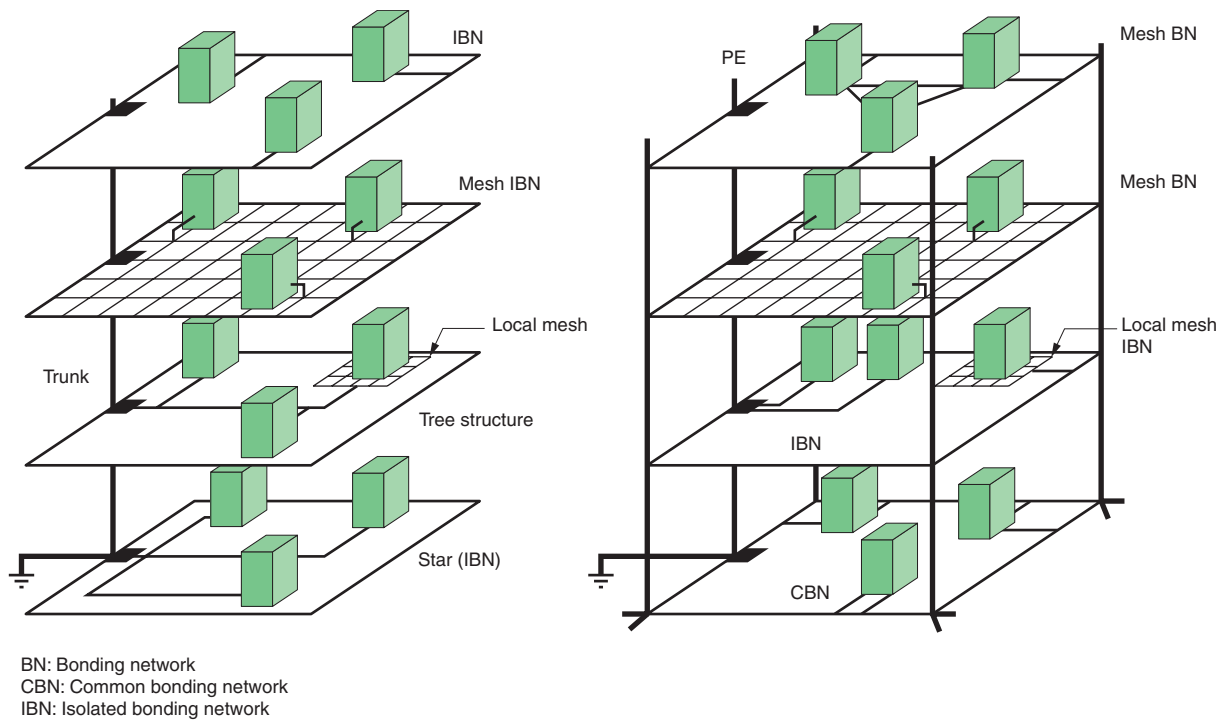


Fig. Q7 : Examples of bonding networks

The length of connections between a structural element and the bonding network does not exceed 50 centimetres and an additional connection should be installed in parallel at a certain distance from the first. The inductance of the connection between the earthing bar of the electrical enclosure for a set of equipment and the bonding network (see below) should be less than one  $\mu\text{Henry}$  ( $0.5 \mu\text{H}$ , if possible). For example, it is possible to use a single 50 cm conductor or two parallel conductors one meter long, installed at a minimum distance from one another (at least 50 cm) to reduce the mutual inductance between the two conductors.

Where possible, connection to the bonding network should be at an intersection to divide the HF currents by four without lengthening the connection. The profile of the bonding conductors is not important, but a flat profile is preferable. The conductor should also be as short as possible.

### Parallel earthing conductor (PEC)

The purpose of a parallel earthing conductor is to reduce the common-mode current flowing in the conductors that also carry the differential-mode signal (the common-mode impedance and the surface area of the loop are reduced).

The parallel earthing conductor must be designed to handle high currents when it is used for protection against lightning or for the return of high fault currents. When cable shielding is used as a parallel earthing conductor, it cannot handle such high currents and the solution is to run the cable along metal structural elements or cableways which then act as other parallel earthing conductors for the entire cable. Another possibility is to run the shielded cable next to a large parallel earthing conductor with both the shielded cable and the parallel earthing conductor connected at each end to the local earthing terminal of the equipment or the device.

For very long distances, additional connections to the network are advised for the parallel earthing conductor, at irregular distances between the devices. These additional connections form a shorter return path for the disturbing currents flowing through the parallel earthing conductor. For U-shaped trays, shielding and tubes, the additional connections should be external to maintain the separation with the interior ("screening" effect).

### Bonding conductors

Bonding conductors may be metal strips, flat braids or round conductors. For high-frequency systems, metal strips and flat braids are preferable (skin effect) because a round conductor has a higher impedance than a flat conductor with the same cross section. Where possible, the length to width ratio should not exceed 5.



### 3.3 Separating cables

The physical separation of high and low-current cables is very important for EMC, particularly if low-current cables are not shielded or the shielding is not connected to the exposed conductive parts (ECPs). The sensitivity of electronic equipment is in large part determined by the accompanying cable system.

If there is no separation (different types of cables in separate cableways, minimum distance between high and low-current cables, types of cableways, etc.), electromagnetic coupling is at its maximum. Under these conditions, electronic equipment is sensitive to EMC disturbances flowing in the affected cables.

Use of busbar trunking systems such as Canalis or busbar ducts for high power ratings is strongly advised. The levels of radiated magnetic fields using these types of trunking systems is 10 to 20 times lower than standard cables or conductors.

The recommendations in the "Cable running" and "Wiring recommendations" sections should be taken into account.

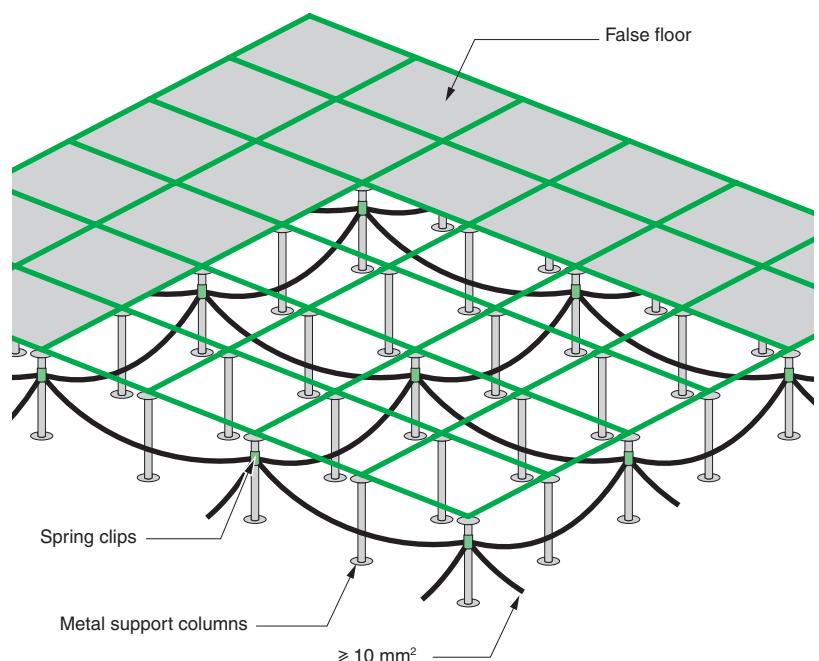
### 3.4 False floors

The inclusion of the floors in the mesh contributes to equipotentiality of the area and consequently to the distribution and dilution of disturbing LF currents.

The screening effect of a false floor is directly related to its equipotentiality. If the contact between the floor plates is poor (rubber antistatic joints, for example) or if the contact between the support brackets is faulty (pollution, corrosion, mildew, etc. or if there are no support brackets), it is necessary to add an equipotential mesh. In this case, it is sufficient to ensure effective electrical connections between the metal support columns. Small spring clips are available on the market to connect the metal columns to the equipotential mesh. Ideally, each column should be connected, but it is often sufficient to connect every other column in each direction. A mesh 1.5 to 2 metres in size is suitable in most cases. The recommended cross-sectional area of the copper is 10 mm<sup>2</sup> or more. In general, a flat braid is used. To reduce the effects of corrosion, it is advised to use tin-plated copper (see **Fig. Q8**).

Perforated floor plates act like normal floor plates when they have a cellular steel structure.

Preventive maintenance is required for the floor plates approximately every five years (depending on the type of floor plate and the environment, including humidity, dust and corrosion). Rubber or polymer antistatic joints must be maintained, similar to the bearing surfaces of the floor plates (cleaning with a suitable product).



**Fig. Q8 :** False floor implementation

### 3.5 Cable running

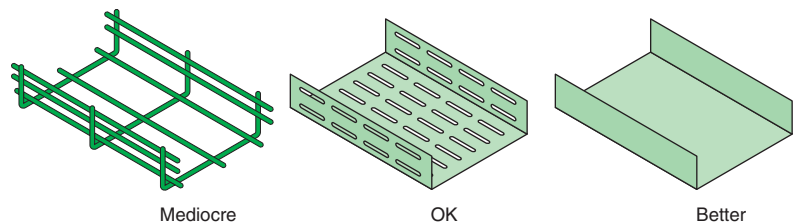
Selection of materials and their shape depends on the following criteria:

- Severity of the EM environment along cableways (proximity of sources of conducted or radiated EM disturbances)
- Authorised level of conducted and radiated emissions
- Type of cables (shielded?, twisted?, optical fibre?)
- EMI withstand capacity of the equipment connected to the wiring system
- Other environmental constraints (chemical, mechanical, climatic, fire, etc.)
- Future extensions planned for the wiring system

Non-metal cableways are suitable in the following cases:

- A continuous, low-level EM environment
- A wiring system with a low emission level
- Situations where metal cableways should be avoided (chemical environment)
- Systems using optical fibres

For metal cableways, it is the shape (flat, U-shape, tube, etc.) rather than the cross-sectional area that determines the characteristic impedance. Closed shapes are better than open shapes because they reduce common-mode coupling. Cableways often have slots for cable straps. The smaller the better. The types of slots causing the fewest problems are those cut parallel and at some distance from the cables. Slots cut perpendicular to the cables are not recommended (see **Fig. Q9**).

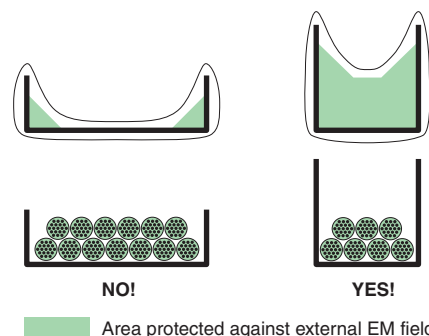


**Fig. Q9** : CEM performance of various types of metal cableways

In certain cases, a poor cableway in EMI terms may be suitable if the EM environment is low, if shielded cables or optical fibres are employed, or separate cableways are used for the different types of cables (power, data processing, etc.).

It is a good idea to reserve space inside the cableway for a given quantity of additional cables. The height of the cables must be lower than the partitions of the cableway as shown below. Covers also improve the EMC performance of cableways.

In U-shaped cableways, the magnetic field decreases in the two corners. That explains why deep cableways are preferable (see **Fig. Q10**).



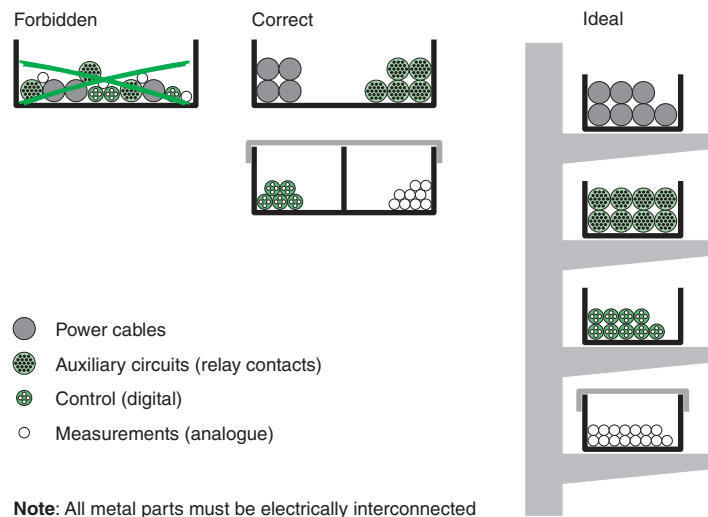
**Fig. Q10** : Installation of different types of cables

Different types of cables (power and low-level connections) should not be installed in the same bundle or in the same cableway. Cableways should never be filled to more than half capacity.

### 3 Implementation

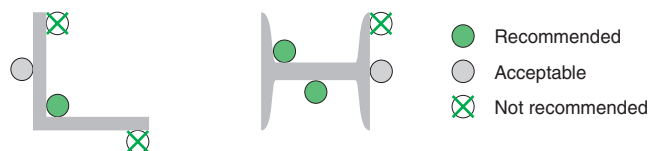
It is recommended to electromagnetically separate groups from one another, either using shielding or by installing the cables in different cableways. The quality of the shielding determines the distance between groups. If there is no shielding, sufficient distances must be maintained (see **Fig. Q11**).

The distance between power and control cables must be at least 5 times the radius of the larger power cable.



**Fig. Q11** : Recommendation to install groups of cables in metal cableways

Metal building components can be used for EMC purposes. Steel beams (L, H, U or T shaped) often form an uninterrupted earthed structure with large transversal sections and surfaces with numerous intermediate earthing connections. Cables should if possible be run along such beams. Inside corners are better than the outside surfaces (see **Fig. Q12**).



**Fig. Q12** : Recommendation to install cables in steel beams

Both ends of metal cableways must always be connected to local earth electrodes. For very long cableways, additional connections to the earthing system are recommended between connected devices. Where possible, the distance between these earthing connections should be irregular (for symmetrical wiring systems) to avoid resonance at identical frequencies. All connections to the earthing system should be short.

Metal and non-metal cableways are available. Metal solutions offer better EMC characteristics. A cableway (cable trays, conduits, cable brackets, etc.) must offer a continuous, conducting metal structure from beginning to end.

An aluminium cableway has a lower DC resistance than a steel cableway of the same size, but the transfer impedance ( $Z_t$ ) of steel drops at a lower frequency, particularly when the steel has a high relative permeability  $\mu_r$ . Care must be taken when different types of metal are used because direct electrical connection is not authorised in certain cases to avoid corrosion. That could be a disadvantage in terms of EMC.

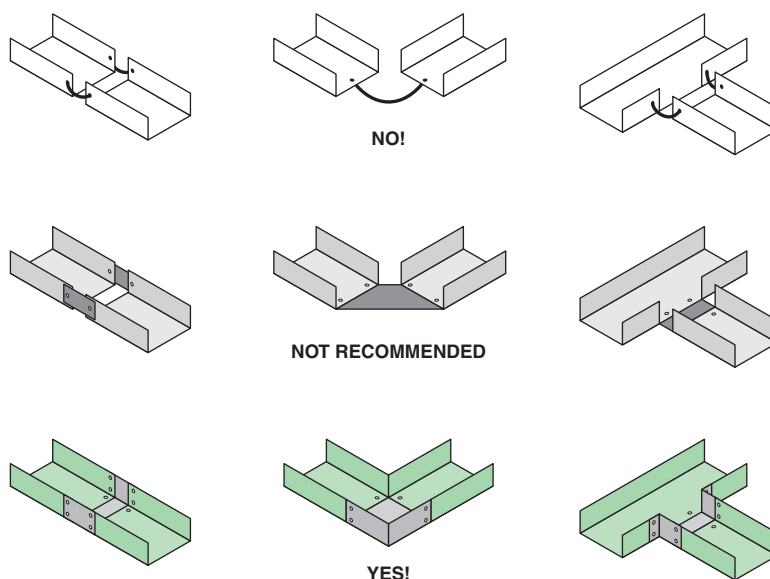
When devices connected to the wiring system using unshielded cables are not affected by low-frequency disturbances, the EMC of non-metal cableways can be improved by adding a parallel earthing conductor (PEC) inside the cableway. Both ends must be connected to the local earthing system. Connections should be made to a metal part with low impedance (e.g. a large metal panel of the device case). The PEC should be designed to handle high fault and common-mode currents.

### Implementation

When a metal cableway is made up of a number of short sections, care is required to ensure continuity by correctly bonding the different parts. The parts should preferably be welded along all edges. Riveted, bolted or screwed connections are authorised as long as the contact surfaces conduct current (no paint or insulating coatings) and are protected against corrosion. Tightening torques must be observed to ensure correct pressure for the electrical contact between two parts.

When a particular shape of cableway is selected, it should be used for the entire length. All interconnections must have a low impedance. A single wire connection between two parts of the cableway produces a high local impedance that cancels its EMC performance.

Starting at a few MHz, a ten-centimetre connection between two parts of the cableway reduces the attenuation factor by more than a factor of ten (see **Fig. Q13**).

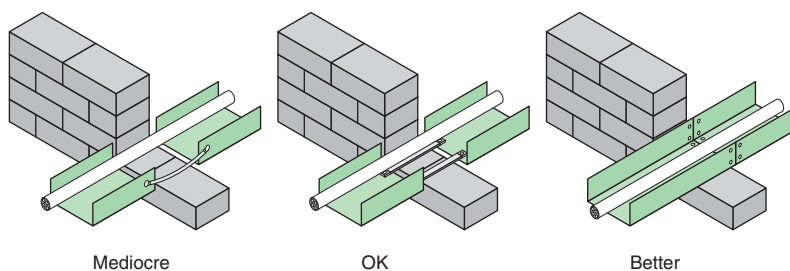


**Fig. Q13** : Metal cableways assembly

Each time modifications or extensions are made, it is very important to make sure they are carried out according to EMC rules (e.g. never replace a metal cableway by a plastic version!).

Covers for metal cableways must meet the same requirements as those applying to the cableways themselves. A cover should have a large number of contacts along the entire length. If that is not possible, it must be connected to the cableway at least at the two ends using short connections (e.g. braided or meshed connections).

When cableways must be interrupted to pass through a wall (e.g. firewalls), low-impedance connections must be used between the two parts (see **Fig. Q14**).



**Fig. Q14** : Recommendation for metal cableways assembly to pass through a wall

### 3.6 Implementation of shielded cables

When the decision is made to use shielded cables, it is also necessary to determine how the shielding will be bonded (type of earthing, connector, cable entry, etc.), otherwise the benefits are considerably reduced. To be effective, the shielding should be bonded over 360°. **Figure Q15** below show different ways of earthing the cable shielding.

For computer equipment and digital links, the shielding should be connected at each end of the cable.

Connection of the shielding is very important for EMC and the following points should be noted.

If the shielded cable connects equipment located in the same equipotential bonding area, the shielding must be connected to the exposed conductive parts (ECP) at both ends. If the connected equipment is not in the same equipotential bonding area, there are a number of possibilities.

■ Connection of only one end to the ECPs is dangerous. If an insulation fault occurs, the voltage in the shielding can be fatal for an operator or destroy equipment. In addition, at high frequencies, the shielding is not effective.

■ Connection of both ends to the ECPs can be dangerous if an insulation fault occurs. A high current flows in the shielding and can damage it. To limit this problem, a parallel earthing conductor (PEC) must be run next to the shielded cable. The size of the PEC depends on the short-circuit current in the given part of the installation. It is clear that if the installation has a well meshed earthing network, this problem does not arise.

All bonding connections must be made to bare metal

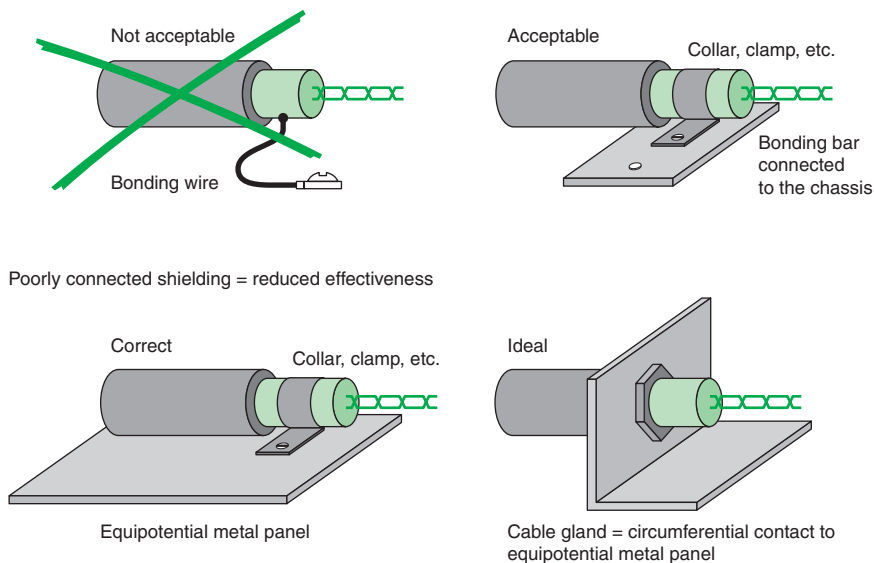


Fig. Q15 : Implementation of shielded cables

### 3.7 Communication networks

Communication networks cover large distances and interconnect equipment installed in rooms that may have distribution systems with different system earthing arrangements. In addition, if the various sites are not equipotential, high transient currents and major differences in potential may occur between the various devices connected to the networks. As noted above, this is the case when insulation faults and lightning strikes occur. The dielectric withstand capacity (between live conductors and exposed conductive parts) of communication cards installed in PCs or PLCs generally does not exceed 500 V. At best, the withstand capacity can reach 1.5 kV. In meshed installations with the TN-S system and relatively small communication networks, this level of withstand capacity is acceptable. In all cases, however, protection against lightning strikes (common and differential modes) is recommended.

The type of communication cable employed is an important parameter. It must be suited to the type of transmission. To create a reliable communication link, the following parameters must be taken into account:

- Characteristic impedance
- Twisted pairs or other arrangement
- Resistance and capacitance per unit length
- Signal attenuation per unit length
- The type(s) of shielding used

In addition, it is important to use symmetrical (differential) transmission links because they offer higher performance in terms of EMC.

In environments with severe EM conditions, however, or for wide communication networks between installations that are not or are only slightly equipotential, in conjunction with IT, TT or TN-C systems, it is highly recommended to use optical fibre links.

For safety reasons, the optical fibre must not have metal parts (risk of electric shock if the fibre links two areas with different potentials).

### 3.8 Implementation of surge arrestors

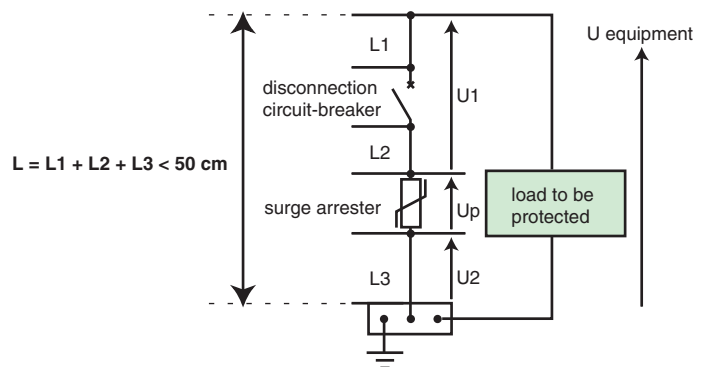
#### Connections

They must be as short as possible. In fact, one of the essential characteristics for equipment protection is the maximum level of voltage that the equipment can withstand at its terminals. A surge arrester with a protection level suitable for the equipment to be protected should be chosen (see **Fig. 16**). The total length of the connections is  $L = L1 + L2 + L3$ . It represents an impedance of roughly  $1 \mu\text{H/m}$  for high frequency currents.

Application of the rule  $\Delta U = L \frac{di}{dt}$

with an 8/20  $\mu\text{s}$  wave and a current of 8 kA leads to a voltage of 1,000 V peak per metre of cable.

$$\Delta U = 1.10^{-6} \times \frac{8 \cdot 10^3}{8 \cdot 10^{-6}} = 1,000 \text{ V}$$



**Fig. Q16** : Surge arrester connection:  $L < 50 \text{ cm}$

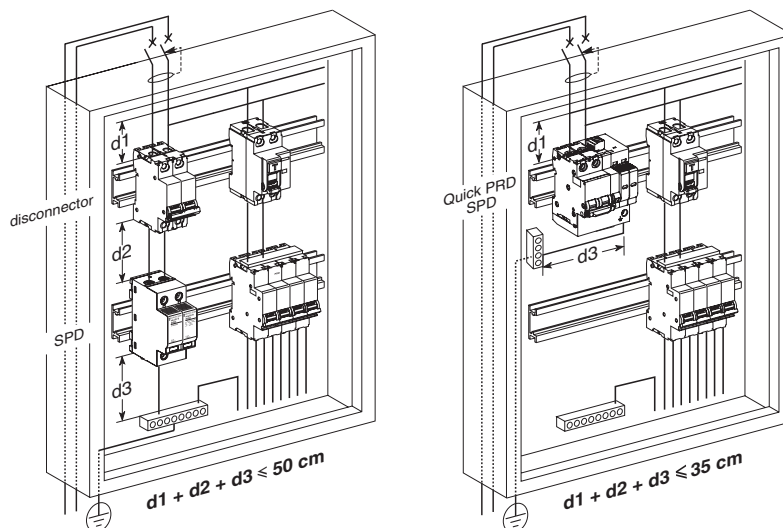
This gives  $U_{\text{equipment}} = U_p + U_1 + U_2$ .

If  $L1 + L2 + L3 = 50 \text{ cm}$ , this will result in a voltage surge of 500 V for a current of 8 kA.

### Wiring rules

#### ■ Rule 1

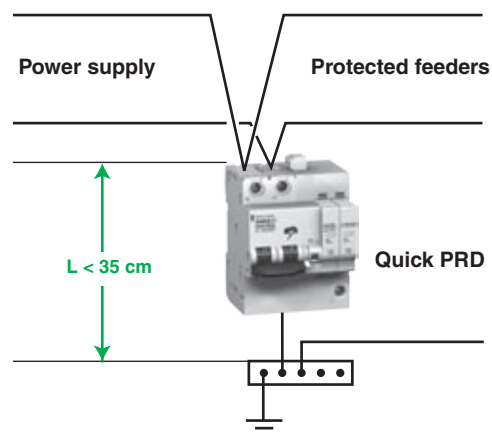
The first rule to be respected is not to exceed a distance of 50 cm when connecting the surge arrester to its disconnection circuit-breaker. The surge arrester connections are shown in **Figure Q17**.



**Fig. Q17** : SPD with separate or integrated disconnector

#### ■ Rule 2

The outgoing feeders of the protected conductors must be connected right at the terminals of the surge arrester and disconnection circuit-breaker (see **Fig. Q18**).



**Fig. Q18** : Connections are right at the SPD's terminals

#### ■ Rule 3

The phase, neutral and PE incoming wires must be tightly coupled to reduce the loop surfaces (see Fig. Q19).

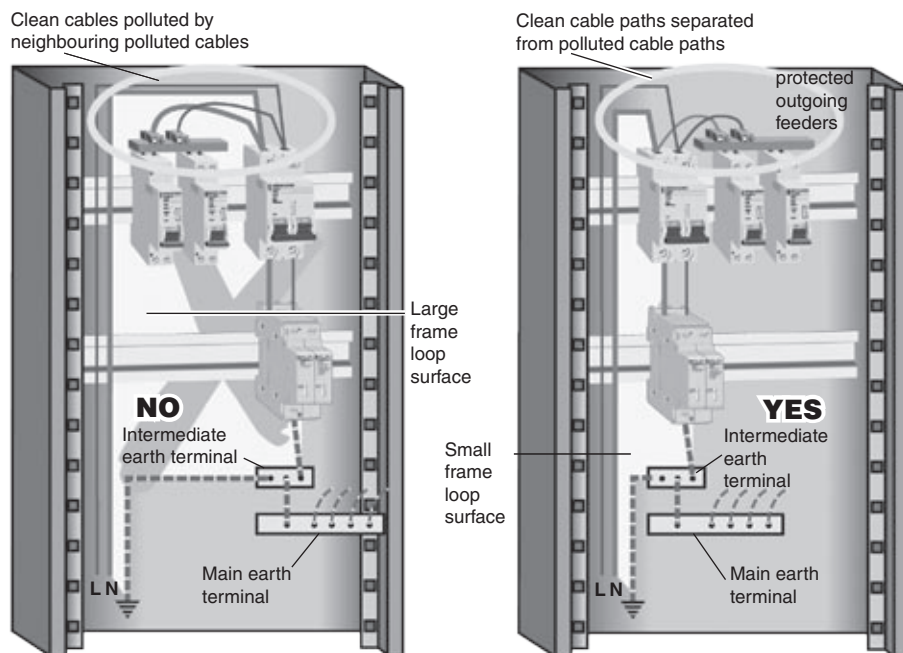


Fig. Q19 : Example of wiring precautions to be taken in a box (rules 2, 3, 4, 5)

#### ■ Rule 4

The surge arrester's incoming wires must be moved away from the outgoing wires to avoid mixing the polluted cables with the protected cables (see Fig. Q19).

#### ■ Rule 5

The cables must be flattened against the metallic frames of the box in order to minimise the frame loops and thus benefit from a disturbance screening effect. If the box is made of plastic and the loads particularly sensitive, it must be replaced by a metal box.

In all cases, you must check that the metallic frames of the boxes or cabinets are frame grounded by very short connections.

Finally, if screened cables are used, extra lengths which serve no purpose ("pigtailed"), must be cut off as they reduce screening effectiveness.



### 3.9 Cabinet cabling (Fig. Q20)

Each cabinet must be equipped with an earthing bar or a ground reference metal sheet. All shielded cables and external protection circuits must be connected to this point. Anyone of the cabinet metal sheets or the DIN rail can be used as the ground reference.

Plastic cabinets are not recommended. In this case, the DIN rail must be used as ground reference.

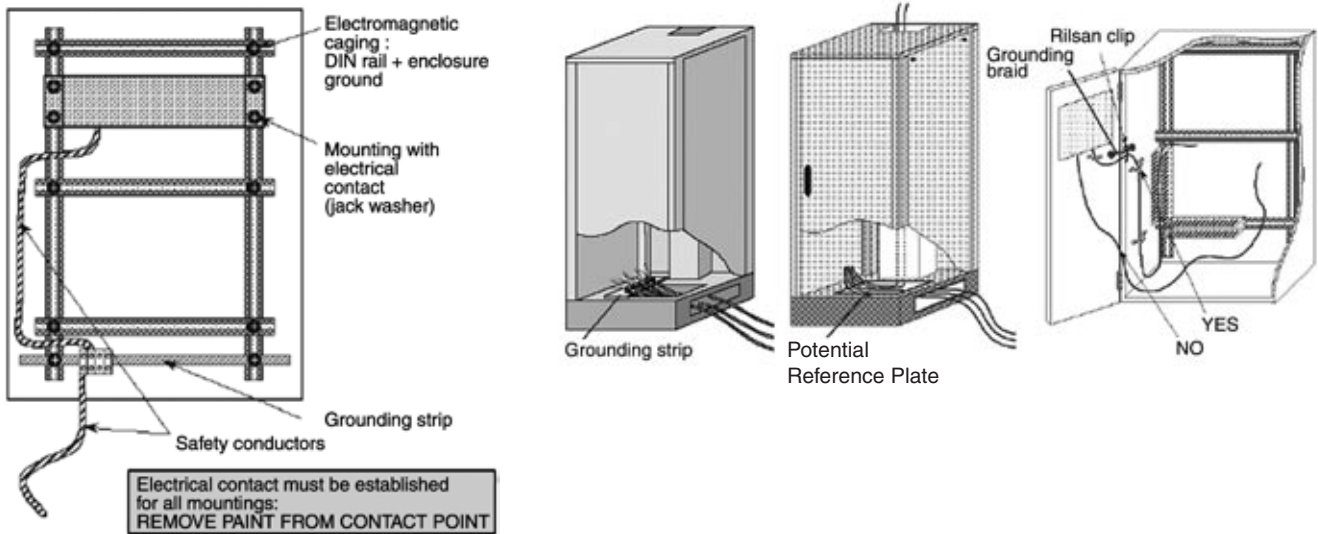


Fig. Q20 : The protected device must be connected to the surge-arrestor terminals

### 3.10 Standards

It is absolutely essential to specify the standards and recommendations that must be taken into account for installations.

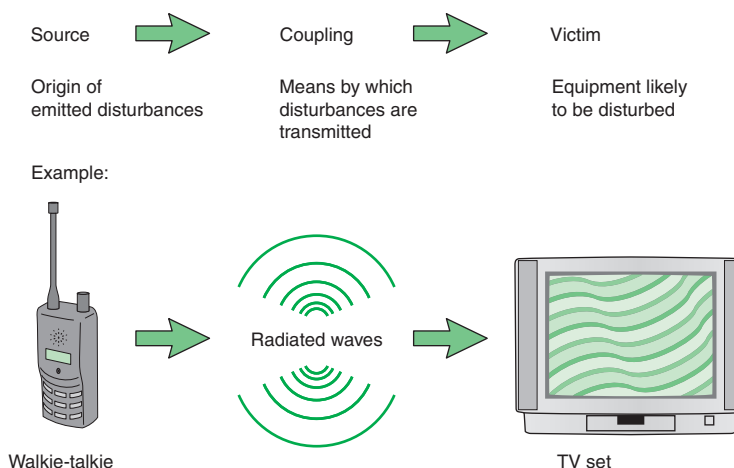
Below are several documents that may be used:

- EN 50174-1 Information technology - Cabling installation. Part 1: Specification and quality assurance
- EN 50174-2 Information technology - Cabling installation. Part 2: Installation planning and practices inside buildings

## 4 Coupling mechanisms and counter-measures

### 4.1 General

An EM interference phenomenon may be summed up in **Figure Q21** below.



**Fig. Q21** : EM interference phenomenon

The different sources of disturbances are:

- Radio-frequency emissions
- Wireless communication systems (radio, TV, CB, radio telephones, remote controls)
- Radar
- Electrical equipment
- High-power industrial equipment (induction furnaces, welding machines, stator control systems)
- Office equipment (computers and electronic circuits, photocopy machines, large monitors)
- Discharge lamps (neon, fluorescent, flash, etc.)
- Electromechanical components (relays, contactors, solenoids, current interruption devices)
- Power systems
- Power transmission and distribution systems
- Electrical transportation systems
- Lightning
- Electrostatic discharges (ESD)
- Electromagnetic nuclear pulses (EMNP)

The potential victims are:

- Radio and television receivers, radar, wireless communication systems
- Analogue systems (sensors, measurement acquisition, amplifiers, monitors)
- Digital systems (computers, computer communications, peripheral equipment)

The different types of coupling are:

- Common-mode impedance (galvanic) coupling
- Capacitive coupling
- Inductive coupling
- Radiated coupling (cable to cable, field to cable, antenna to antenna)

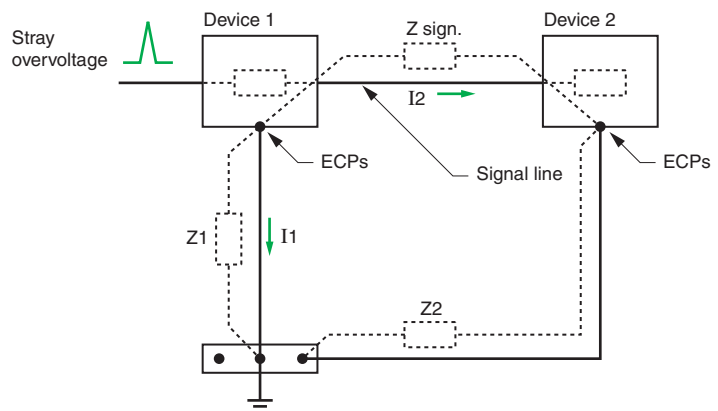
## 4 Coupling mechanisms and counter-measures

### 4.2 Common-mode impedance coupling

#### Definition

Two or more devices are interconnected by the power supply and communication cables (see **Fig. Q22**). When external currents (lightning, fault currents, disturbances) flow via these common-mode impedances, an undesirable voltage appears between points A and B **which are supposed to be equipotential**. This stray voltage can disturb low-level or fast electronic circuits.

All cables, including the protective conductors, have an impedance, particularly at high frequencies.



The exposed conductive parts (ECP) of devices 1 and 2 are connected to a common earthing terminal via connections with impedances  $Z_1$  and  $Z_2$ .

The stray overvoltage flows to the earth via  $Z_1$ . The potential of device 1 increases to  $Z_1 I_1$ . The difference in potential with device 2 (initial potential = 0) results in the appearance of current  $I_2$ .

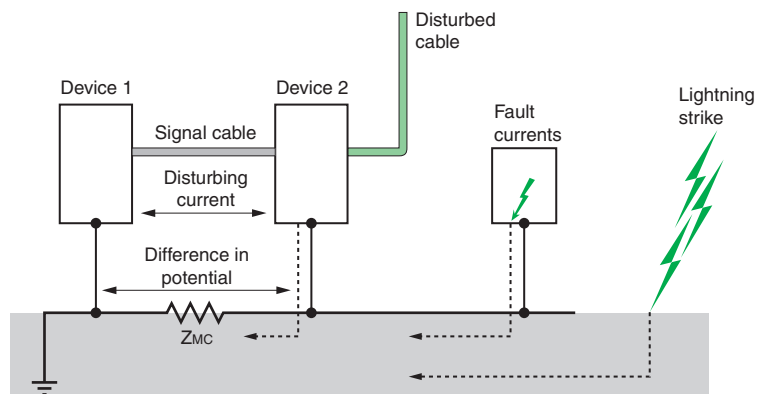
$$Z_1 I_1 = (Z_{\text{sign}} + Z_2) I_2 \Rightarrow \frac{I_2}{I_1} = \frac{Z_1}{(Z_{\text{sign}} + Z_2)}$$

Current  $I_2$ , present on the signal line, disturbs device 2.

**Fig. Q22** : Definition of common-mode impedance coupling

#### Examples (see Fig. Q23)

- Devices linked by a common reference conductor (e.g. PEN, PE) affected by fast or intense ( $di/dt$ ) current variations (fault current, lightning strike, short-circuit, load changes, chopping circuits, harmonic currents, power factor correction capacitor banks, etc.)
- A common return path for a number of electrical sources



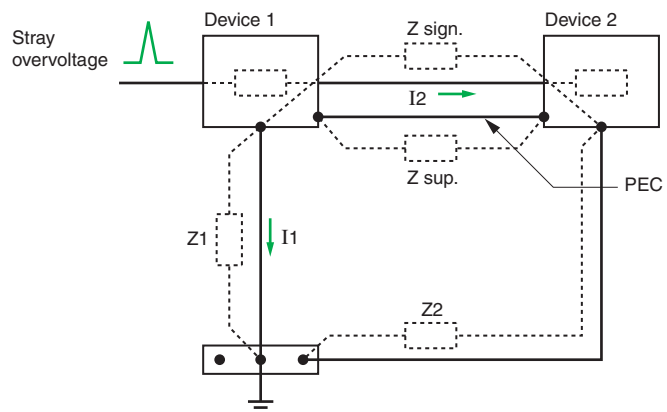
**Fig. Q23** : Example of common-mode impedance coupling

## 4 Coupling mechanisms and counter-measures

### Counter-measures (see Fig. Q24)

If they cannot be eliminated, common-mode impedances must at least be as low as possible. To reduce the effects of common-mode impedances, it is necessary to:

- Reduce impedances:
  - Mesh the common references,
  - Use short cables or flat braids which, for equal sizes, have a lower impedance than round cables,
  - Install functional equipotential bonding between devices.
- Reduce the level of the disturbing currents by adding common-mode filtering and differential-mode inductors



If the impedance of the parallel earthing conductor PEC ( $Z_{sup}$ ) is very low compared to  $Z_{sign}$ , most of the disturbing current flows via the PEC, i.e. not via the signal line as in the previous case.

The difference in potential between devices 1 and 2 becomes very low and the disturbance acceptable.

Fig. Q24 : Counter-measures of common-mode impedance coupling

### 4.3 Capacitive coupling

#### Definition

The level of disturbance depends on the voltage variations ( $dv/dt$ ) and the value of the coupling capacitance between the disturber and the victim.

Capacitive coupling increases with:

- The frequency
- The proximity of the disturber to the victim and the length of the parallel cables
- The height of the cables with respect to a ground referencing plane
- The input impedance of the victim circuit (circuits with a high input impedance are more vulnerable)
- The insulation of the victim cable ( $\epsilon_r$  of the cable insulation), particularly for tightly coupled pairs

Figure Q25 shows the results of capacitive coupling (cross-talk) between two cables.

#### Examples (see Fig. Q26 opposite page)

- Nearby cables subjected to rapid voltage variations ( $dv/dt$ )
- Start-up of fluorescent lamps
- High-voltage switch-mode power supplies (photocopy machines, etc.)
- Coupling capacitance between the primary and secondary windings of transformers
- Cross-talk between cables

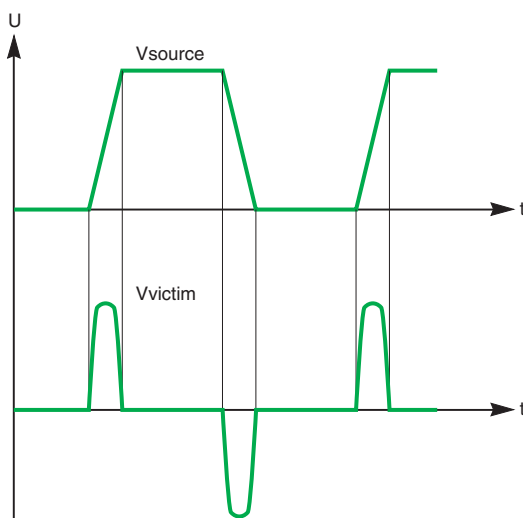
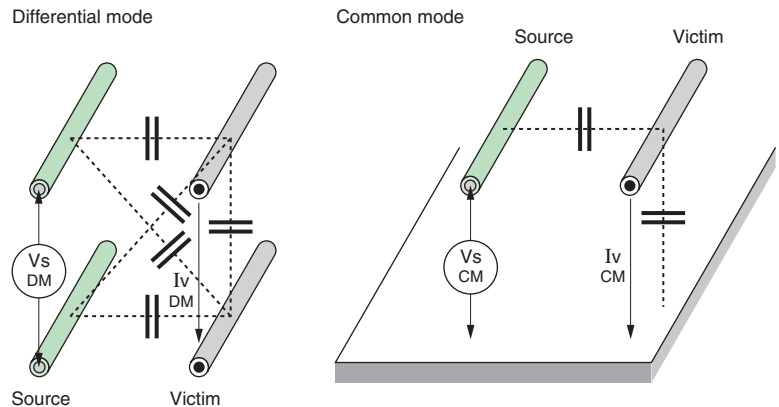


Fig. Q25 : Typical result of capacitive coupling (capacitive cross-talk)

## 4 Coupling mechanisms and counter-measures



$V_{s\ DM}$ : Source of the disturbing voltage (differential mode)  
 $I_{v\ DM}$ : Disturbing current on victim side (differential mode)  
 $V_{s\ CM}$ : Source of the disturbing voltage (common mode)  
 $I_{v\ CM}$ : Disturbing current on victim side (common mode)

Fig. Q26 : Example of capacitive coupling

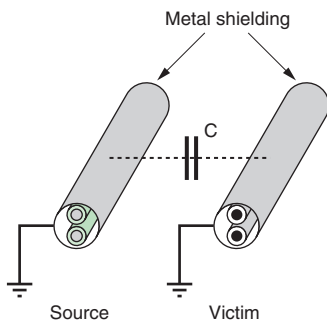


Fig. Q27 : Cable shielding with perforations reduces capacitive coupling

### Counter-measures (see Fig. Q27)

- Limit the length of parallel runs of disturbers and victims to the strict minimum
- Increase the distance between the disturber and the victim
- For two-wire connections, run the two wires as close together as possible
- Position a PEC bonded at both ends and between the disturber and the victim
- Use two or four-wire cables rather than individual conductors
- Use symmetrical transmission systems on correctly implemented, symmetrical wiring systems
- Shield the disturbing cables, the victim cables or both (the shielding must be bonded)
- Reduce the  $dv/dt$  of the disturber by increasing the signal rise time where possible

### 4.4 Inductive coupling

#### Definition

The disturber and the victim are coupled by a magnetic field. The level of disturbance depends on the current variations ( $di/dt$ ) and the mutual coupling inductance.

Inductive coupling increases with:

- The frequency
- The proximity of the disturber to the victim and the length of the parallel cables,
- The height of the cables with respect to a ground referencing plane,
- The load impedance of the disturbing circuit.

#### Examples (see Fig. Q28 next page)

- Nearby cables subjected to rapid current variations ( $di/dt$ )
- Short-circuits
- Fault currents
- Lightning strikes
- Stator control systems
- Welding machines
- Inductors

## 4 Coupling mechanisms and counter-measures

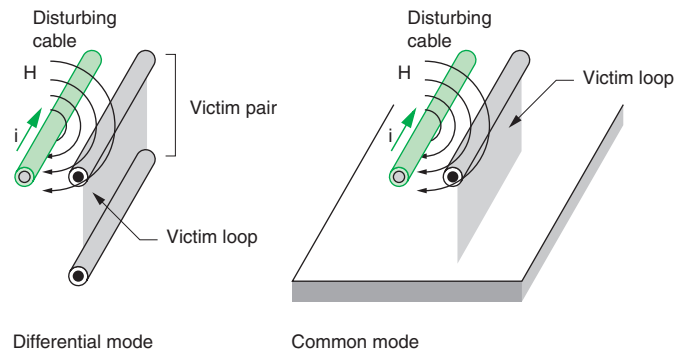


Fig. Q28 : Example of inductive coupling

### Counter-measures

- Limit the length of parallel runs of disturbers and victims to the strict minimum
- Increase the distance between the disturber and the victim
- For two-wire connections, run the two wires as close together as possible
- Use multi-core or touching single-core cables, preferably in a triangular layout
- Position a PEC bonded at both ends and between the disturber and the victim
- Use symmetrical transmission systems on correctly implemented, symmetrical wiring systems
- Shield the disturbing cables, the victim cables or both (the shielding must be bonded)
- Reduce the  $dv/dt$  of the disturber by increasing the signal rise time where possible (series-connected resistors or PTC resistors on the disturbing cable, ferrite rings on the disturbing and/or victim cable)

### 4.5 Radiated coupling

#### Definition

The disturber and the victim are coupled by a medium (e.g. air). The level of disturbance depends on the power of the radiating source and the effectiveness of the emitting and receiving antenna. An electromagnetic field comprises both an electrical field and a magnetic field. The two fields are correlated. It is possible to analyse separately the electrical and magnetic components.

The electrical field (E field) and the magnetic field (H field) are coupled in wiring systems via the wires and loops (see Fig. Q29).

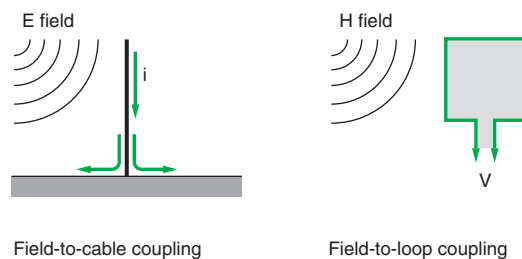


Fig. Q29 : Definition of radiated coupling

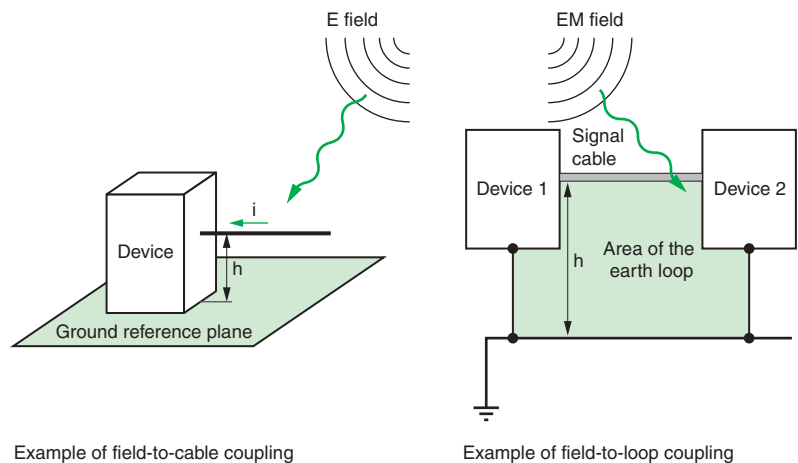
## 4 Coupling mechanisms and counter-measures

When a cable is subjected to a variable electrical field, a current is generated in the cable. This phenomenon is called field-to-cable coupling.

Similarly, when a variable magnetic field flows through a loop, it creates a counter electromotive force that produces a voltage between the two ends of the loop. This phenomenon is called field-to-loop coupling.

### Examples (see Fig. Q30)

- Radio-transmission equipment (walkie-talkies, radio and TV transmitters, mobile services)
- Radar
- Automobile ignition systems
- Arc-welding machines
- Induction furnaces
- Power switching systems
- Electrostatic discharges (ESD)
- Lighting



Example of field-to-cable coupling

Example of field-to-loop coupling

Fig. Q30 : Examples of radiated coupling

### Counter-measures

To minimise the effects of radiated coupling, the measures below are required.

#### For field-to-cable coupling

- Reduce the antenna effect of the victim by reducing the height ( $h$ ) of the cable with respect to the ground referencing plane
- Place the cable in an uninterrupted, bonded metal cableway (tube, trunking, cable tray)
- Use shielded cables that are correctly installed and bonded
- Add PECs
- Place filters or ferrite rings on the victim cable

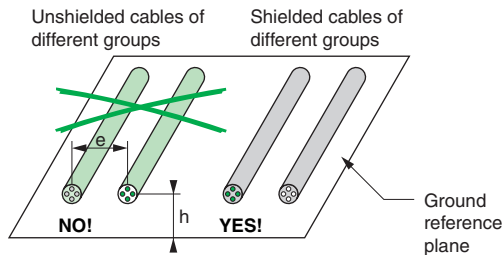
#### For field-to-loop coupling

- Reduce the surface of the victim loop by reducing the height ( $h$ ) and the length of the cable. Use the solutions for field-to-cable coupling. Use the Faraday cage principle.

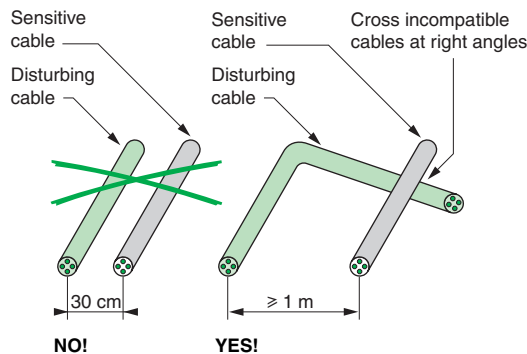
Radiated coupling can be eliminated using the Faraday cage principle. A possible solution is a shielded cable with both ends of the shielding connected to the metal case of the device. The exposed conductive parts must be bonded to enhance effectiveness at high frequencies.

Radiated coupling decreases with the distance and when symmetrical transmission links are used.

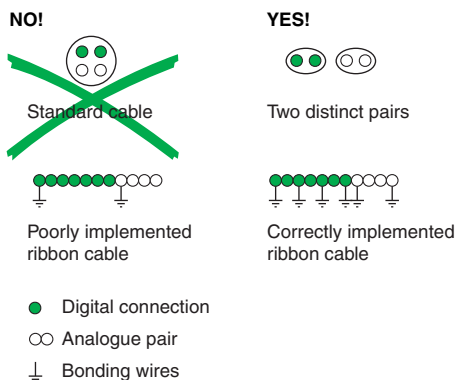
## 5.1 Signal classes (see Fig. Q31)



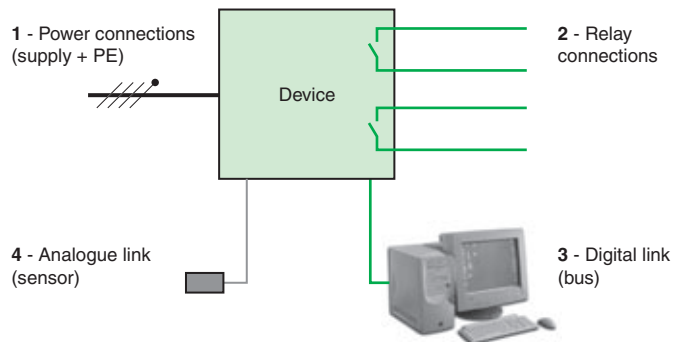
Risk of cross-talk in common mode if  $e < 3$  h



**Fig. Q32** : Wiring recommendations for cables carrying different types of signals



**Fig. Q33** : Use of cables and ribbon cable



**Fig. Q31** : Internal signals can be grouped in four classes

Four classes of internal signals are:

### ■ Class 1

Mains power lines, power circuits with a high  $di/dt$ , switch-mode converters, power-regulation control devices.

This class is not very sensitive, but disturbs the other classes (particularly in common mode).

### ■ Class 2

Relay contacts.

This class is not very sensitive, but disturbs the other classes (switching, arcs when contacts open).

### ■ Class 3

Digital circuits (HF switching).

This class is sensitive to pulses, but also disturbs the following class.

### ■ Class 4

Analogue input/output circuits (low-level measurements, active sensor supply circuits). This class is sensitive.

It is a good idea to use conductors with a specific colour for each class to facilitate identification and separate the classes. This is useful during design and troubleshooting.

## 5.2 Wiring recommendations

**Cables carrying different types of signals must be physically separated** (see Fig. Q32 above)

**Disturbing cables (classes 1 and 2) must be placed at some distance from the sensitive cables (classes 3 and 4)** (see Fig. Q32 and Fig. Q33)

In general, a 10 cm separation between cables laid flat on sheet metal is sufficient (for both common and differential modes). If there is enough space, a distance of 30 cm is preferable. If cables must be crossed, this should be done at right angles to avoid cross-talk (even if they touch). There are no distance requirements if the cables are separated by a metal partition that is equipotential with respect to the ECPs. However, the height of the partition must be greater than the diameter of the cables.



**A cable should carry the signals of a single group (see Fig. Q34)**

If it is necessary to use a cable to carry the signals of different groups, internal shielding is necessary to limit cross-talk (differential mode). The shielding, preferably braided, must be bonded at each end for groups 1, 2 and 3.

**It is advised to overshield disturbing and sensitive cables (see Fig. Q35)**

The overshielding acts as a HF protection (common and differential modes) if it is bonded at each end using a circumferential connector, a collar or a clamp. However, a simple bonding wire is not sufficient.

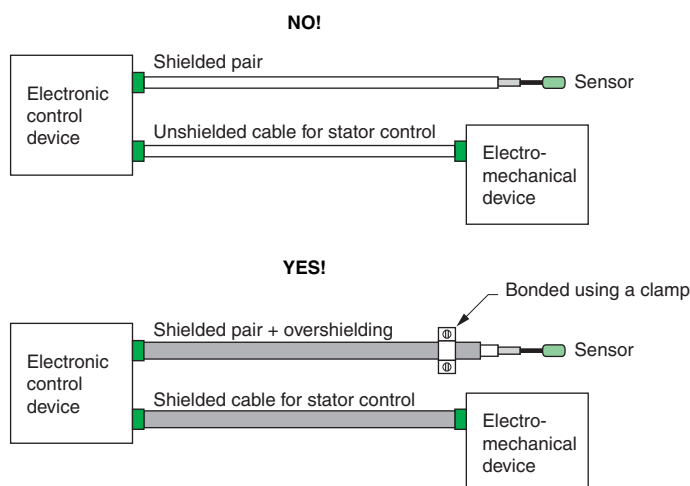


Fig. Q35 : Shielding and overshielding for disturbing and/or sensitive cables

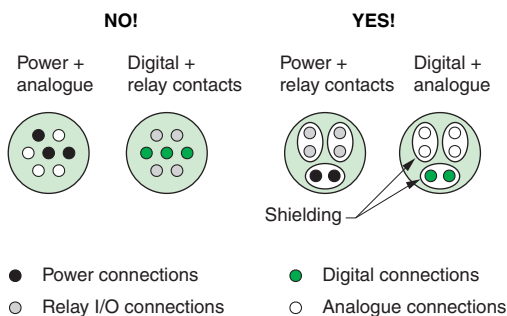


Fig. Q34 : Incompatible signals = different cables

**Avoid using a single connector for different groups (see Fig. Q36)**

Except where necessary for groups 1 and 2 (differential mode). If a single connector is used for both analogue and digital signals, the two groups must be separated by at least one set of contacts connected to 0 V used as a barrier.

**All free conductors (reserve) must always be bonded at each end (see Fig. Q37)**

For group 4, these connections are not advised for lines with very low voltage and frequency levels (risk of creating signal noise, by magnetic induction, at the transmission frequencies).

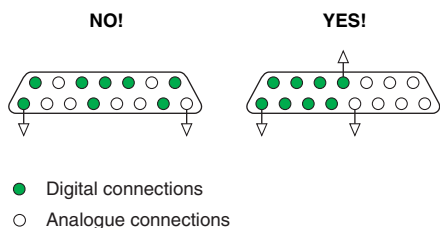


Fig. Q36 : Segregation applies to connectors as well!

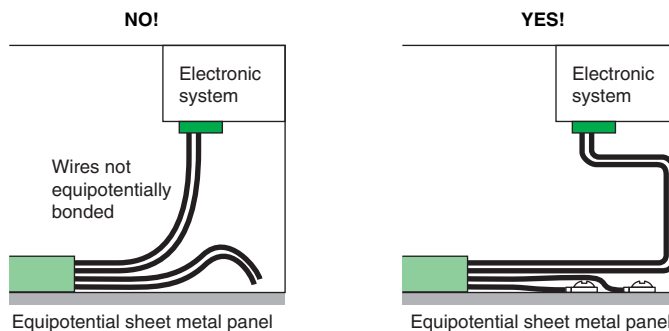
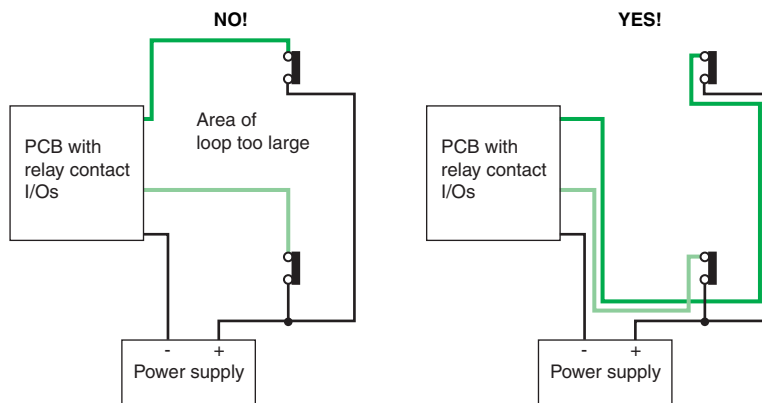


Fig. Q37 : Free wires must be equipotentially bonded

**The two conductors must be installed as close together as possible** (see Fig. Q38)

This is particularly important for low-level sensors. Even for relay signals with a common, the active conductors should be accompanied by at least one common conductor per bundle. For analogue and digital signals, twisted pairs are a minimum requirement. A twisted pair (differential mode) guarantees that the two wires remain together along their entire length.



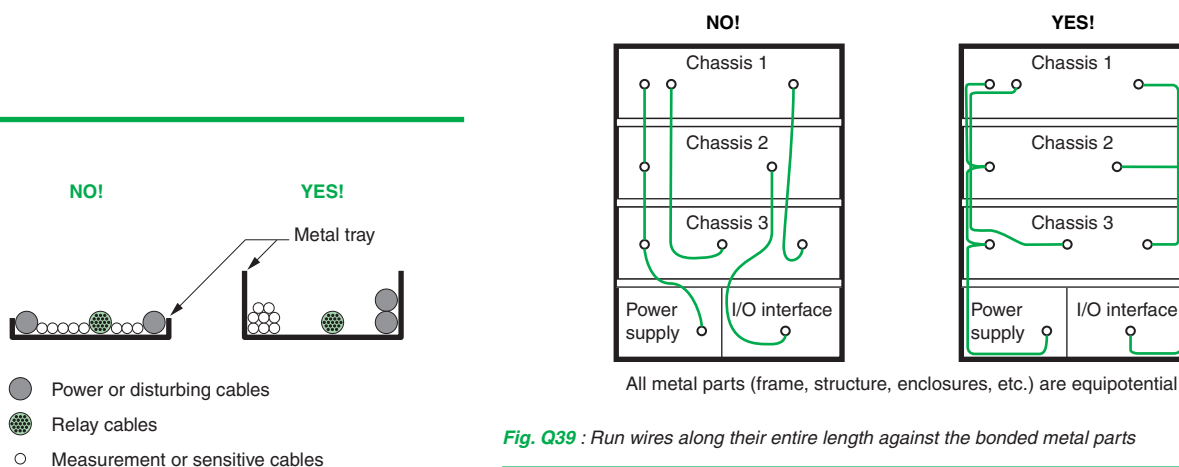
**Fig. Q38** : The two wires of a pair must always be run close together

**Group-1 cables do not need to be shielded if they are filtered**

But they should be made of twisted pairs to ensure compliance with the previous section.

**Cables must always be positioned along their entire length against the bonded metal parts of devices** (see Fig. Q39)

For example: Covers, metal trunking, structure, etc. In order to take advantage of the dependable, inexpensive and significant reduction effect (common mode) and anti-cross-talk effect (differential mode).



All metal parts (frame, structure, enclosures, etc.) are equipotential

**Fig. Q39** : Run wires along their entire length against the bonded metal parts

**Fig. Q40** : Cable distribution in cable trays

**The use of correctly bonded metal trunking considerably improves internal EMC** (see Fig. Q40)

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