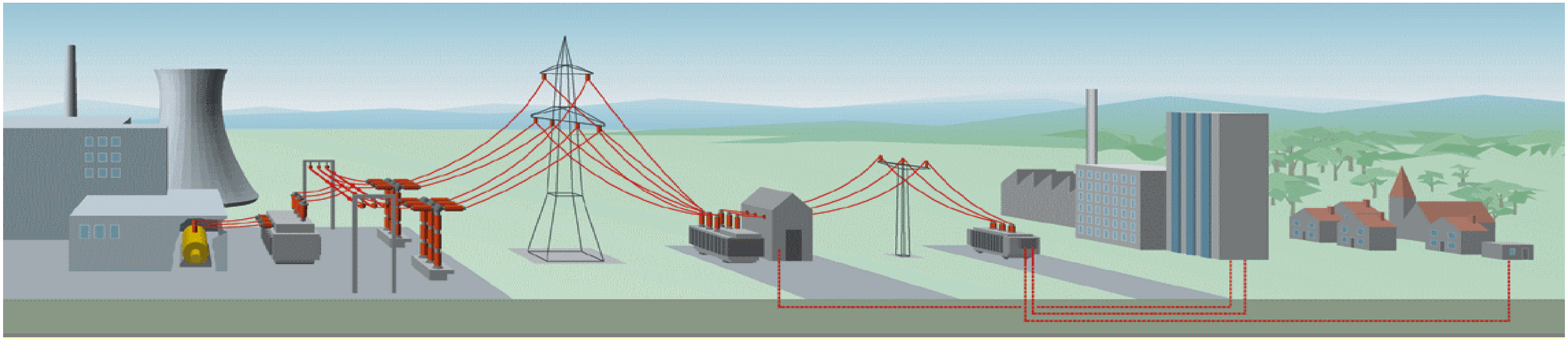
Digital Differential Protection

G. Ziegler



Differential Protection: Discussion Subjects

- Mode of operation
- Measuring technique
- Current transformers
- Communications
- Generator and motor differential protection
- Transformer differential protection
- Line differential protection
- Busbar differential protection

Digital Differential Protection

Principles and Application

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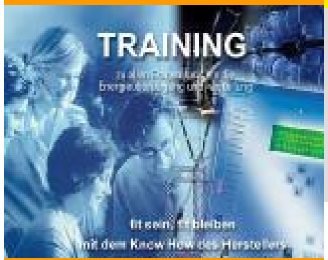
Contents



Digital Differential Protection

Mode of operation

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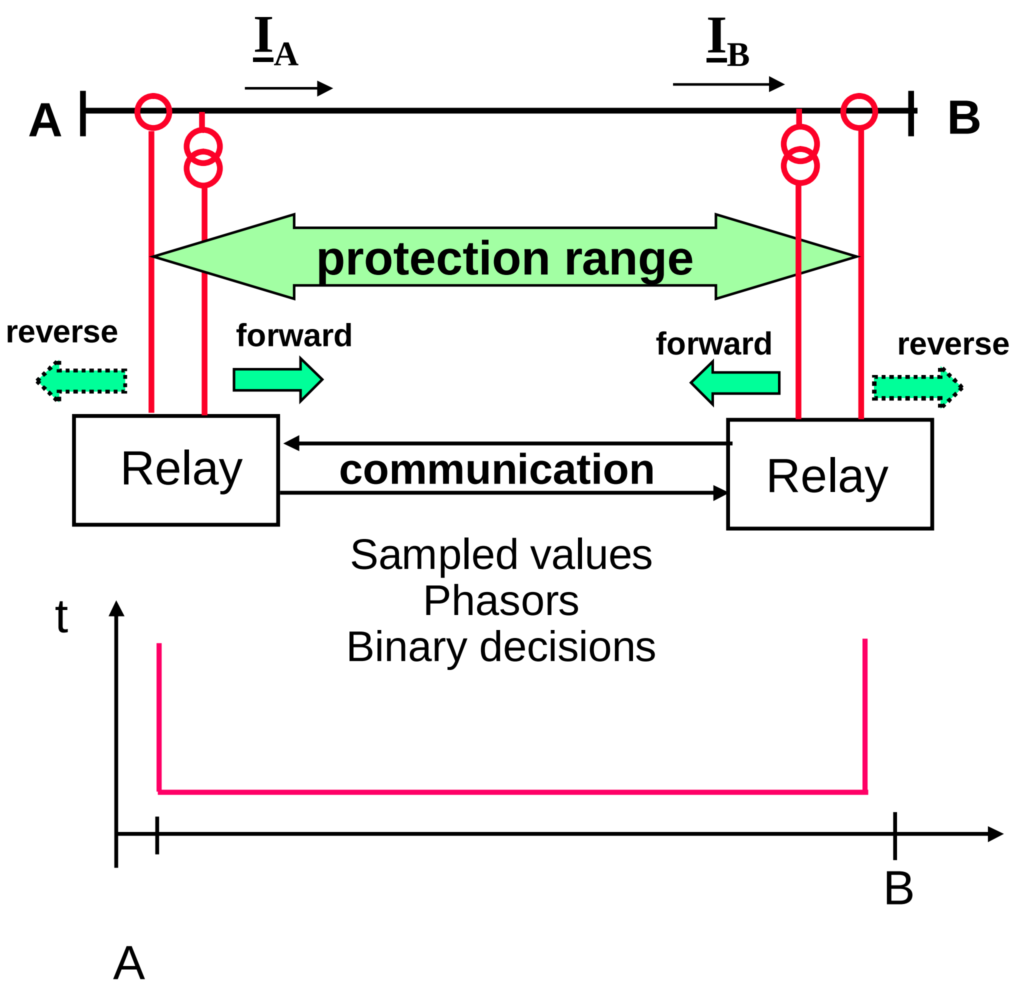
Comparison protection - Principles

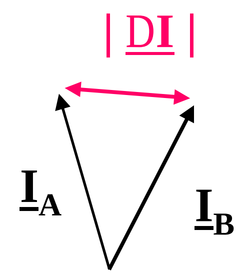
Absolute selectivity by using communications



- Directional comparison

Exchange of YES / NO signals
(fault forward / reverse)

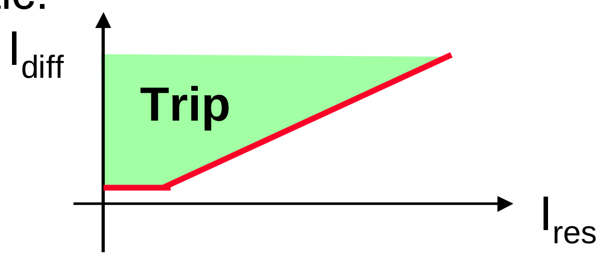
- Current comparison

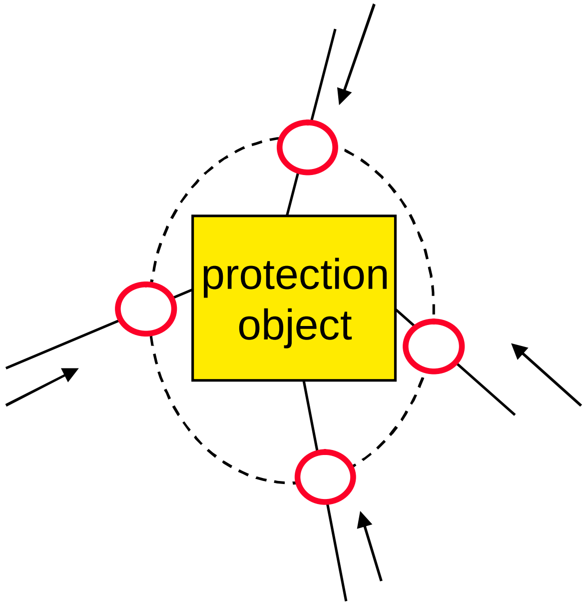


- comparison of
momentary values or phasors
- $|\Delta\underline{I}| = |\underline{I}_A - \underline{I}_B| >$ limiting value

Protection Criterion "current difference" (differential protection)

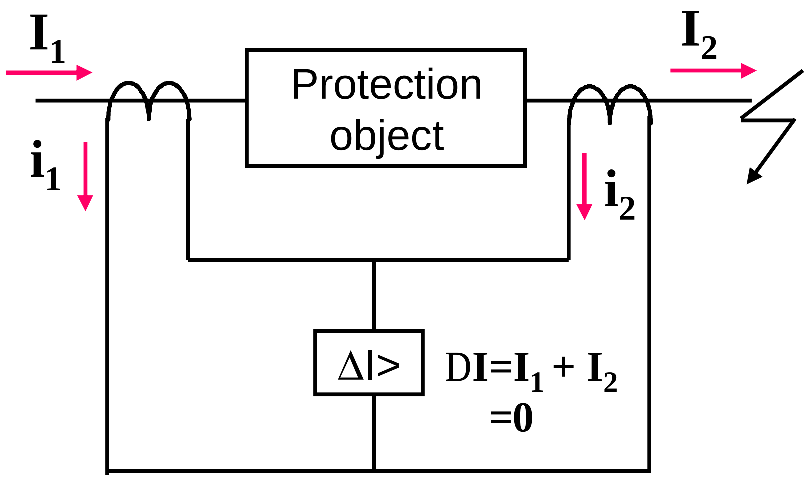
- Kirchhoff's law: $|\underline{I}_1 + \underline{I}_2 + \underline{I}_3 + \dots \underline{I}_n| = I_{diff} = 0$;
  Current difference indicates fault
- Security by through-current dependent restraint
  $|I1|+|I2|+ \dots |In| = I_{Res}$
- Characteristic:



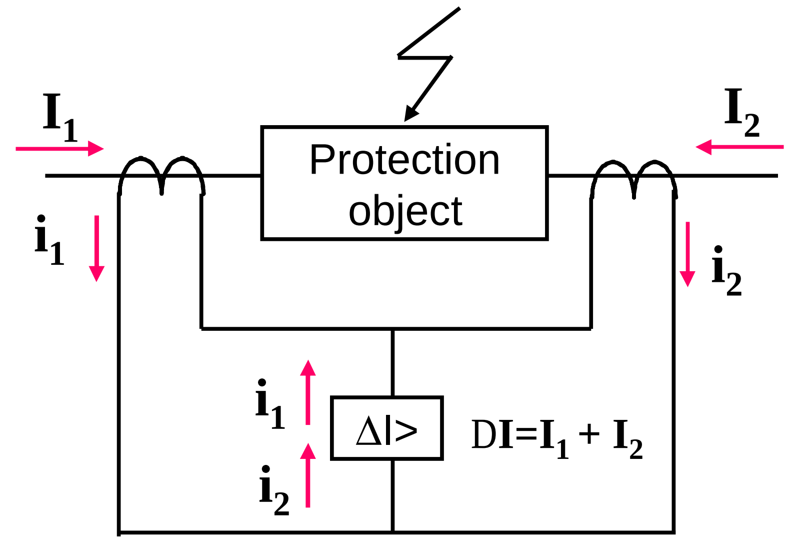


- Absolute zone selectivity (limits: CT locations)
  No "back-up" for external faults
- Differential protection: for generators, motors, transformers, lines and busbars

Current differential protection: Basic principle



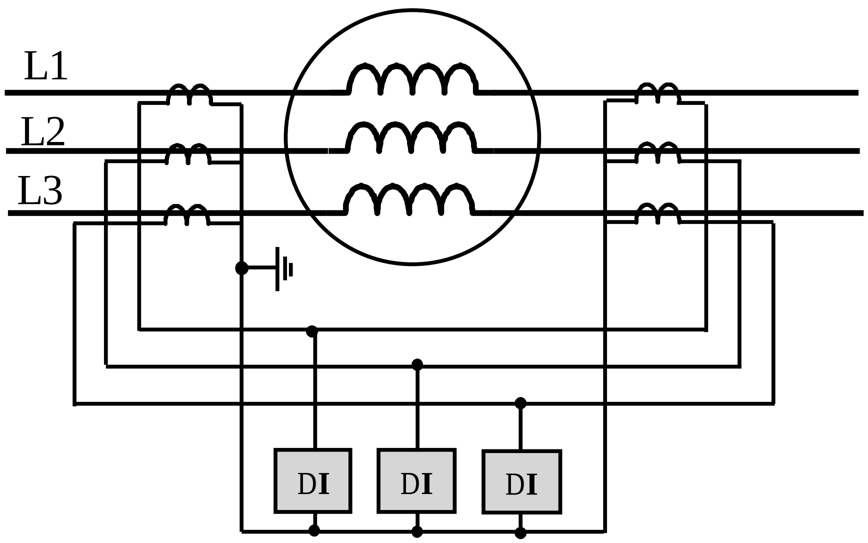
external fault or load



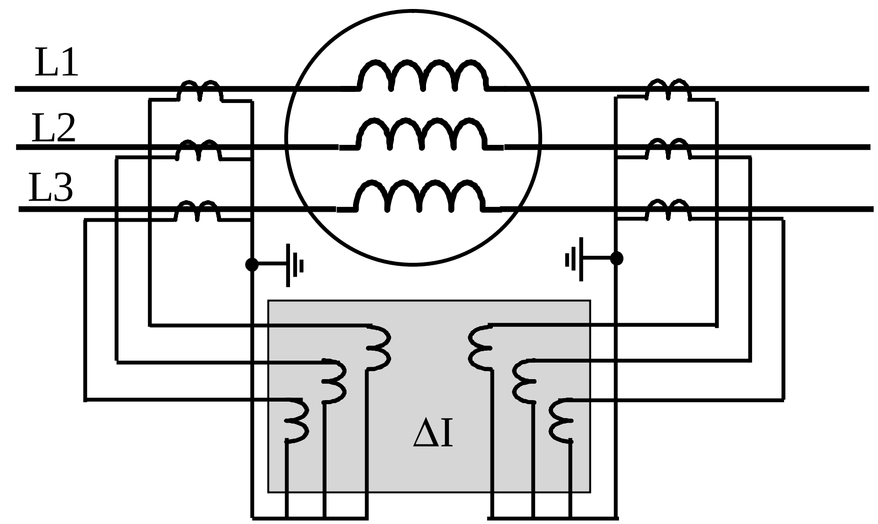
internal fault

Differential protection: Connection circuit

Traditional technique



Digital technique



Galvanically connected circuits must only be earthed once!

CT circuits of digital relays are segregated and must each be earthed !

Different CT ratios need to be adapted by auxiliary CTs!

Digital relays have integrated numerical ratio adaptation !

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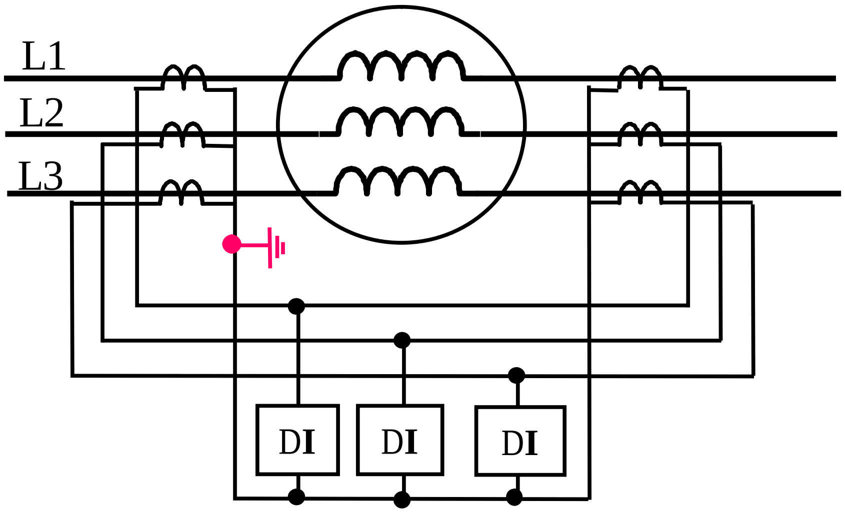
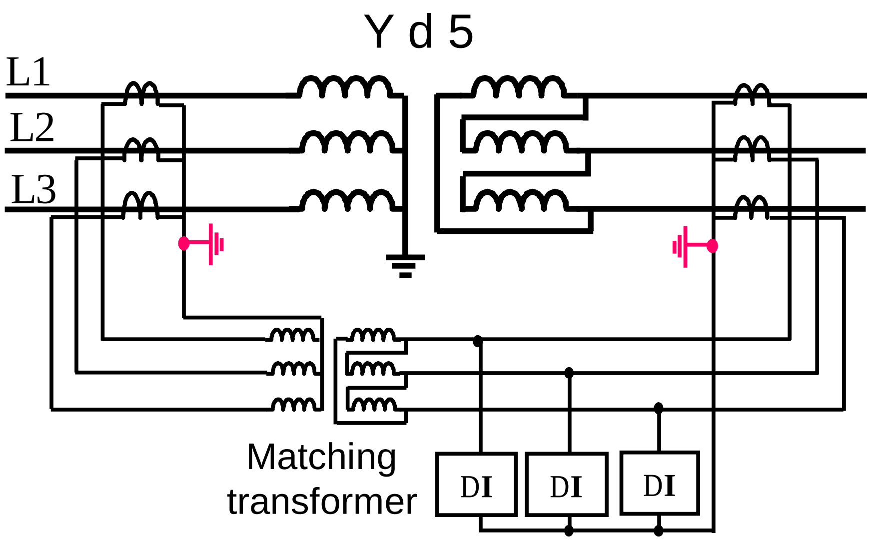
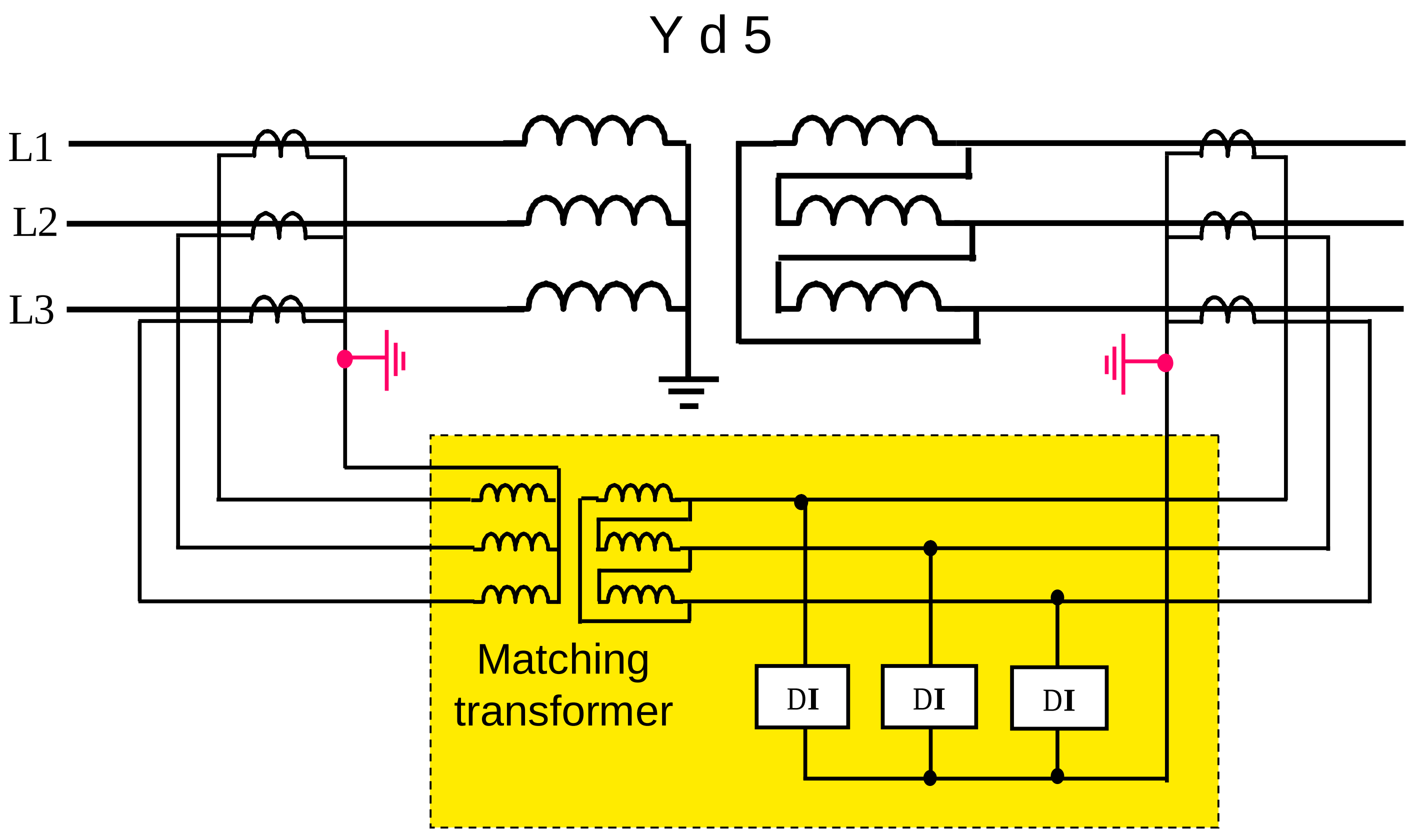
Generator and transformer differential protection



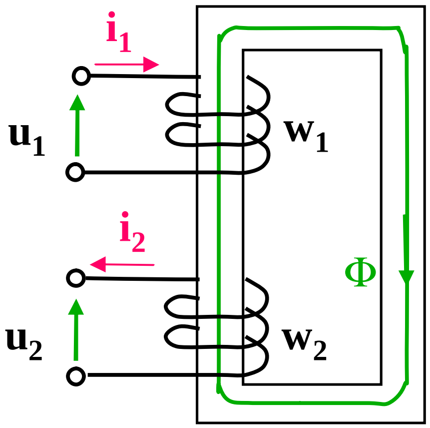


Transformer differential protection



Current transformer:

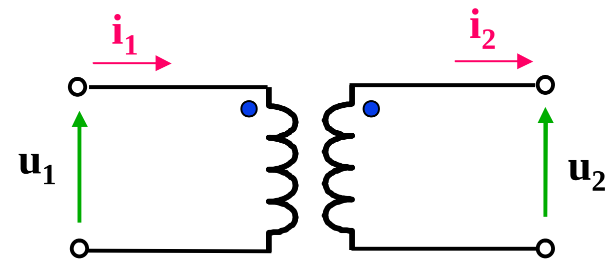
Principle, transformation ratio, polarity



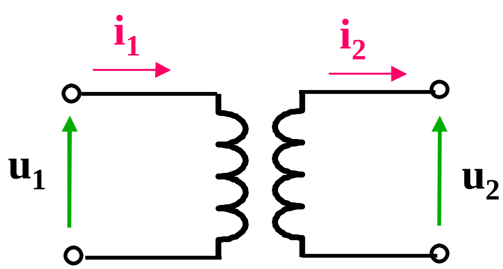
① $i_1 \cdot w_1 = i_2 \cdot w_2$

② $\frac{u_1}{w_1} = \frac{u_2}{w_2}$

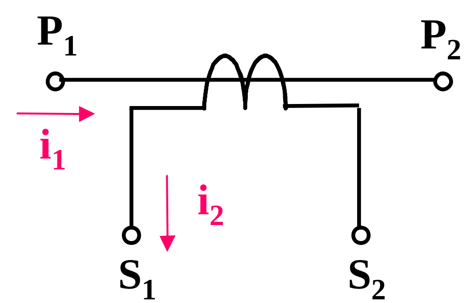
Function principle



Polarity marks



Equivalent electrical circuit

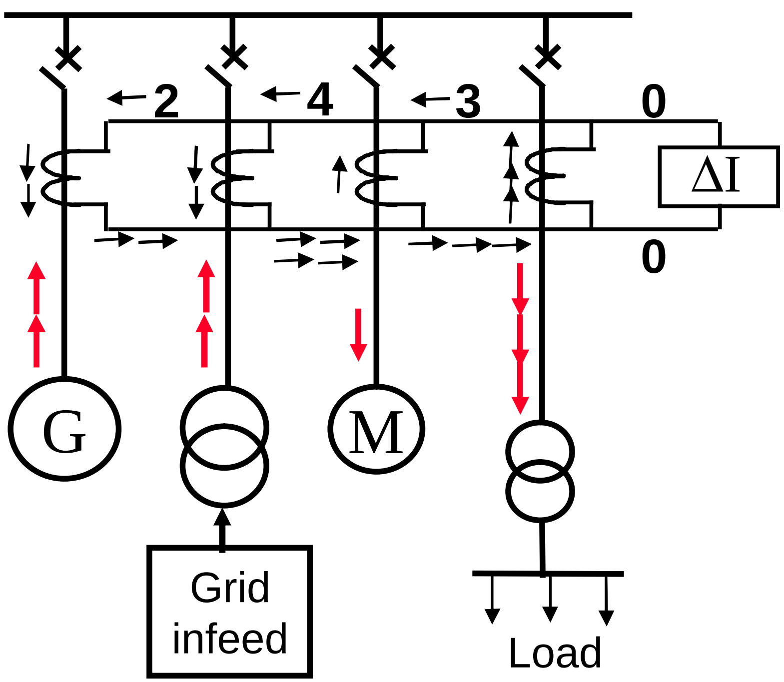


Designation of CT terminals according to IEC 60044-1

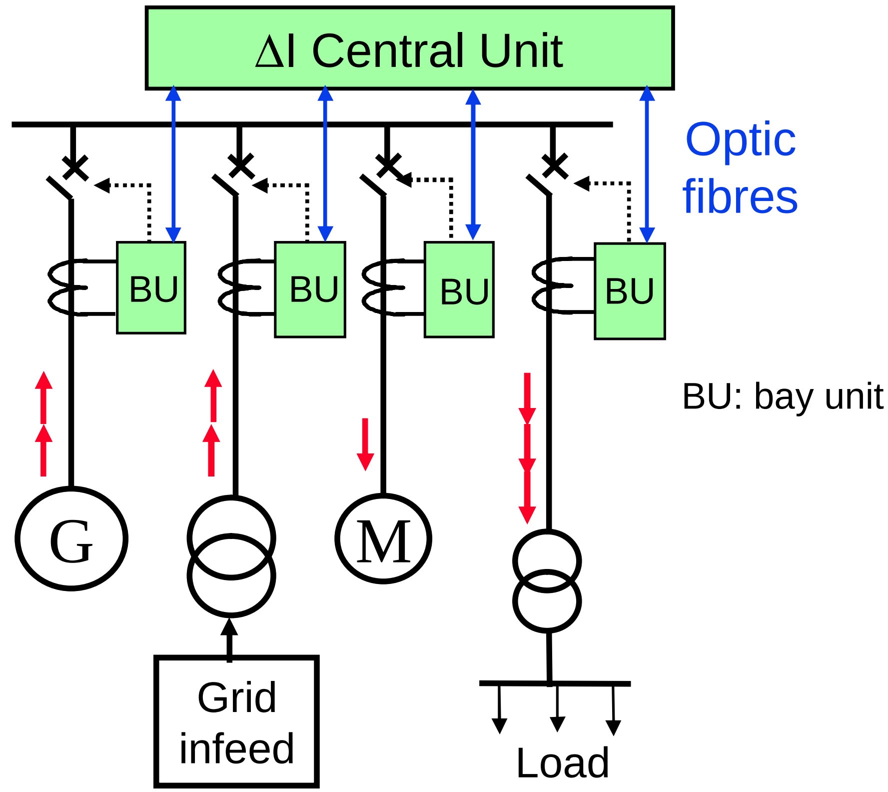
Busbar differential protection

Analog protection 7SS10/11/13

7SS600 with digital measuring relay (ΔI)

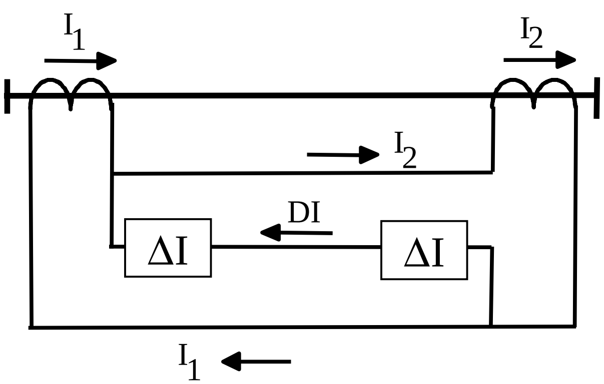


Digital protection 7SS52

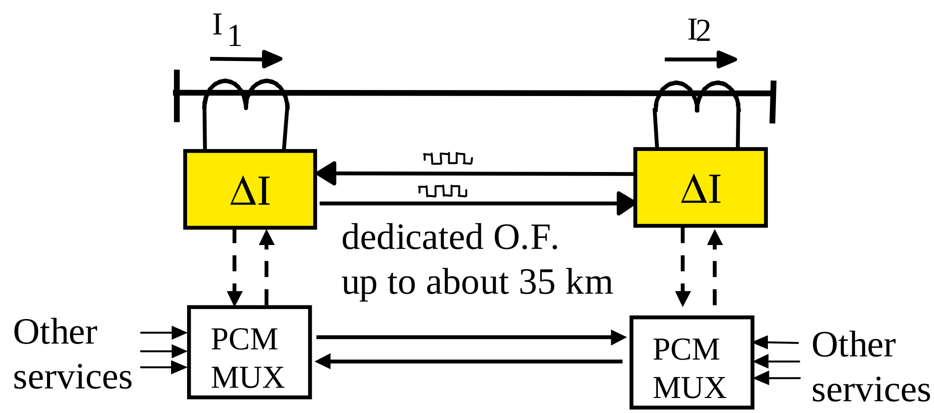


Line differential protection

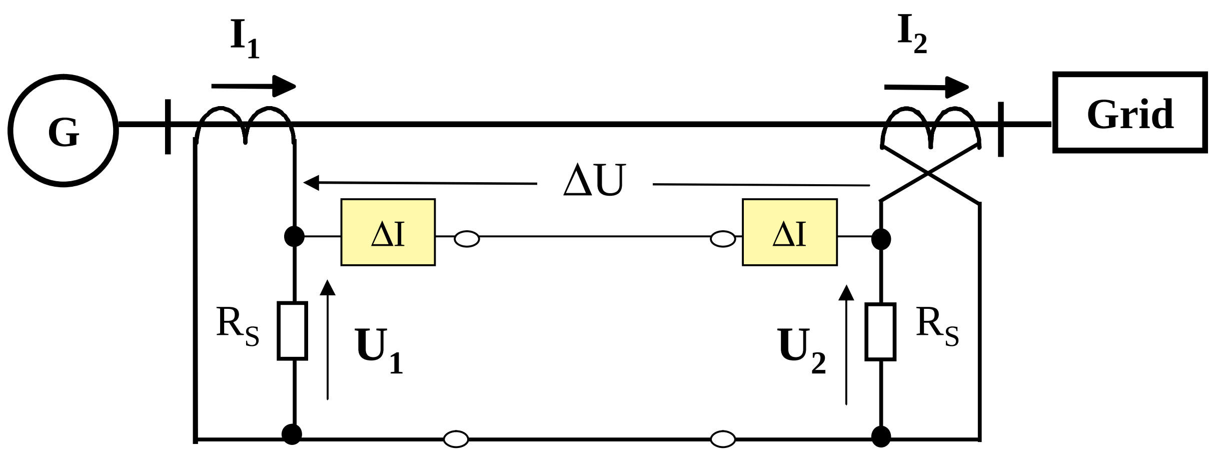
50/60 Hz current comparison through wire connection

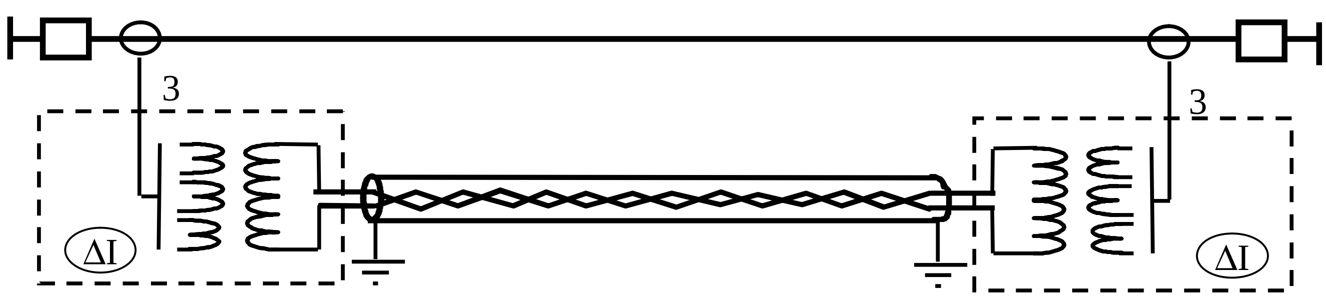


Phasor with digital communication via OF, microwave or pilot wires



Two wire (pilot wire) line differential protection
Voltage comparison principle





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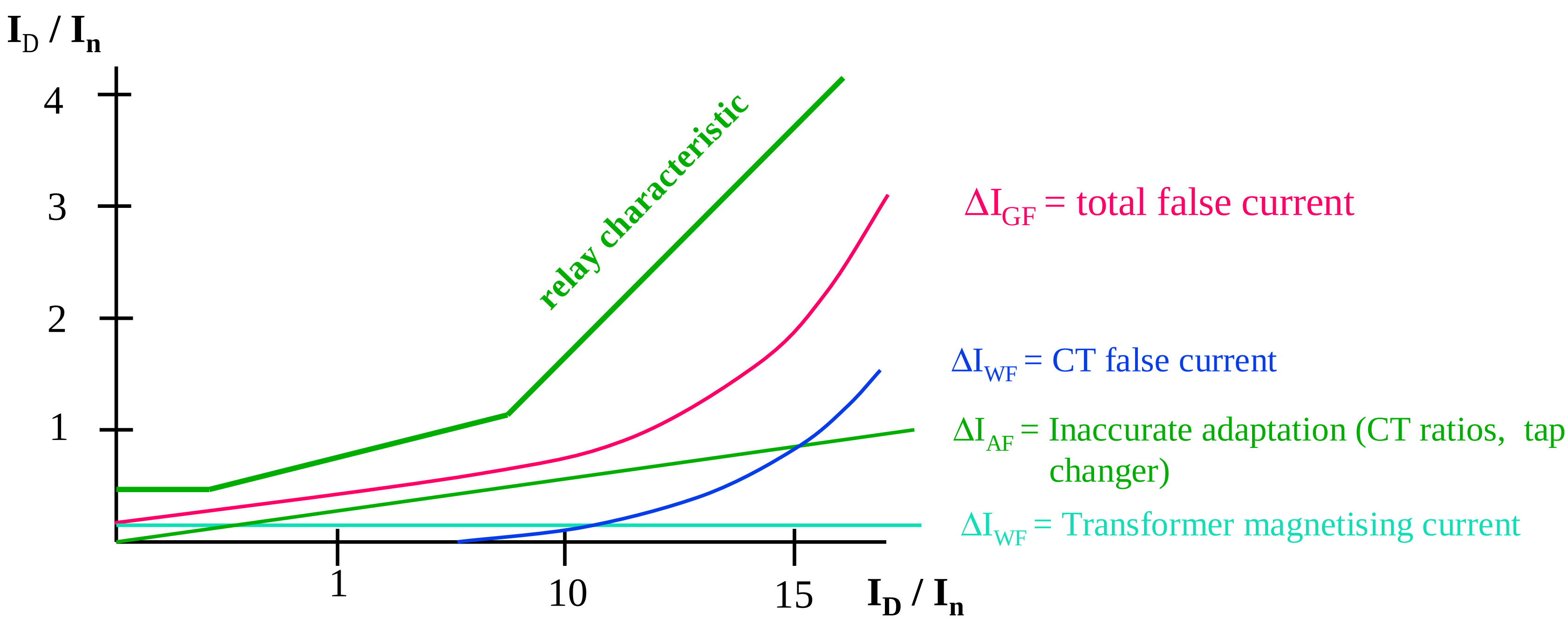
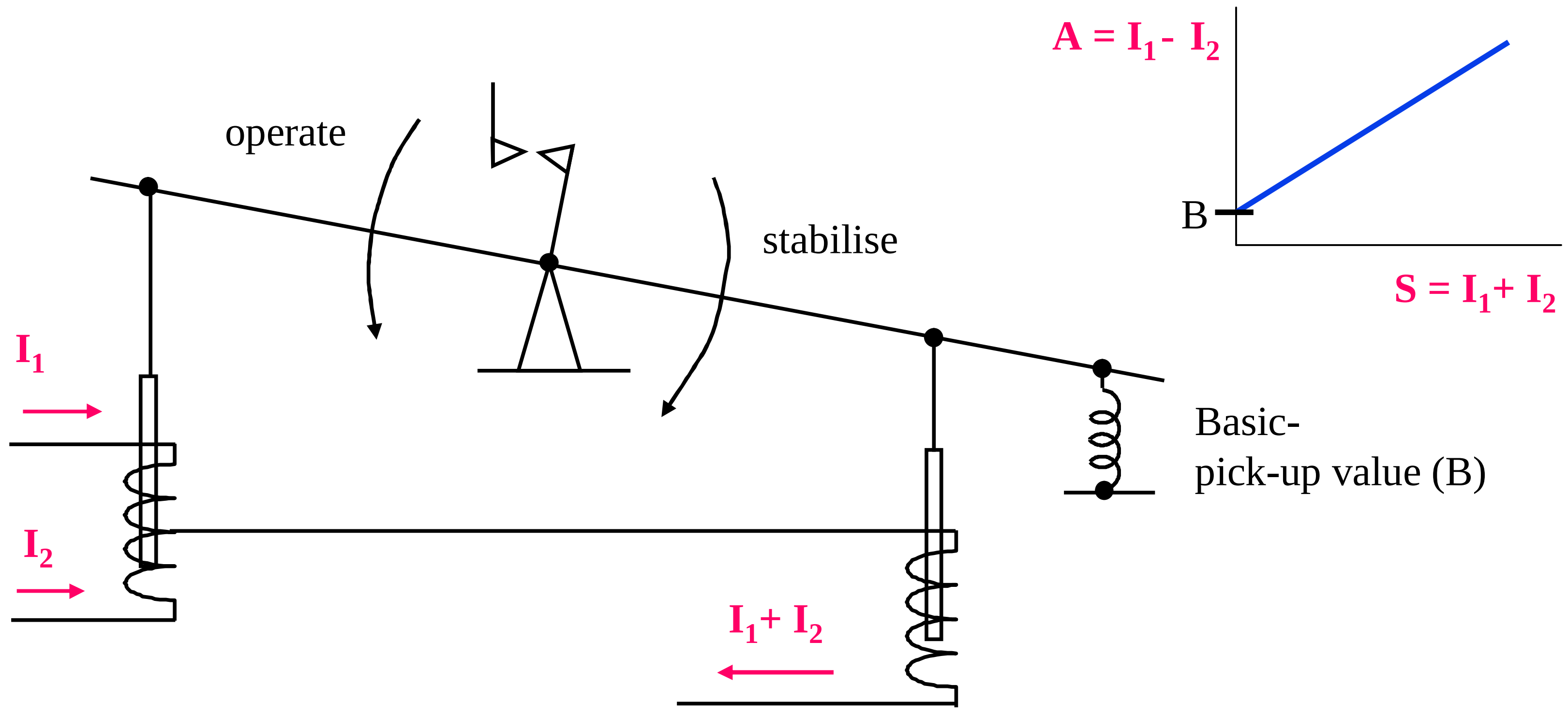
False differential currents during load or external faults

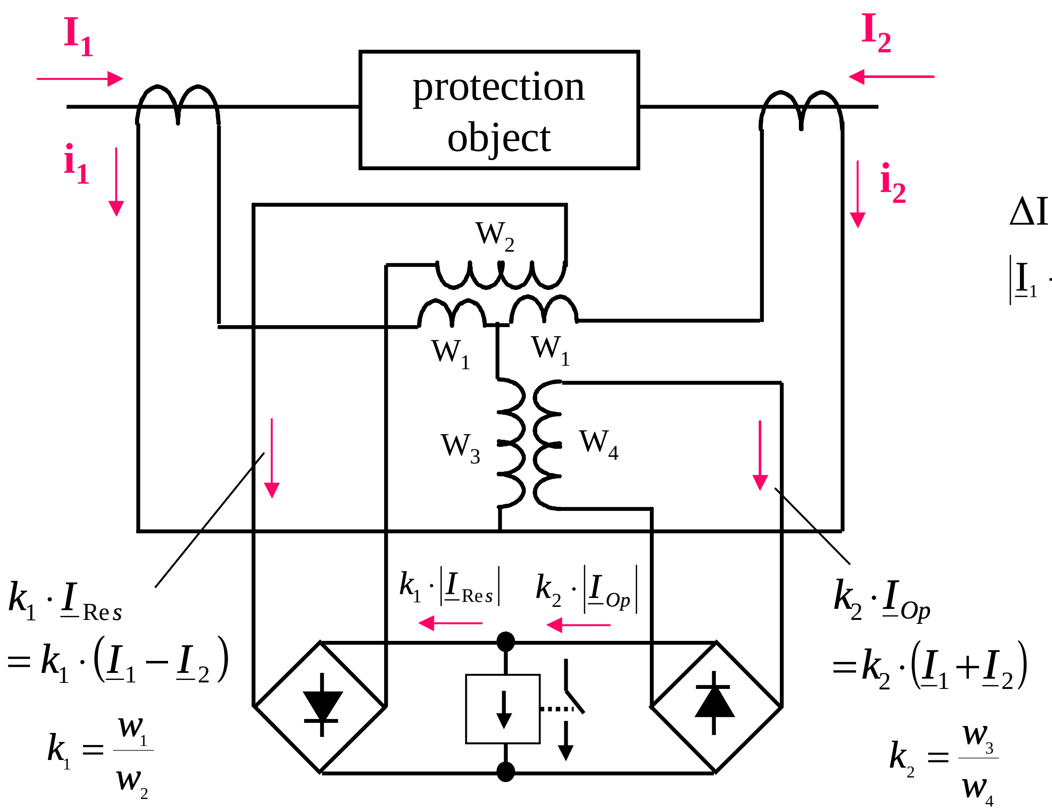


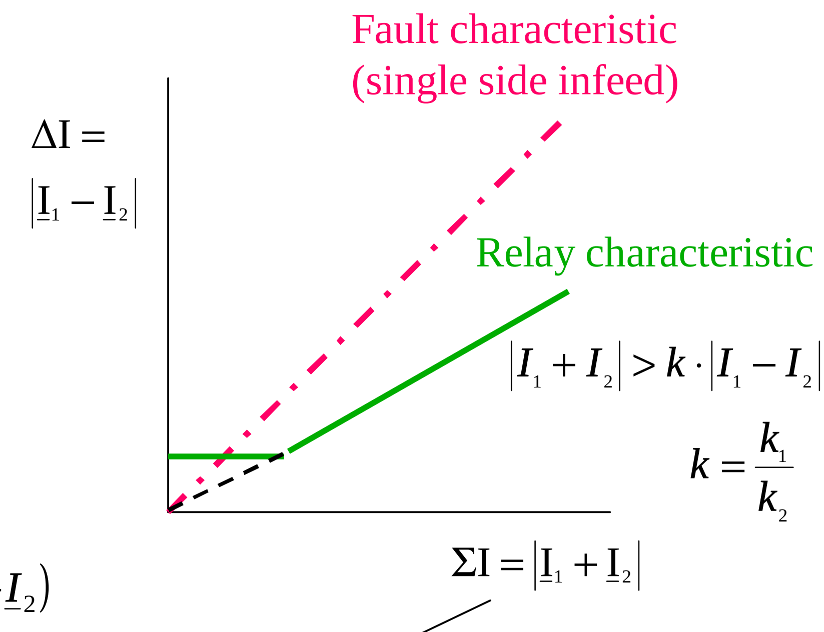
Percentage differential relay



Differential protection: analog measuring circuit

Rectifier bridge comparator with moving coil relay





with digital relays: $\Sigma I = |I_1| + |I_2|$

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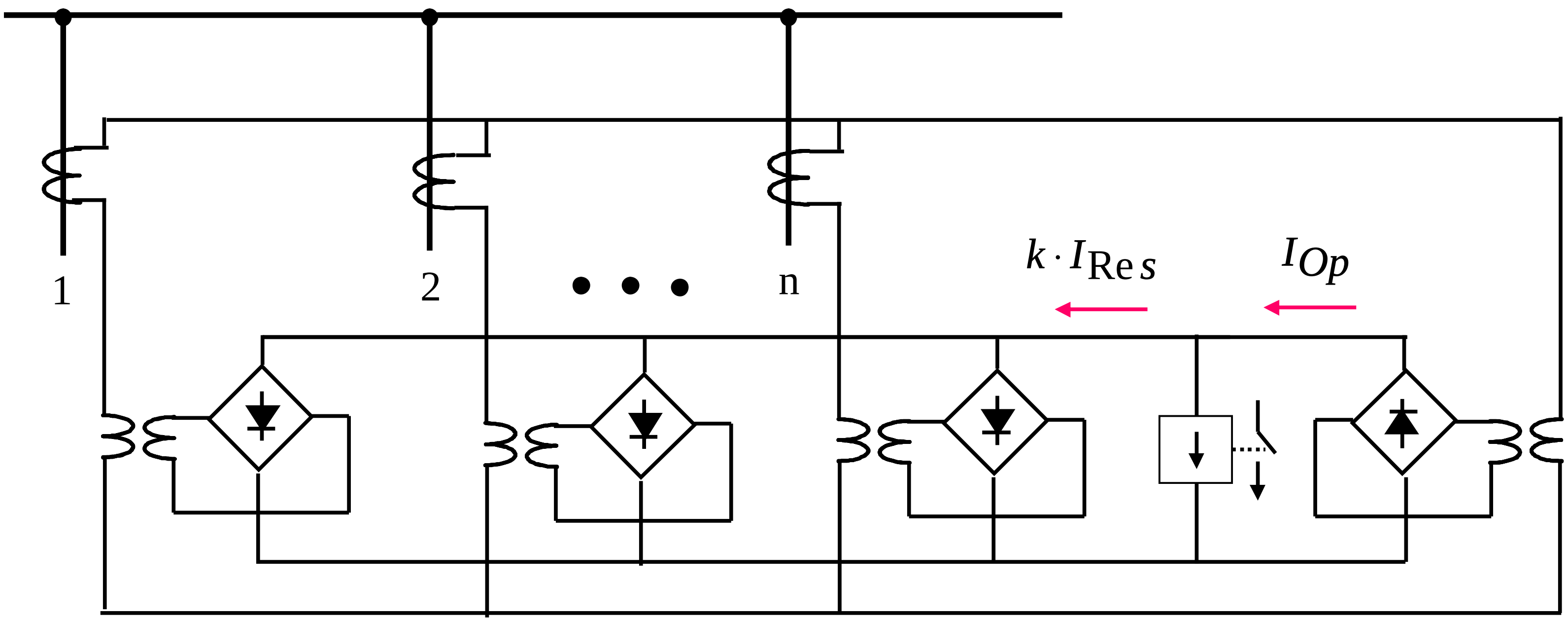
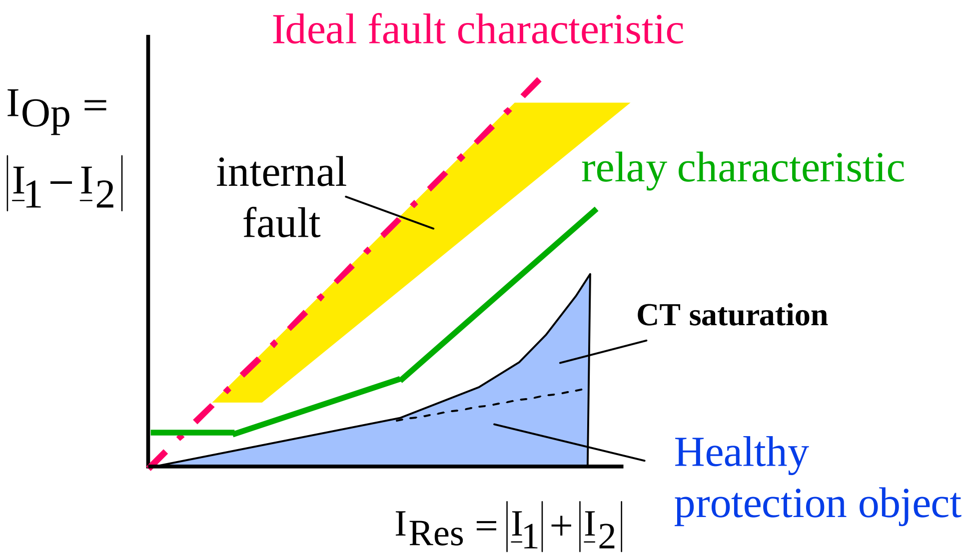
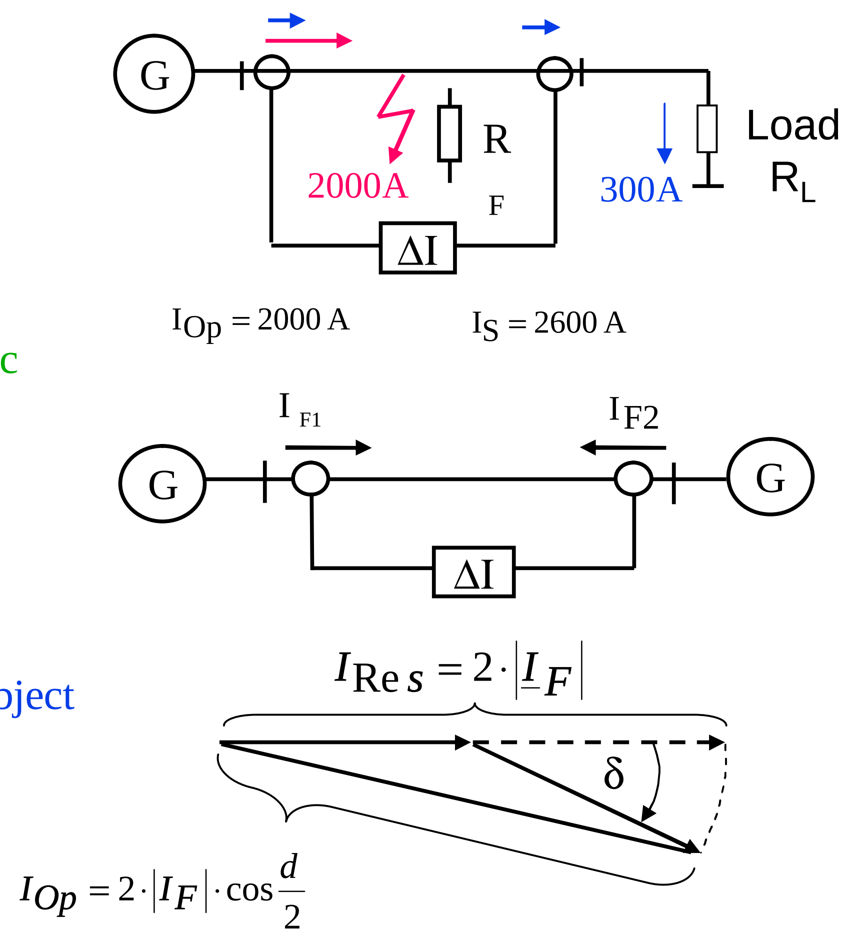
Multi-end differential protection: Analog measuring principle



$$I_{op} = \left|\underline{I}_1 + \underline{I}_2 + ... + \underline{I}_n\right| = \Sigma\left|\underline{I}\right| \qquad I_{Res} = \left|\underline{I}_1\right| + \left|\underline{I}_2\right| + ... + \left|\underline{I}_n\right| = \left|\Sigma \underline{I}\right|$$

Optimised relay characteristic





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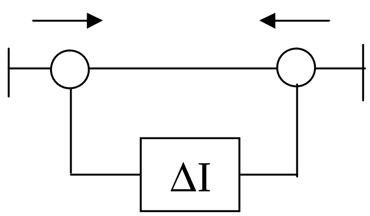
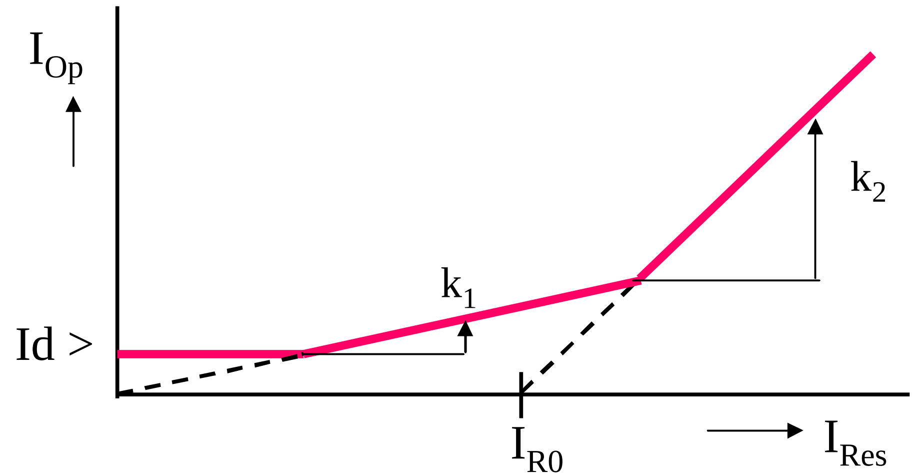
Digital differential protection: Relay characteristic

Positive current polarity





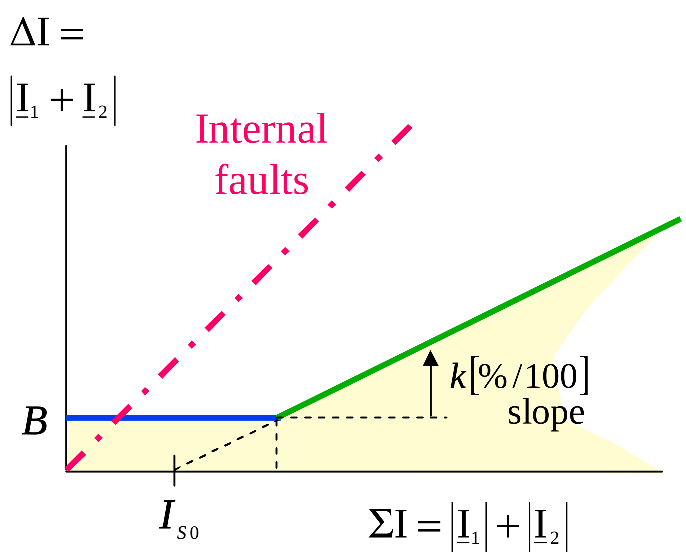
$$I_{Op} = |\Sigma I| = |\underline{I}_1 + \underline{I}_2|$$

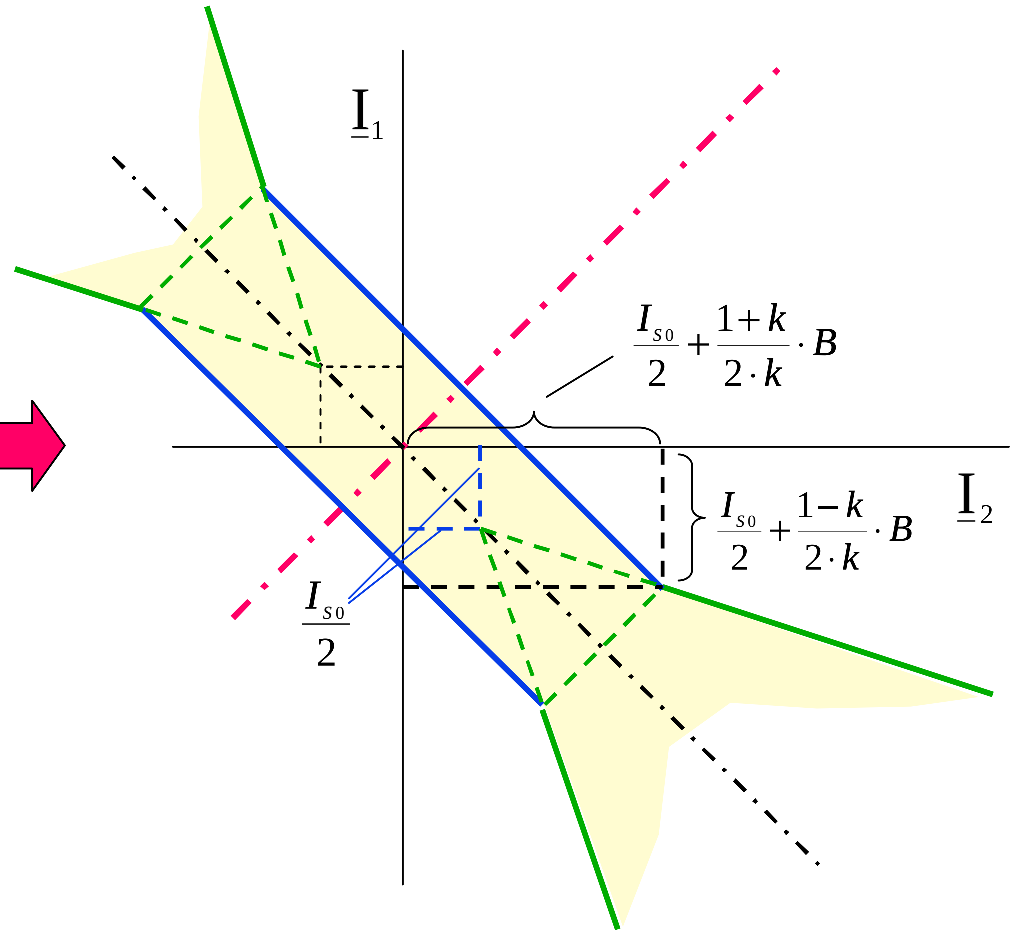
$$I_{Res} = \Sigma |I| = |\underline{I}_1| + |\underline{I}_2|$$

Settings:

- Pick-up value Id >
- slope k_1
- slope k_2 with footing point I_{R0}

$\Delta I / \Sigma I$ und I_1 / I_2 diagram





① $\left|\underline{I}_1 + \underline{I}_2\right| > k\left(\left|\underline{I}_1\right| + \left|\underline{I}_2\right| - I_{S0}\right)$

② $\left|\underline{I}_1 + \underline{I}_2\right| > B$

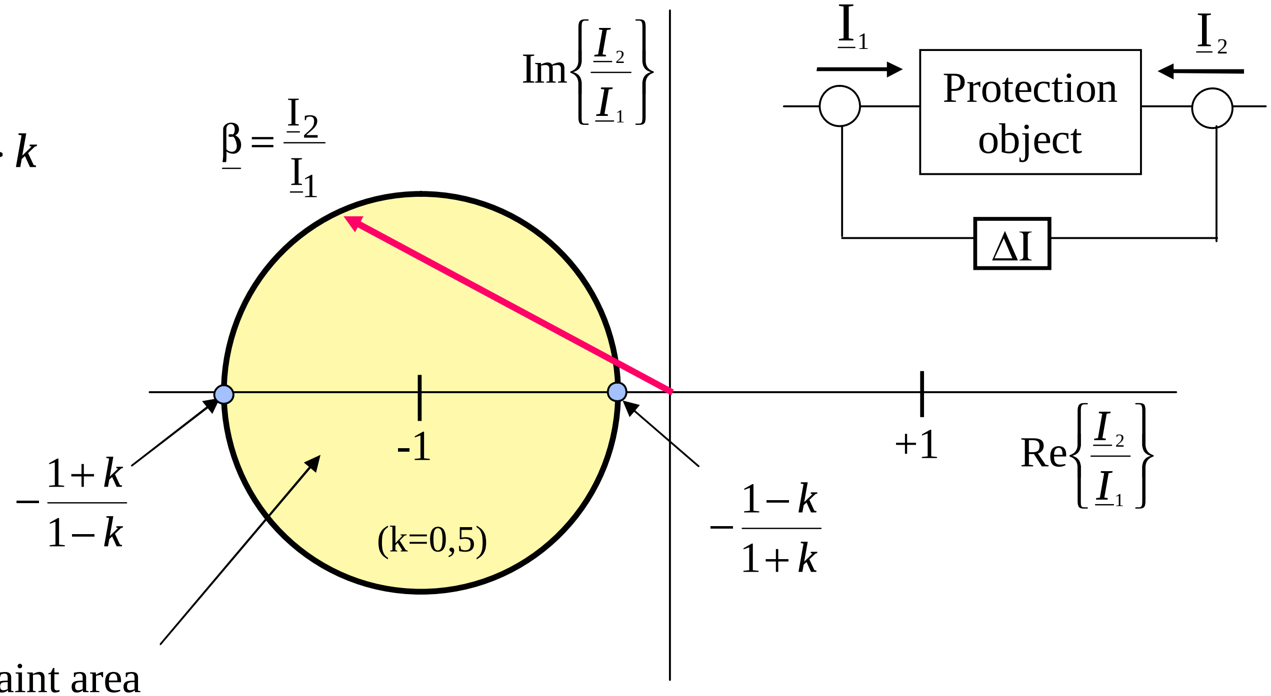
Polar diagram of differential protection

$$\left|\underline{I}_1 + \underline{I}_2\right| > k \cdot \left|\underline{I}_1 - \underline{I}_2\right|$$

$$\frac{\left|1 + \frac{\underline{I}_2}{\underline{I}_1}\right|}{\left|1 - \frac{\underline{I}_2}{\underline{I}_1}\right|} > k \quad or \quad \frac{\left|1 + \underline{\beta}\right|}{\left|1 - \underline{\beta}\right|} > k$$

$$with \ \ \underline{\beta} = \frac{\underline{I}_2}{\underline{I}_1}$$

β-Plane (remote/local current)



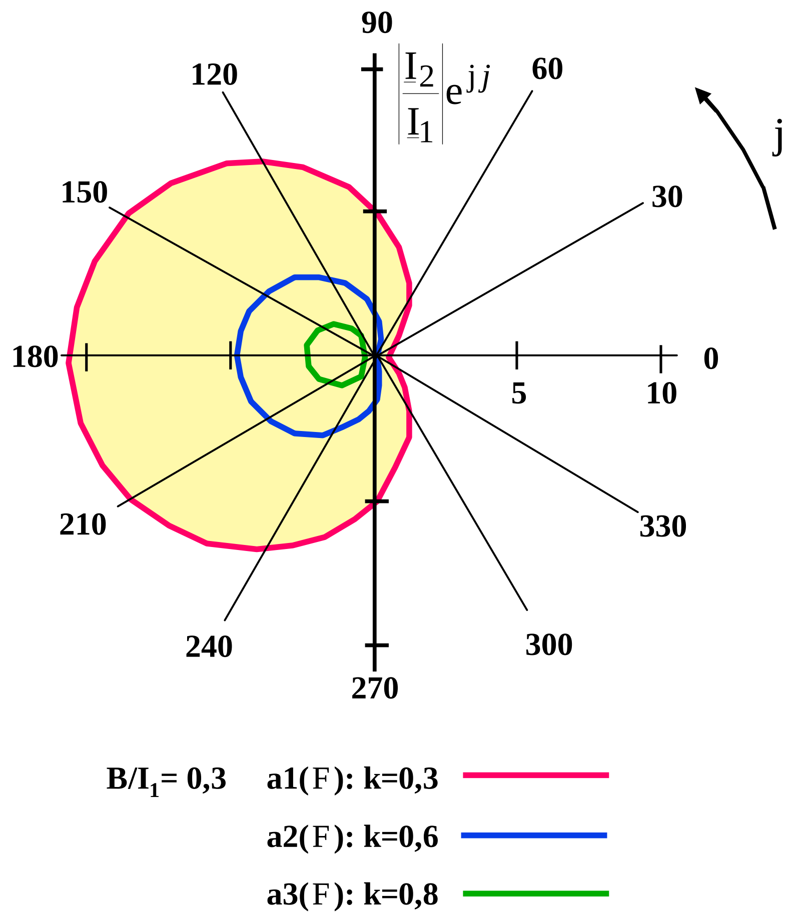
Polar diagram of digital differential protection:

Basic pick-up value B > 0

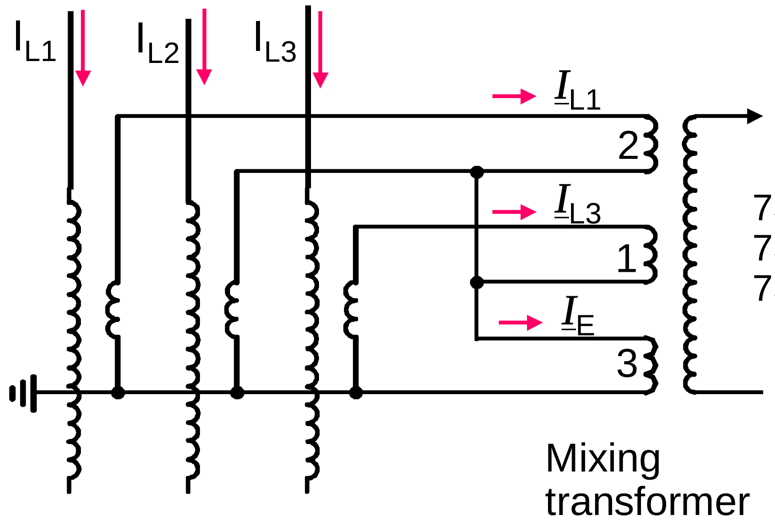
$$\left|\underline{I}_1 + \underline{I}_2\right| > k \cdot \left(\left|\underline{I}_1\right| + \left|\underline{I}_2\right|\right) + B$$

or

$$\left|1 + \frac{\underline{I}_2}{\underline{I}_1}\right| > k \cdot \left(1 + \left|\frac{\underline{I}_2}{\underline{I}_1}\right|\right) + \frac{B}{\left|\underline{I}_1\right|}$$



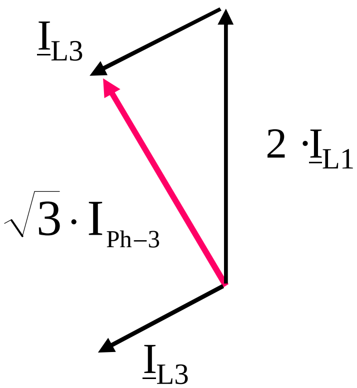
Mixing transformer of composed current differential protection

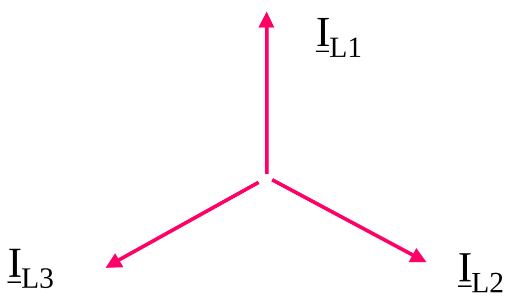


7SD503: I_M = 100 mA
7SS600: I_M = 100 mA
7SD502: I_M = 20 mA

Composed current during symmetrical 3-ph fault or load

$$I_M = \frac{1}{w} \cdot \sqrt{3} \cdot I_{Ph-3}$$





$$\underline{I}_M = 2 \cdot \underline{I}_{L1} + 1 \cdot \underline{I}_{L3} + 3 \cdot \underline{I}_E$$
$$= 5 \cdot \underline{I}_{L1} + 3 \cdot \underline{I}_{L2} + 4 \cdot \underline{I}_{L3}$$

$\Rightarrow$ composed current (vector sum)

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Mixing transformer:

Pickup sensitivity of standard connection ($I_M = 2I_{L1} + I_{L3} + 3I_E$)

Fault type	Composed current		Per unit composed current related to 3-phase symmetrical current
L1-E	$I_{ML1-E} = 5\ I_{L1}$	$I_{L2} = I_{L3} = 0$	$I_{ML1-E} / I_M = 5 / \sqrt{3} = 2.9$
L2-E	$I_{ML2-E} = 3\ I_{L2}$	$I_{L1} = I_{L3} = 0$	$I_{ML2-E} / I_M = 3 / \sqrt{3} = 1.73$
L3-E	$I_{ML3-E} = 4\ I_{L3}$	$I_{L1} = I_{L2} = 0$	$I_{ML3-E} / I_M = 4 / \sqrt{3} = 2.3$
L1-L2	$I_{ML12} = 5\ I_{L1} + 3\ I_{L2}$	$I_{L3} = 0$	$I_{ML12} / I_M = 2 / \sqrt{3} = 1.15$
L2-L3	$I_{ML23} = 3\ I_{L2} + 4\ I_{L3}$	$I_{L1} = 0$	$I_{ML23} / I_M = 1 / \sqrt{3} = 0.58$
L1-L3	$I_{ML13} = 5\ I_{L1} + 4\ I_{L3}$	$I_{L2} = 0$	$I_{ML13} / I_M = 1 / \sqrt{3} = 0.58$
L1-L2-L3	$I_{ML123} = 5\ I_{L1} + 3I_{L2} + 4I_{L3}$	$\lvert I_{L1}\rvert = \lvert I_{L2}\rvert = \lvert I_{L3}\rvert$	$I_{ML123} / I_M = \sqrt{3} / \sqrt{3} = 1$

Highest sensitivity

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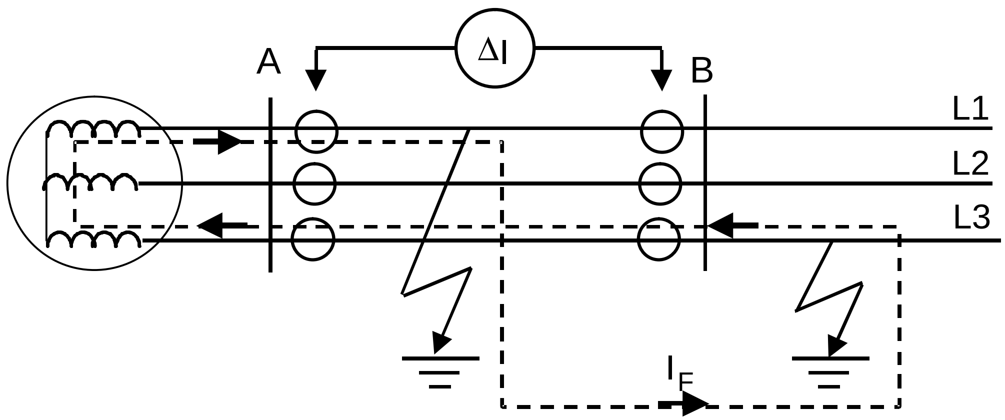
Composed current differential protection
Behaviour during cross country fault (isolated/compensated network)



L1 internal und L3 external:

$I_{M-A} = 5 \cdot I_F - 4 \cdot I_F = 1 \cdot I_F$ und $I_{M-B} = +4 \cdot I_F$

$\Delta I = |I_{M-A} + I_{M-B}| = 5 I_F$ und $\Sigma I = |I_{M-A}| + |I_{M-B}| = 5 \cdot I_F$

$\Delta I / \Sigma I = 5/5 = 1.0$

} Tripping

L2 internal, L3 external

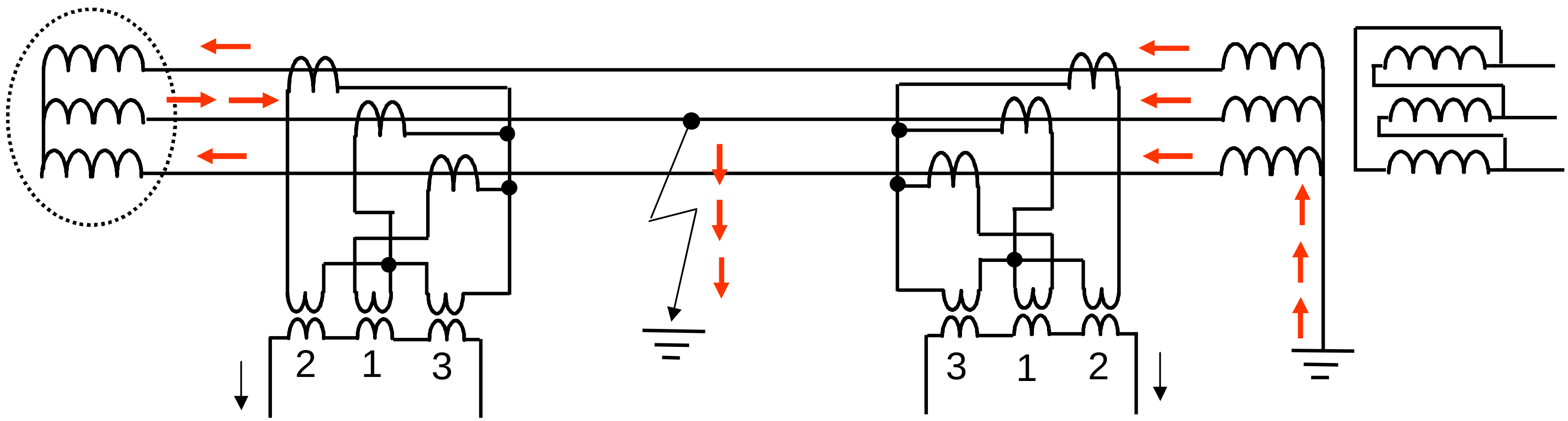
$I_{M-A} = -1 \cdot I_F$ und $I_{M-B} = +4 \cdot I_F$

$\Delta I = |I_{M-A} + I_{M-B}| = 3 \cdot I_F$ und $\Sigma I = |I_{M-A}| + |I_{M-B}| = 5 \cdot I_F$

$\Delta I / \Sigma I = 3/5 = 0.6$

} Tripping if k-setting < 0.6

Composed current differential protection
Through current stabilisation with unsymmetrical earthing conditions



$I_{M1} = 2 \cdot I_{L1} + 1 \cdot I_{L3} + 3 \cdot I_E$
$= 2 \cdot (-I_F) + 1 \cdot (-I_F) + 3 \cdot 0 = -3 \cdot I_F$

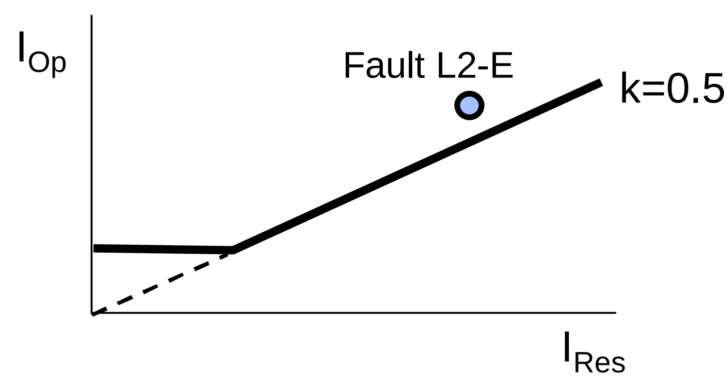
$I_{M2} = 2 \cdot I_{L1} + 1 \cdot I_{L3} + 3 \cdot I_E$
$= 2 \cdot I_F + 1 \cdot I_F + 3 \cdot 3 I_F = +12 \cdot I_F$

$I_{Op} = |\, I_{M1} + I_{M2} \,| = 9 \cdot I_F$
$I_{Res} = |I_{M1}| + |I_{M2}| = 15 \cdot I_F$ } k=9/15 = 0.6

Faults in other phases:

Fault L1-E: $I_{Op} = (3+12) \cdot I_F = 15 \cdot I_F$,
$I_{Res} = (3+12) \cdot I_F = 15 \cdot I_F$, } k=1

Fault L3-E: $I_{Op} = (0+12) \cdot I_F = 12 \cdot I_F$,
$I_{Res} = (0+12) \cdot I_F = 12 \cdot I_F$, } k=1



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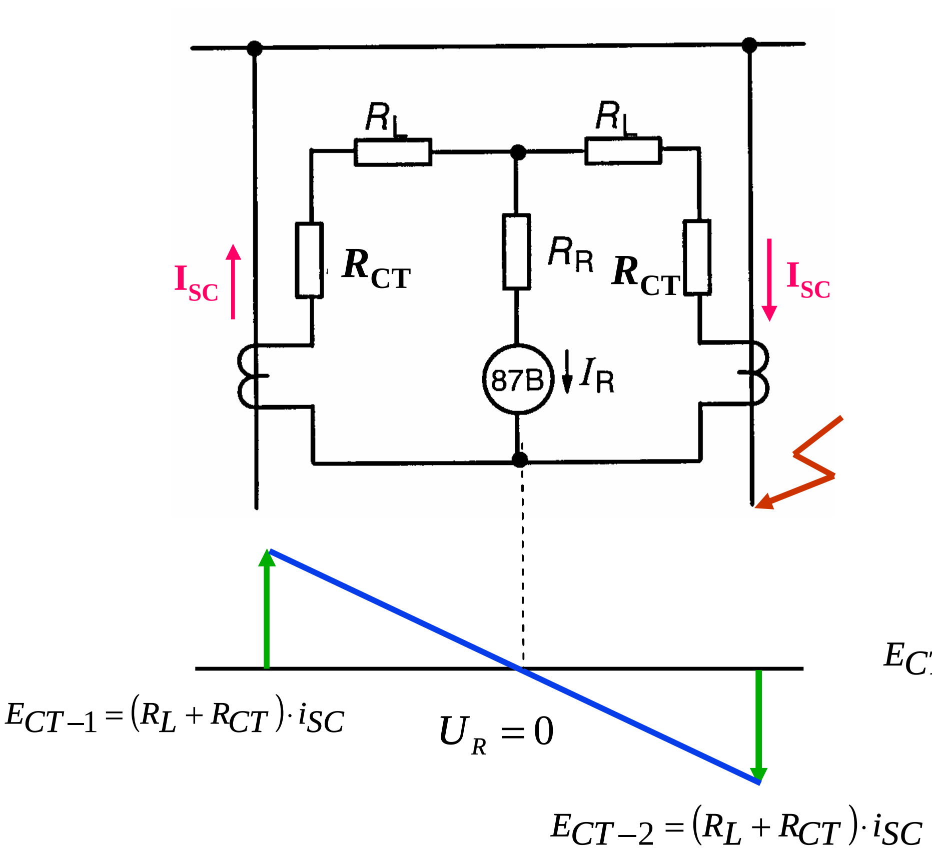
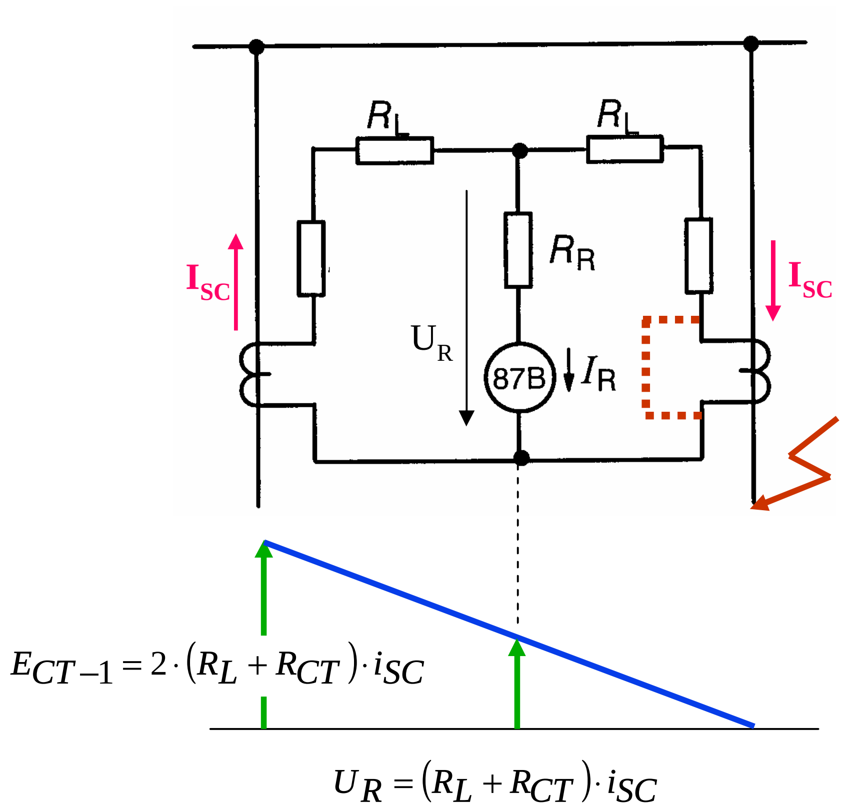
High impedance differential protection: Principle

Behaviour during external fault

with ideal current transformers



with CT saturation



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High impedance differential protection: Calculation example (busbar protection)

Given: n = 8 feeders
r_{CT} = 600/1 A
U_{KN} = 500 V
R_{CT} = 4 Ohm
I_{mR} = 30 mA (at relay pick-up value)

R_L= 3 Ohm (max.)
$I_{R\text{-pick-up.}}$= 20 mA (fixed value)

R_R = 10 kOhm
I_{var} = 50 mA (at relay pick-up value)

Pick-up sensitivity:

$$I_{F-\min} = r_{CT} \cdot \left(I_{R-pick-up} + I_{Var} + n \cdot I_{mR}\right)$$

$$I_{F-\min} = \frac{600}{1} \cdot (0.02 + 0.05 + 8 \cdot 0.03)$$

$$I_{F-\min} = 186 A \cdot (31\%)$$

Stability:

$$I_{F-through-\max} < r_{CT} \cdot \frac{R_R}{R_L + R_{SW}} \cdot I_{R-pick-up}$$

$$I_{F-throuh-\max} < \frac{600}{1} \cdot \frac{10{,}000}{3+4} \cdot 0.02$$

$$I_{F-through-\max} < 17kA = 28 \cdot I_n$$

Digital Differential Protection

Measuring Technique

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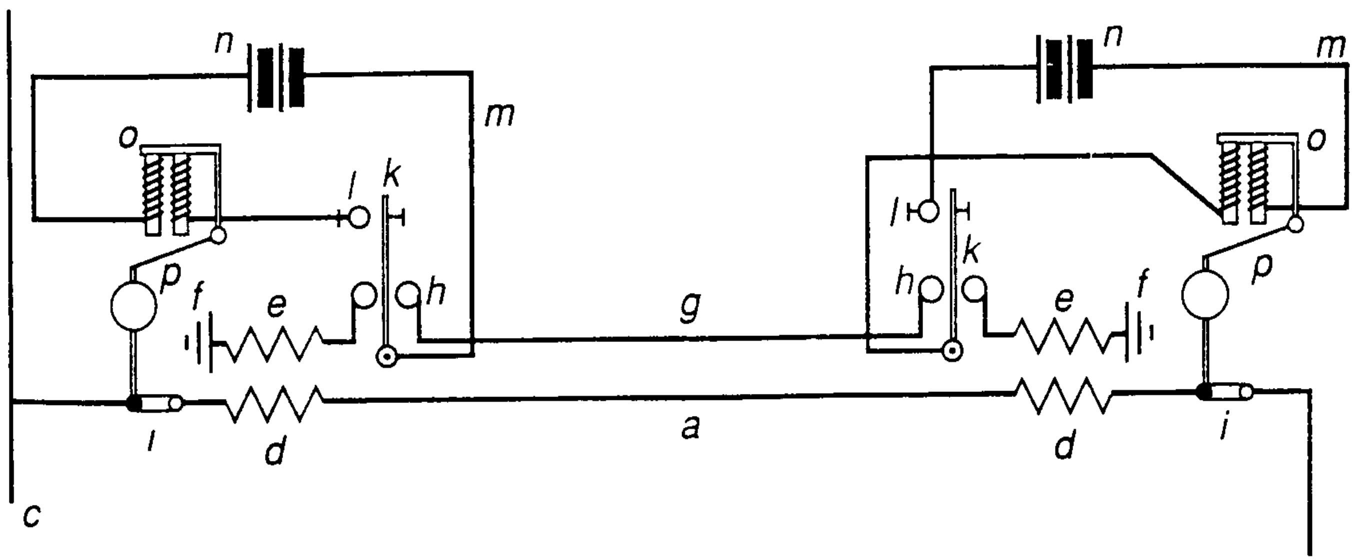
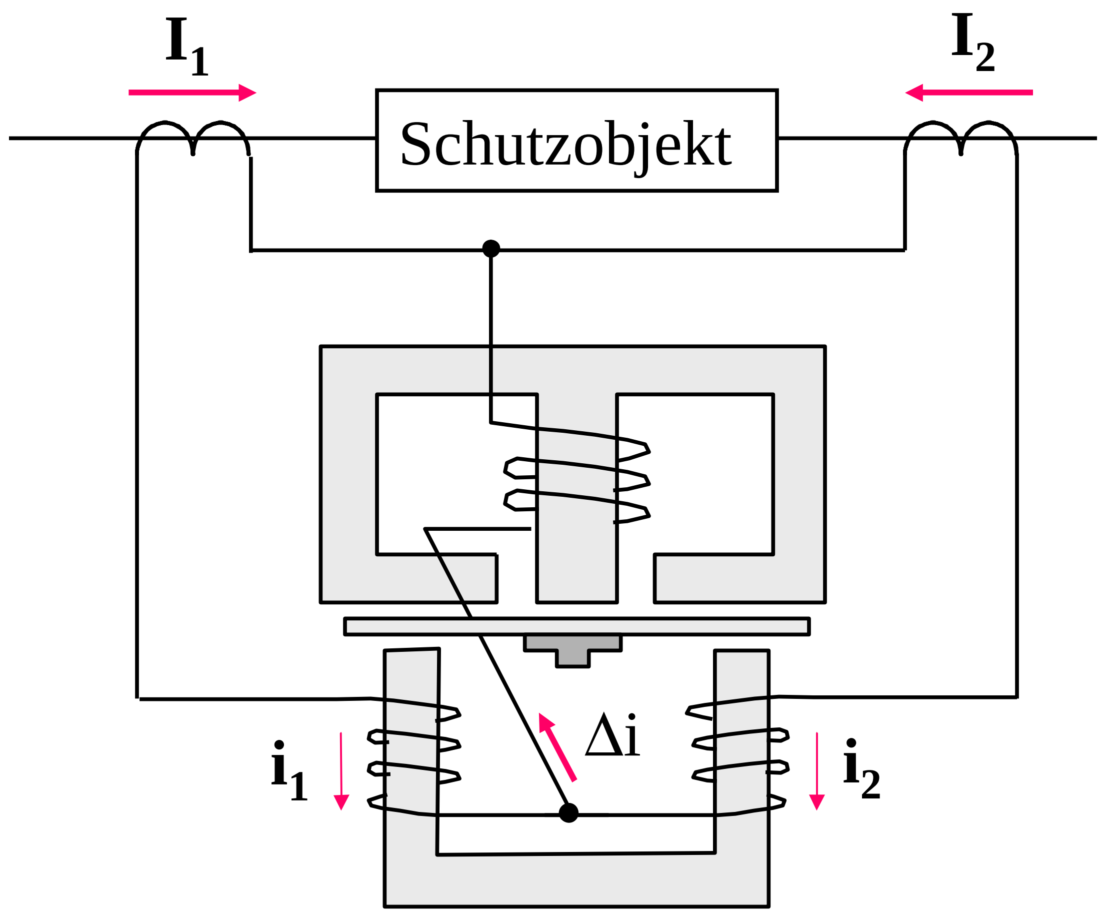
Merz and Price differential protection

Patent dated 1904



a: feeder, b: generator, c: substation, d: primary winding of CT, e: secondary winding of CT, f: earth or return conductor, g: pilot wire, h: relay windings, i: circuit breakers, k,l: movable and fixed relay contacts, m: circuit, n: battery, o: electromagnetic device with armature p.

Electro-mechanical differential protection based on induction relay



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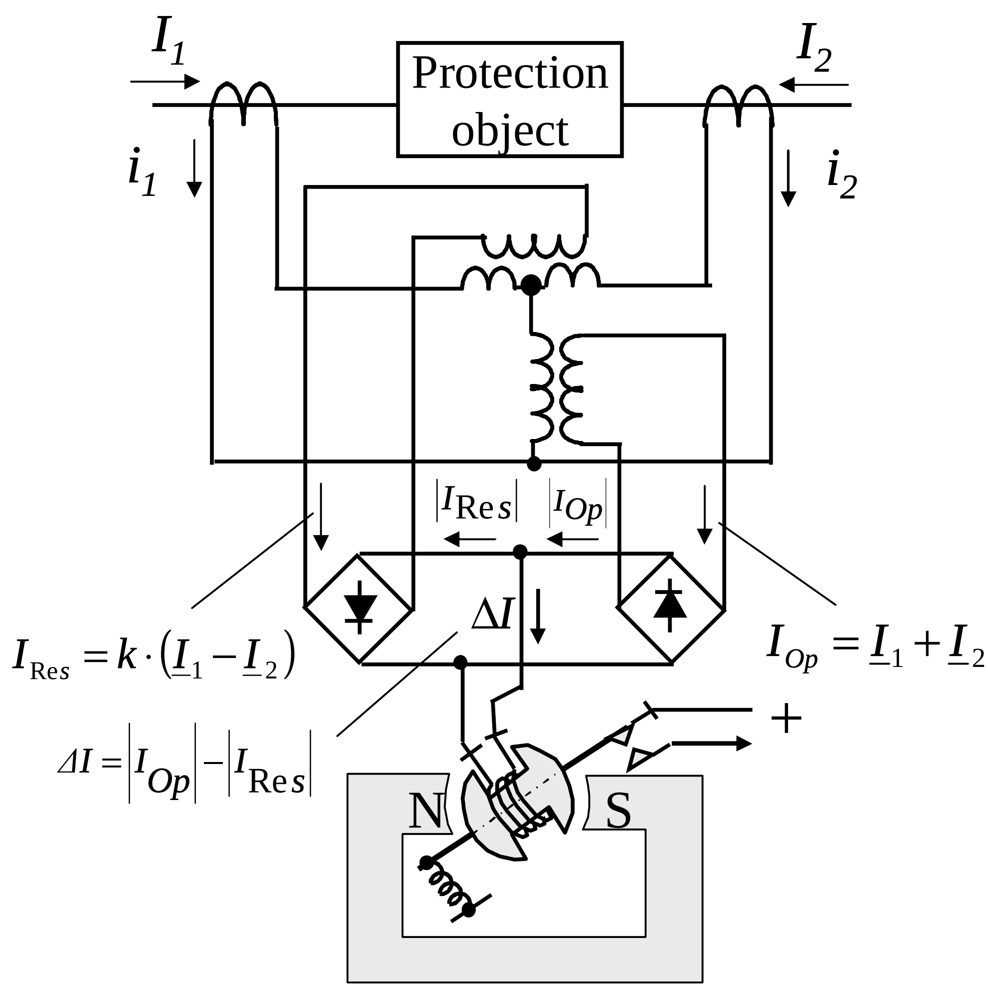
Electro-mechanical differential protection
Rectifier bridge comparator with moving coil relay



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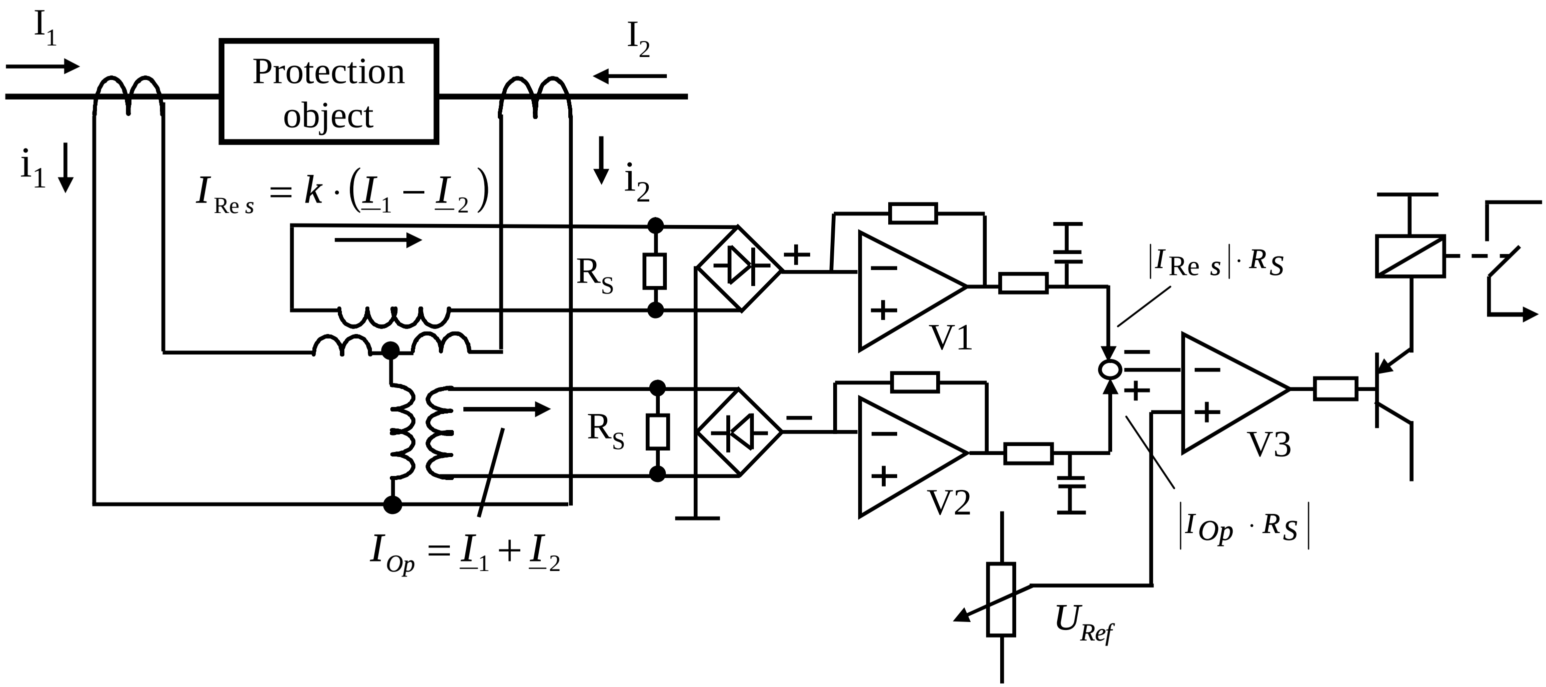
Differential protection
Analog static measuring circuit



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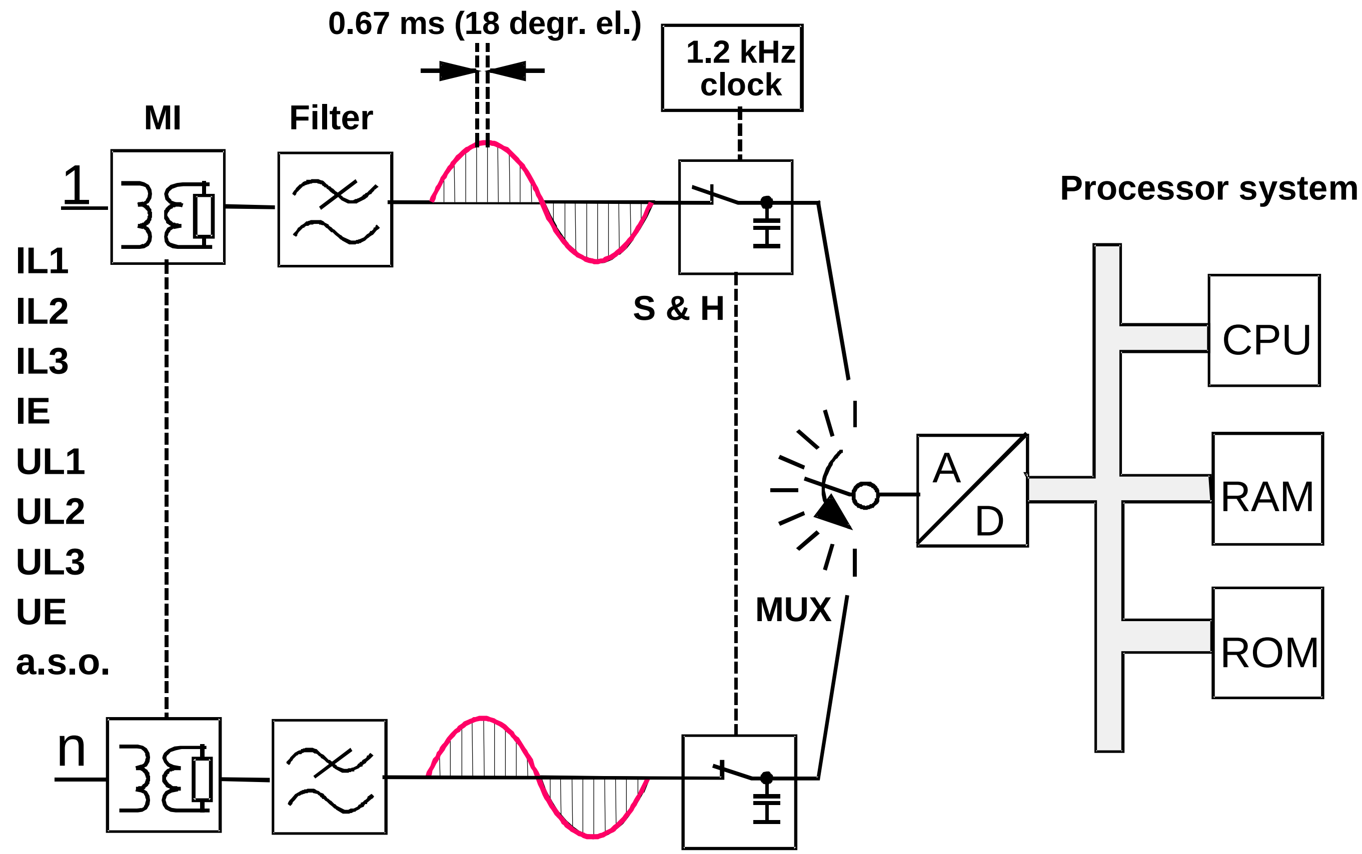
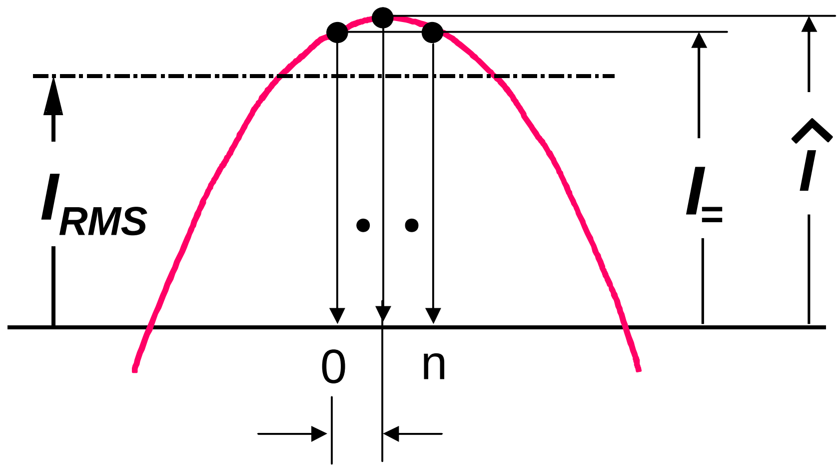
Digital differential protection
Measuring value acquisition and processing



Digital protection:
Measurement based on momentary values



$\Delta T_{samp.}$ corresponds to $\Delta\varphi$ (60Hz: 0.67 ms = 18^{O} el.)

$$\hat{I} = \frac{I_{=}}{\cos\left(\frac{n-1}{2} \cdot \Delta j\right)}$$

when n sampled values exceed the pick-up limit $I_{=}$

$$I_{RMS} = \frac{\hat{I}}{\sqrt{2}}$$

$$\Delta j = w \cdot \Delta T_{samp.} = \frac{f_N}{f_A} \cdot 360^{O}$$

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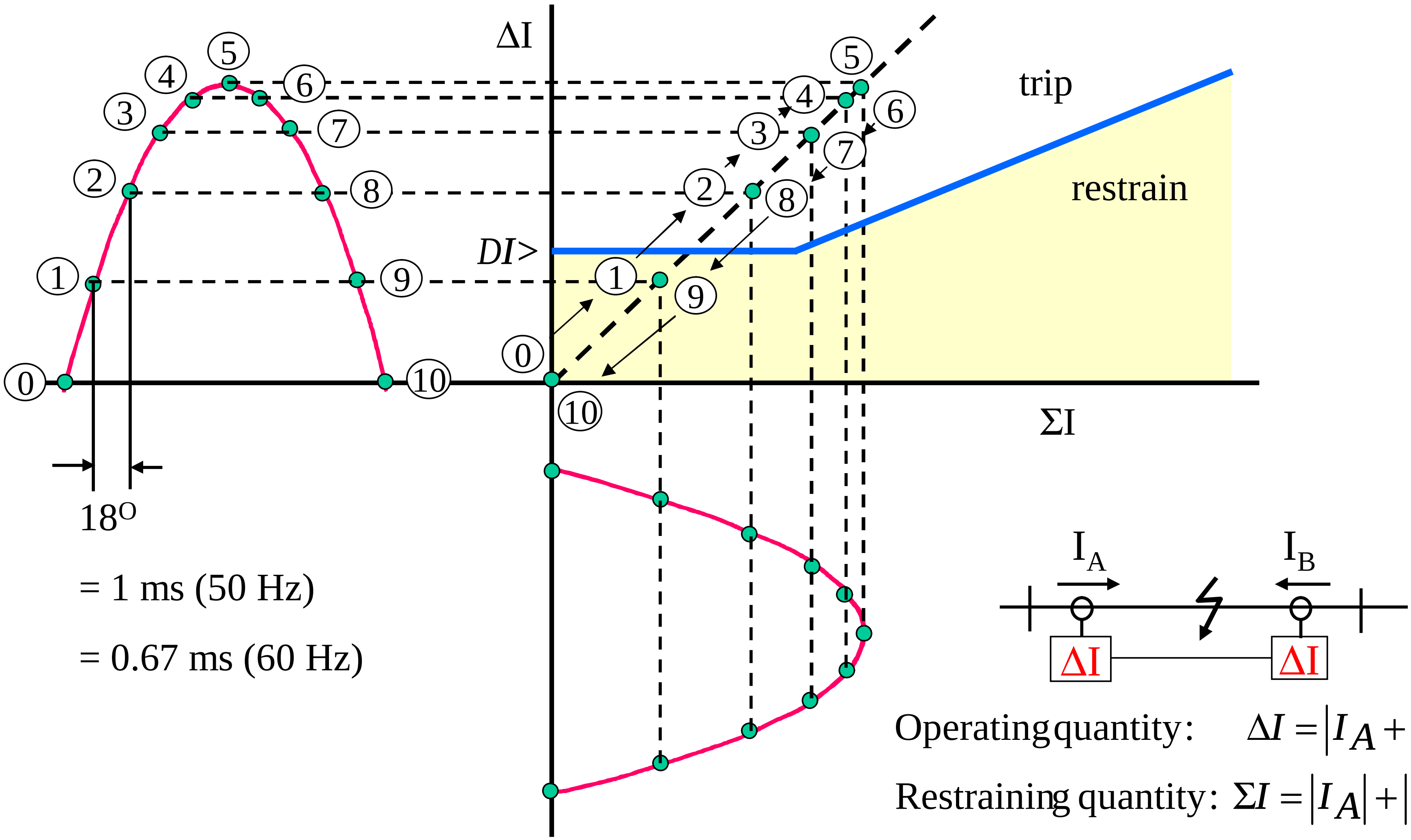
Digital differential protection: Measurement based on momentary values



= 1 ms (50 Hz)

= 0.67 ms (60 Hz)

Operating quantity: $\Delta I = |I_A + I_B|$

Restraining quantity: $\Sigma I = |I_A| + |I_B|$

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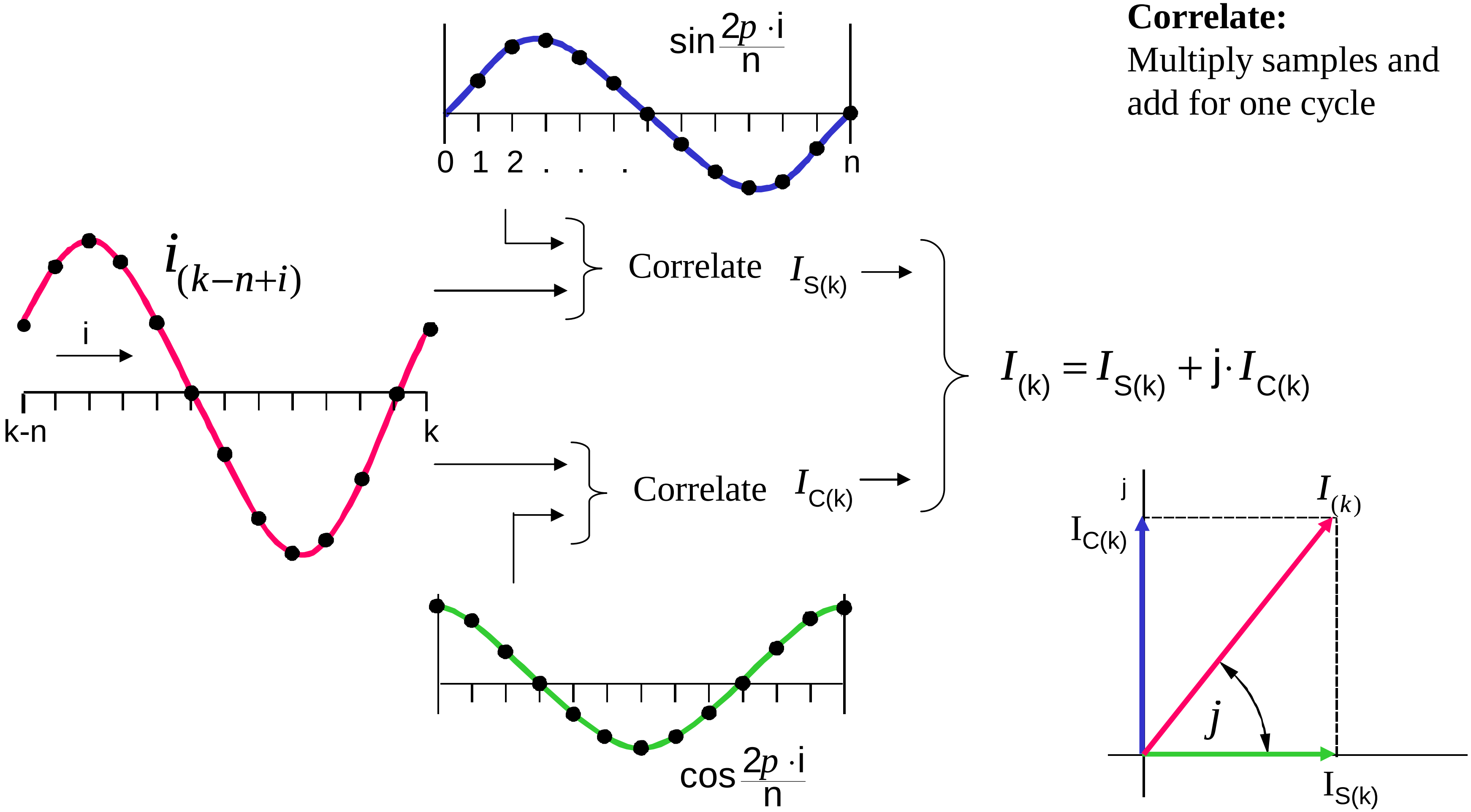
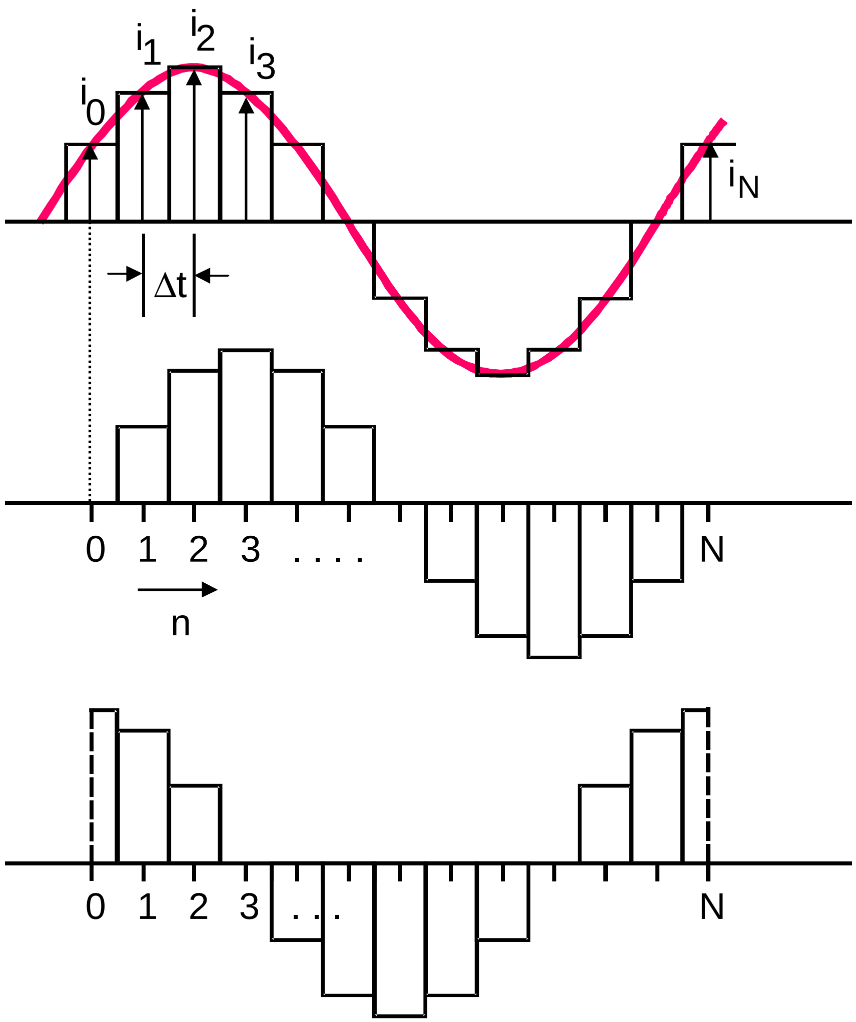
Discrete Fourier-Transformation (Principle)

Correlate:
Multiply samples and add for one cycle



Discrete Fourier-Transformation (calculation formulae)



$$I_S = \frac{2}{N}\left[\sum_{n=1}^{N-1} \sin(\omega \cdot n \cdot \Delta t)\, i_n\right]$$

$$I_C = \frac{2}{N}\left[\frac{i_0}{2} + \frac{i_N}{2} + \sum_{n=1}^{N-1} \cos(\omega \cdot n \cdot \Delta t)\, i_n\right]$$

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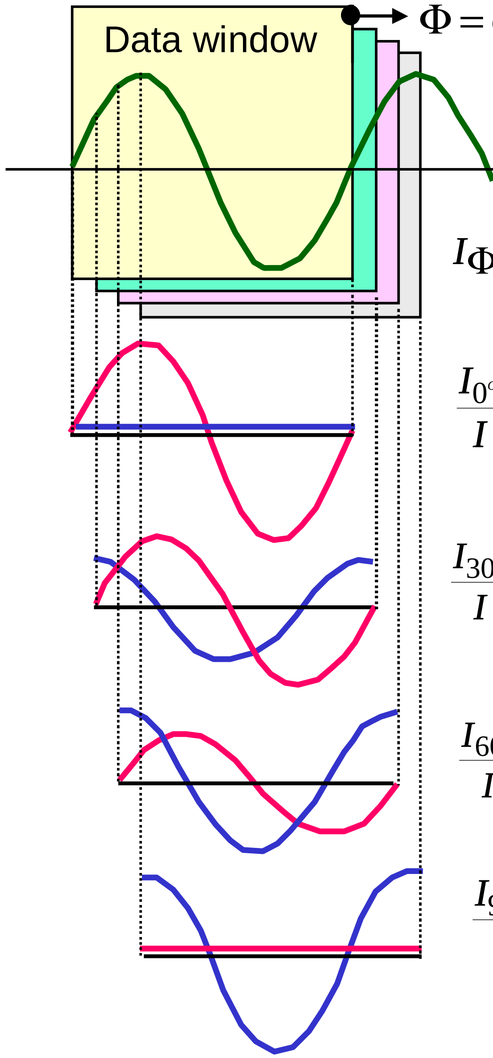
Orthogonal components of a current phasor dependent on the position of the data window



$$I_\Phi = I_S + j \cdot I_C$$

$$\frac{I_{0^o}}{I} = 1 + j \cdot 0$$

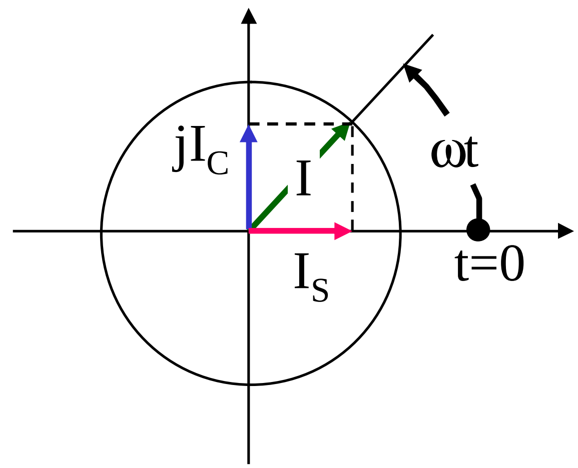
$$\frac{I_{30^o}}{I} = \frac{\sqrt{3}}{2} + j \cdot \frac{1}{2}$$

$$\frac{I_{60^o}}{I} = \frac{1}{2} + j \cdot \frac{\sqrt{3}}{2}$$

$$\frac{I_{90^o}}{I} = 0 + j \cdot 1$$

$$I_S = \frac{1}{2p} \cdot \int_{\Phi-360^o}^{\Phi} I(w \cdot t) \cdot \sin wt \cdot dt$$

$$I_C = \frac{1}{2p} \cdot \int_{\Phi-360^o}^{\Phi} I(w \cdot t) \cdot \cos wt \cdot dt$$



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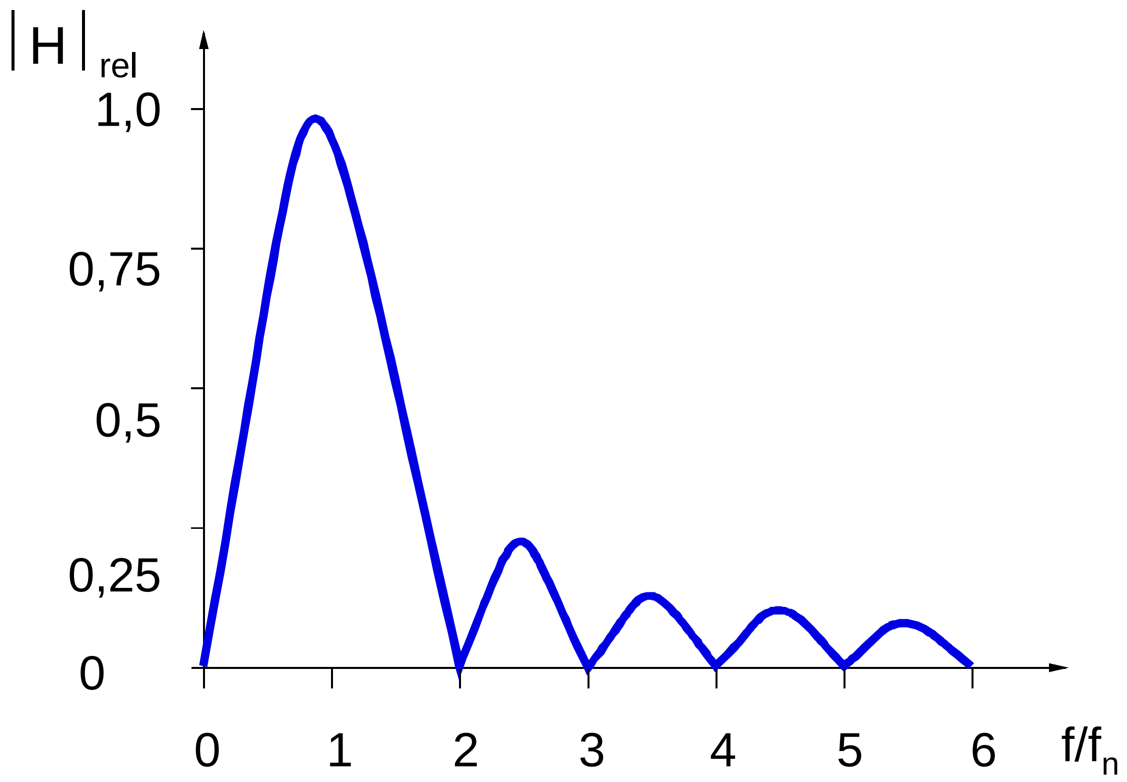
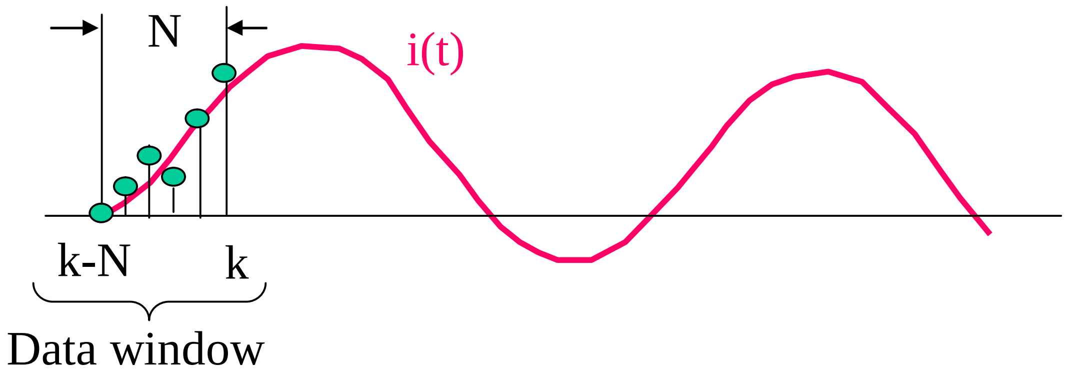
Transfer function of a one cycle Fourier-filter



Digital protection
Fast current phasor estimation



$$i_{(t)} = A \cdot sin(\omega t) + B \cdot \left(cos(\omega t) - e^{-\frac{t}{\tau}} \right) + C \cdot cos(\omega t)$$

Task: Estimation of the coefficients A, B, C on basis of measured currents and voltages

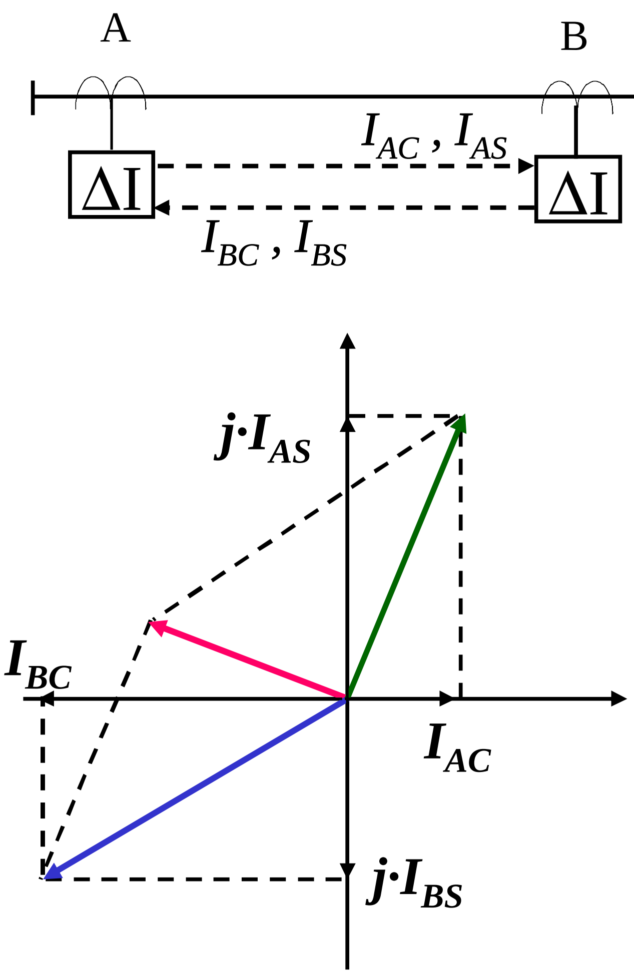
Method: Gauß's *Minimization of error squares:*

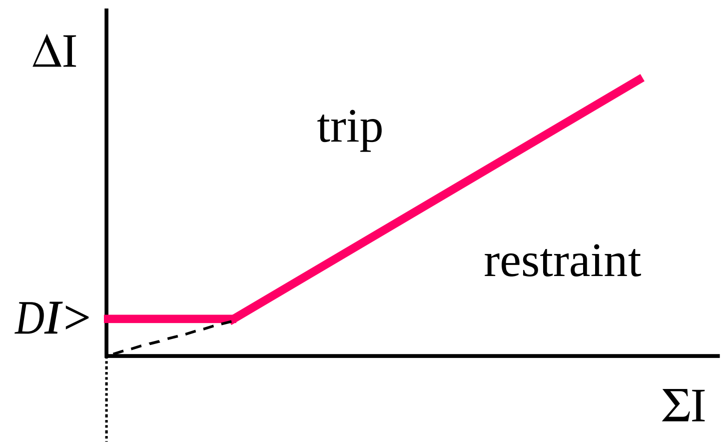
$$Delta = \sum_{n=k-N}^{k} \left(i_{(n \cdot \Delta T)} - f_{(n)} \right)^2 \Rightarrow MIN$$

sampled values

Delta = quality value
k = sampling number
N = length of data window
n = variable
ΔT = sampling interval

Differential protection with phasors (principle)





Operating quantity : $\Delta I = \left| I_A + I_B \right|$

Restrainin g quantity : $\Sigma I = \left| I_A \right| + \left| I_B \right|$

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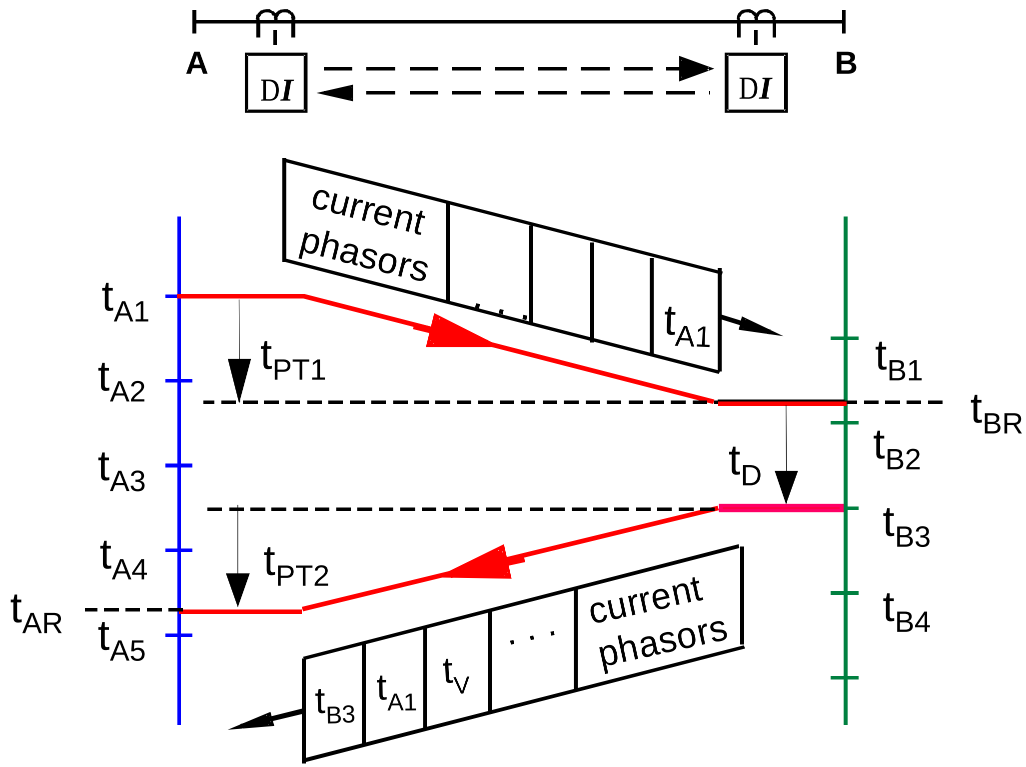
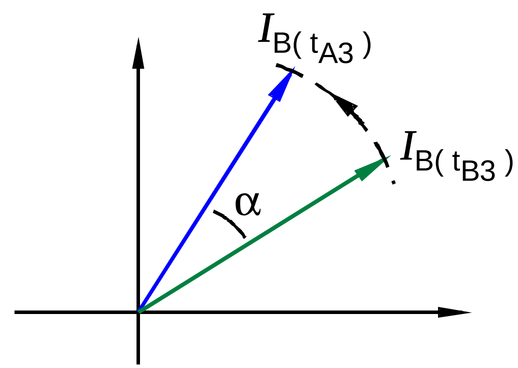
Digital line differential protection
Synchronisation of phasors (ping-pong time alignment)





$$\alpha = \frac{t_{B3} - t_{A3}}{T_P} \cdot 360°$$

Signal transmission time: $t_{PT1} = t_{PT2} = \frac{1}{2}\left(t_{A1} - t_{AR} - t_D\right)$

Sampling instant: $t_{B3} = t_{A3} - t_{PT2}$

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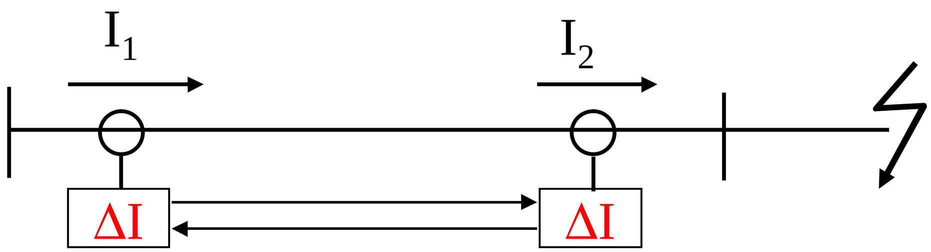
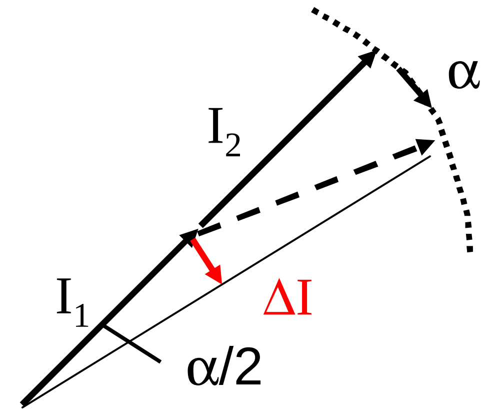
Split path data transmission
Impact of unsymmetrical propagation time





$$\Delta I = I \cdot \sin\frac{\alpha}{2} = I \cdot \sin\frac{\Delta T[\text{ms}] \cdot \frac{180^o}{10\text{ms}}}{2}$$

Example:

Transmit channel time 3 ms
Receive channel time 4.2 ms
→ time difference Δ = 1.2 ms

$$\Delta I = I \cdot \sin\frac{1.2\text{ms} \cdot \frac{180^o}{10\text{ms}}}{2} = I \cdot 0.19$$

ΔI = 19%!

To keep the false differential current below about 2 to 5%, the propagation time difference should not exceed about 0.1 to 0.25 ms!

Otherwise:
→ more insensitive relay setting
→ or GPS synchronisation

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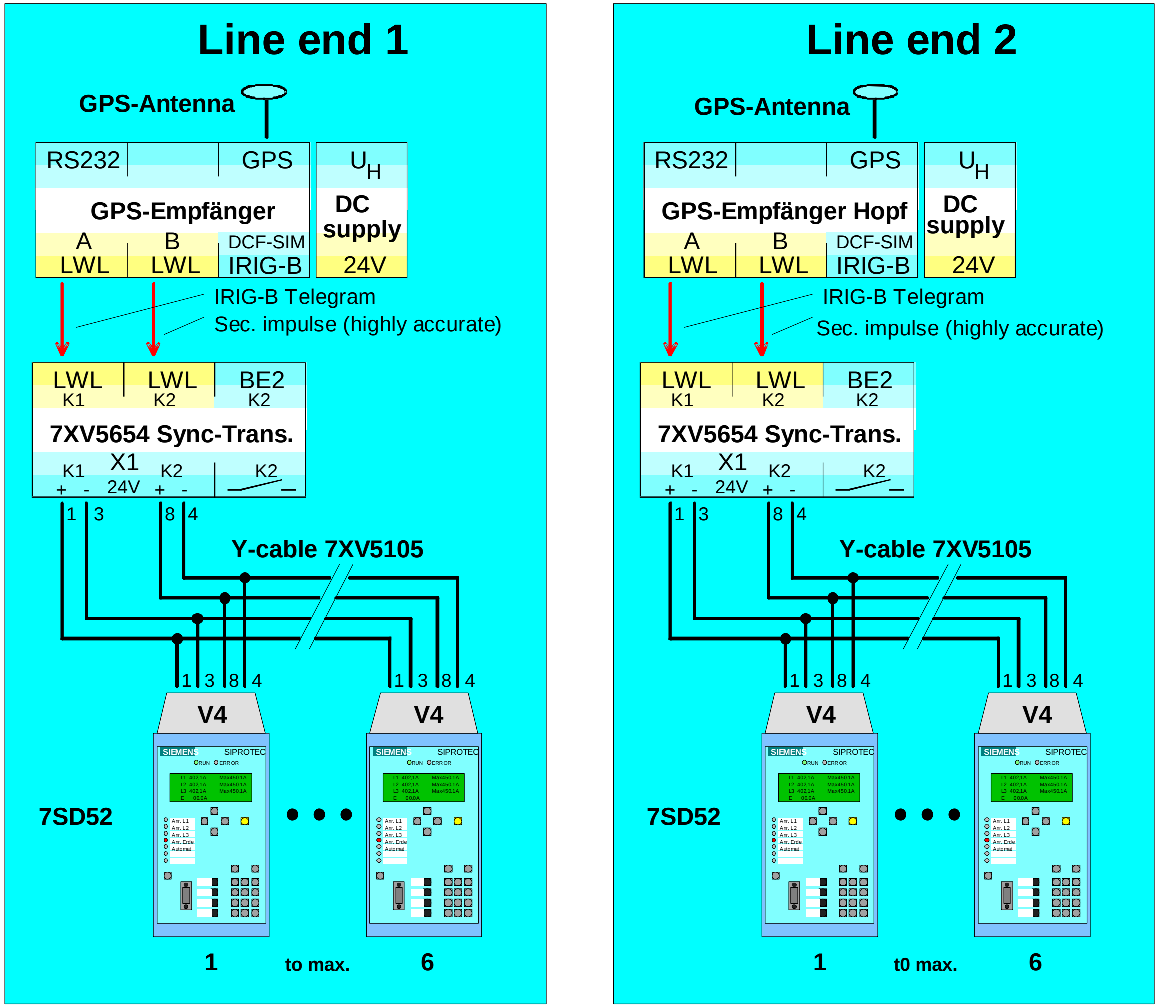
Synchronisation of Differential relays via GPS



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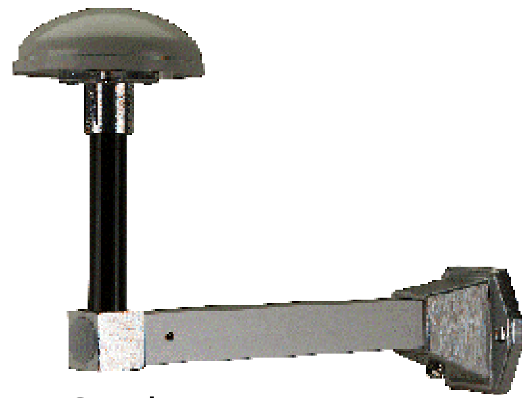
Devices for GPS time synchronisation

- GPS receiver with 2 optical outputs (7XV5664-0AA00).
  Output for IRIB-B telegram and output for second/ minute pulse
- Galvanic separation between the receiver and the tranceiver 7XV5654
- Optic/electric signal conversion in the tranceiver
- Distribution of the electrical signals via Y-bus cable to port A of the relays (telegram)
- Electronic contact for the minute pulse in case of synchronisation through binary input with battery voltage

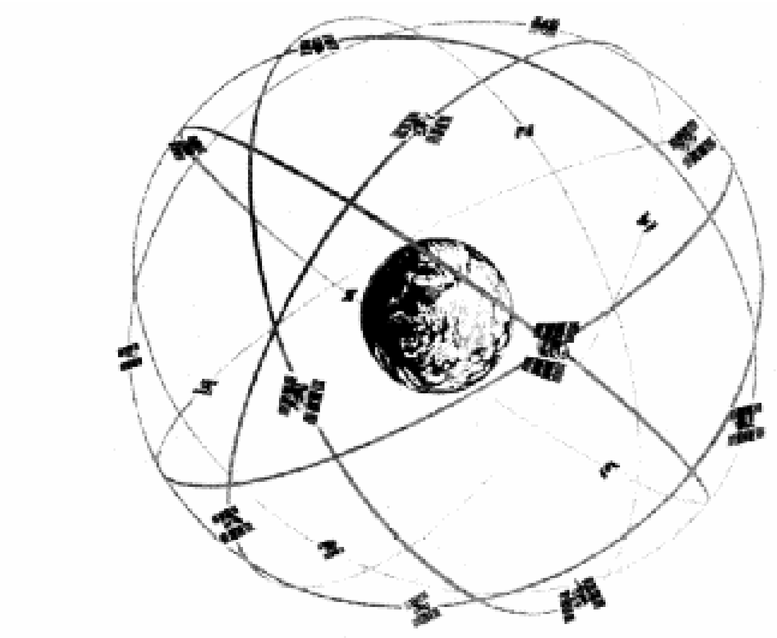


Outdoor antenna
FG4490G10 for GPS

GPS receiver
7XV5664

Tranceiver
7XV5654

Additional components for SICAM SAS
GPS-System



- 24 satellites move in a height of 20 000km on 6 different paths
- Transmission frequency 1,57542GHz
- For a continuous time reception min. 4 satellites is necessary
- High accuracy : 1 usec

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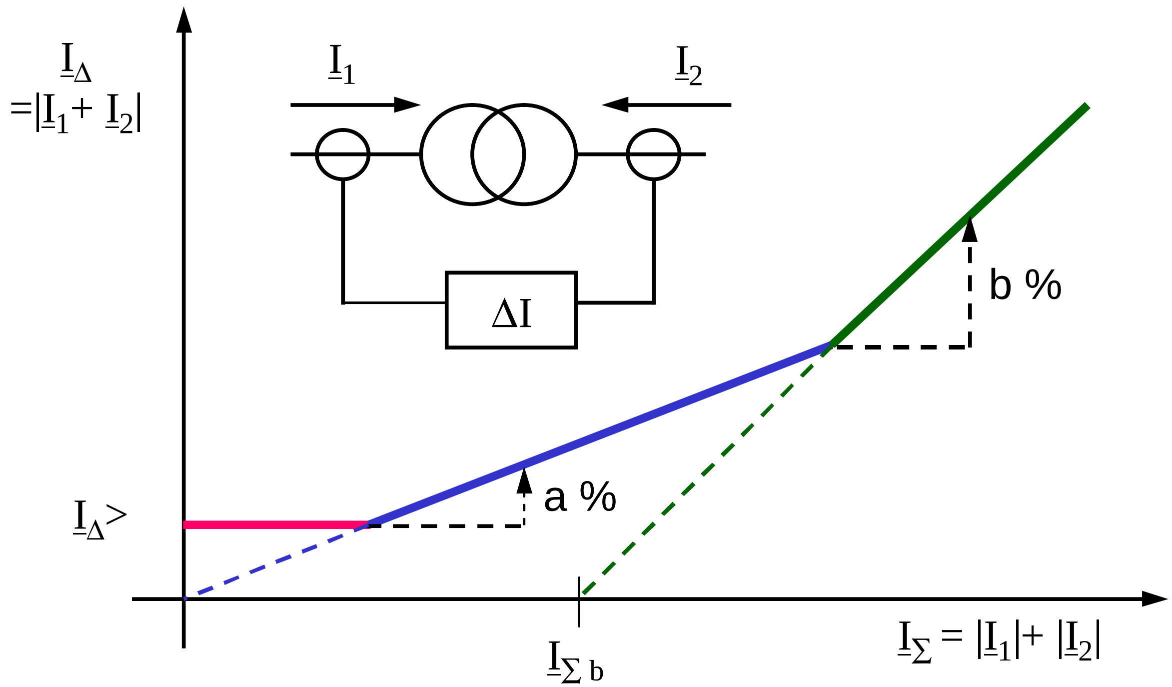
Operating characteristic of digital differential relays



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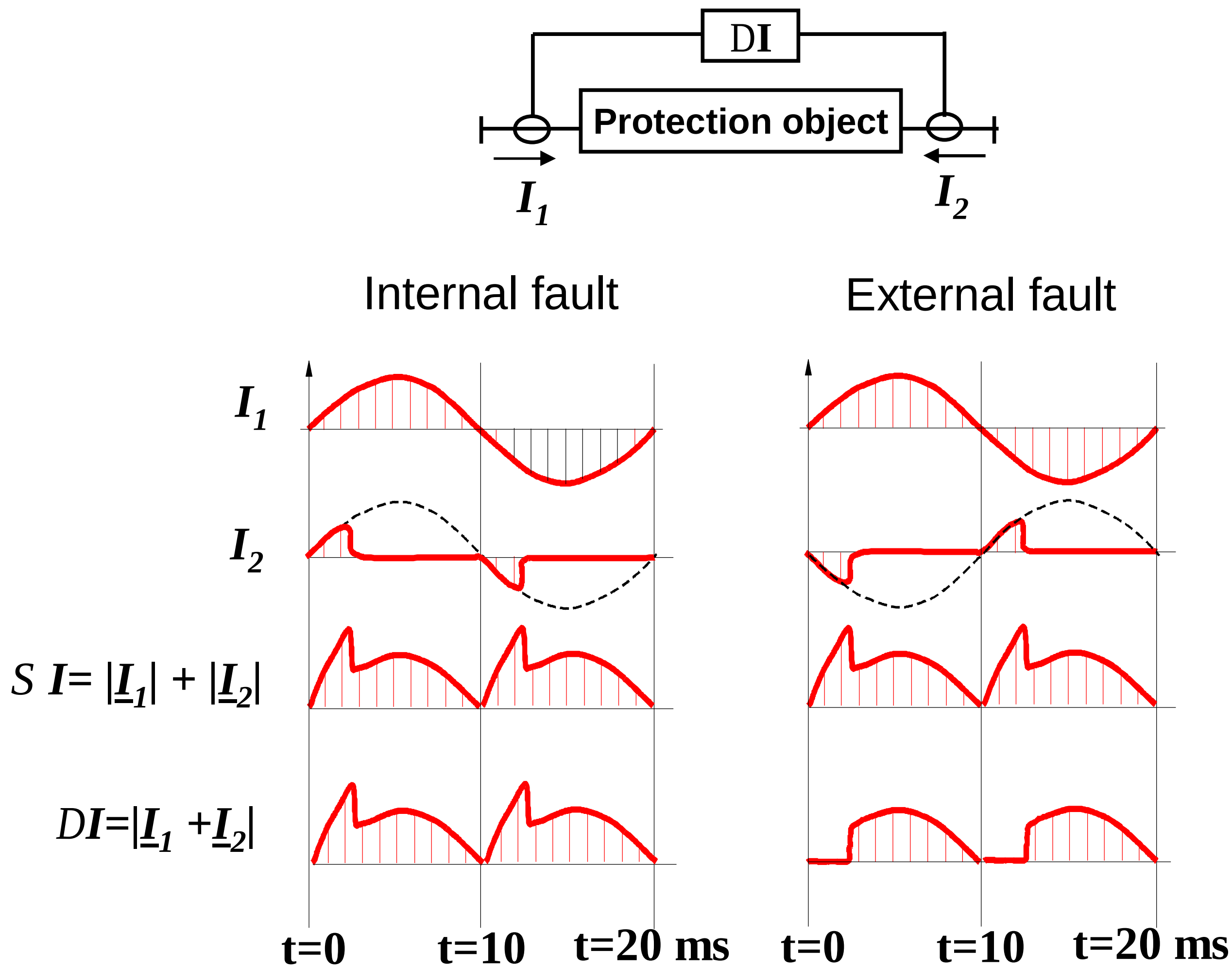
Differential protection
CT saturation with internal and external faults



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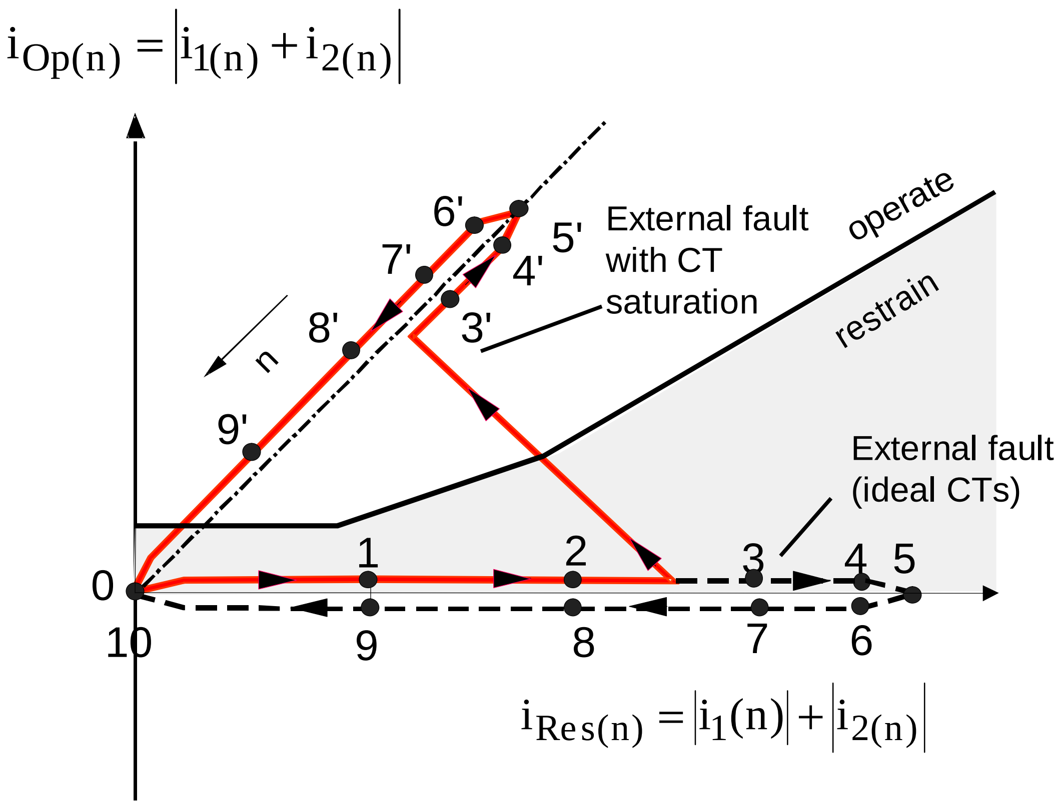
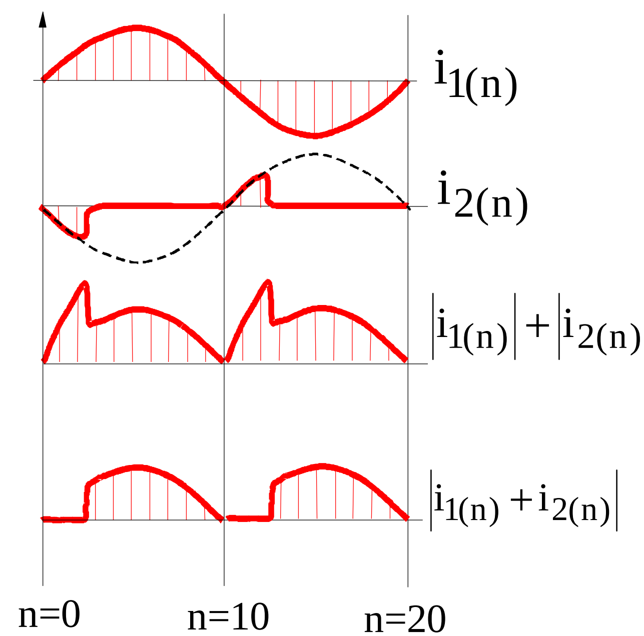
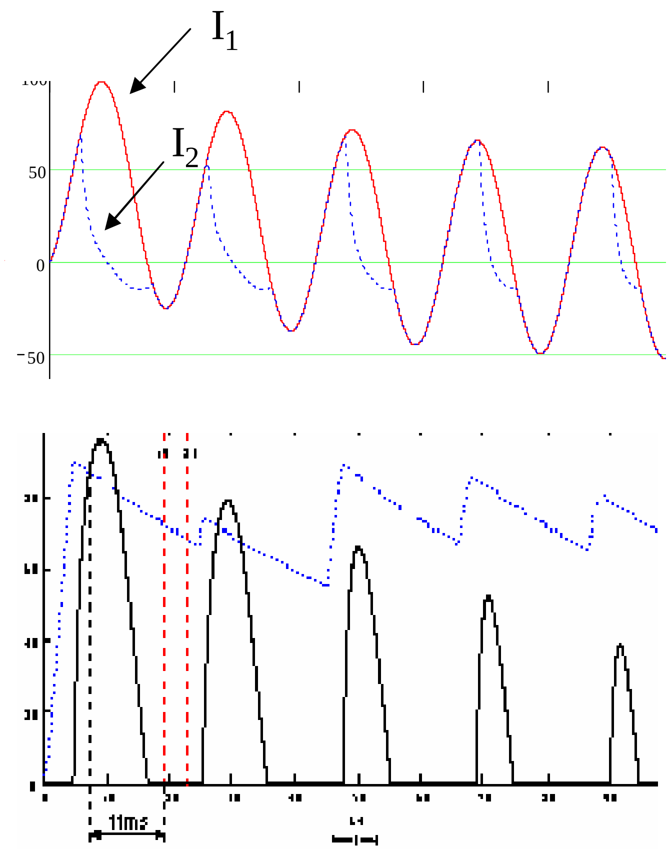
Saturation detector:

Locus of ΔI/ΣI for external faults without and with CT saturation





Differential current caused by transient CT saturation (ext. fault) with operating and restraint current of busbar protection 7SS5

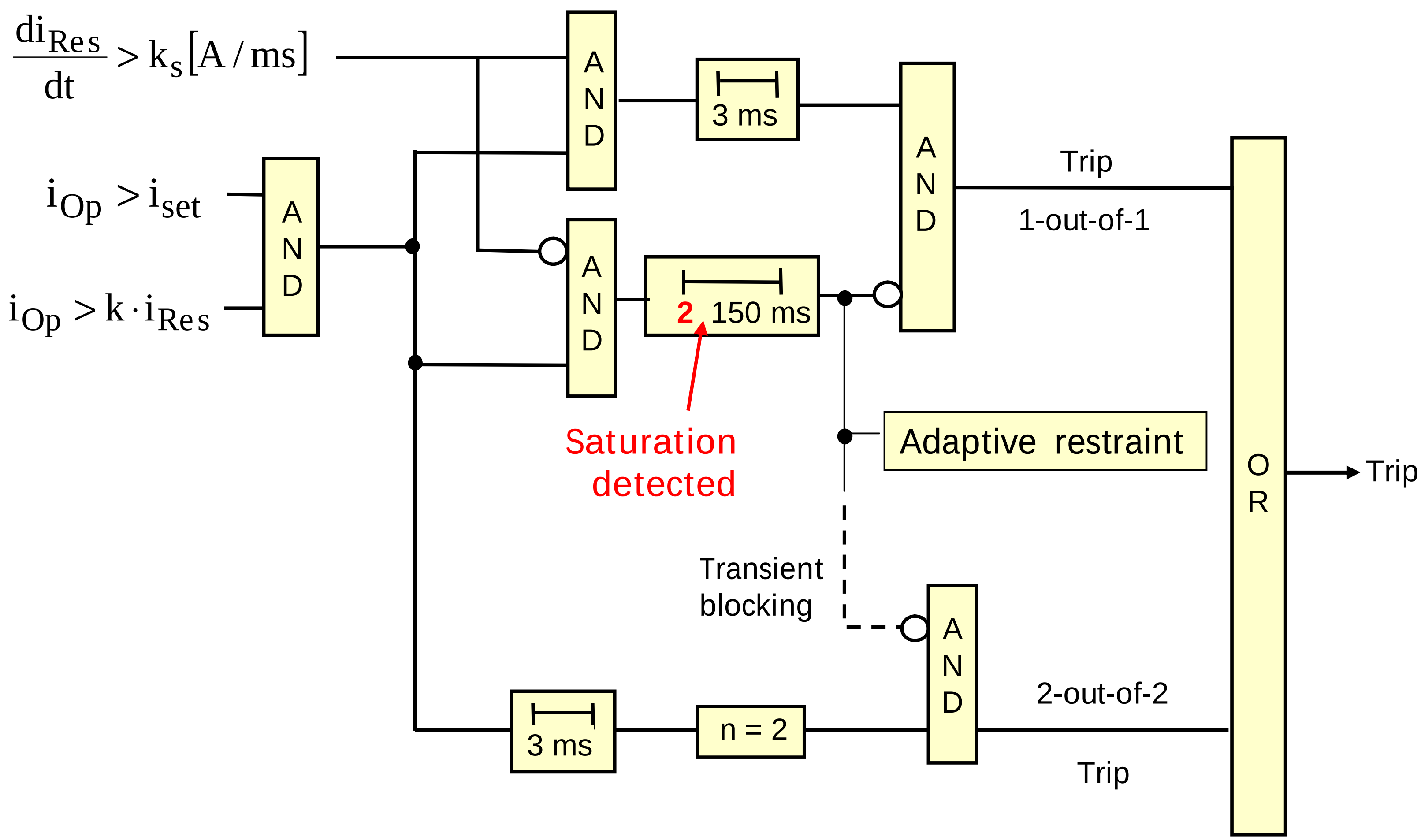


$$I_{Res.} = |\underline{I}_1| + |\underline{I}_2|$$

$$I_{Op} = |\underline{I}_1 + \underline{I}_2|$$

Differential current appears only every second half wave!

Tripping logic of digital busbar protection 7SS600/7SS5 with saturation detector (simplified)



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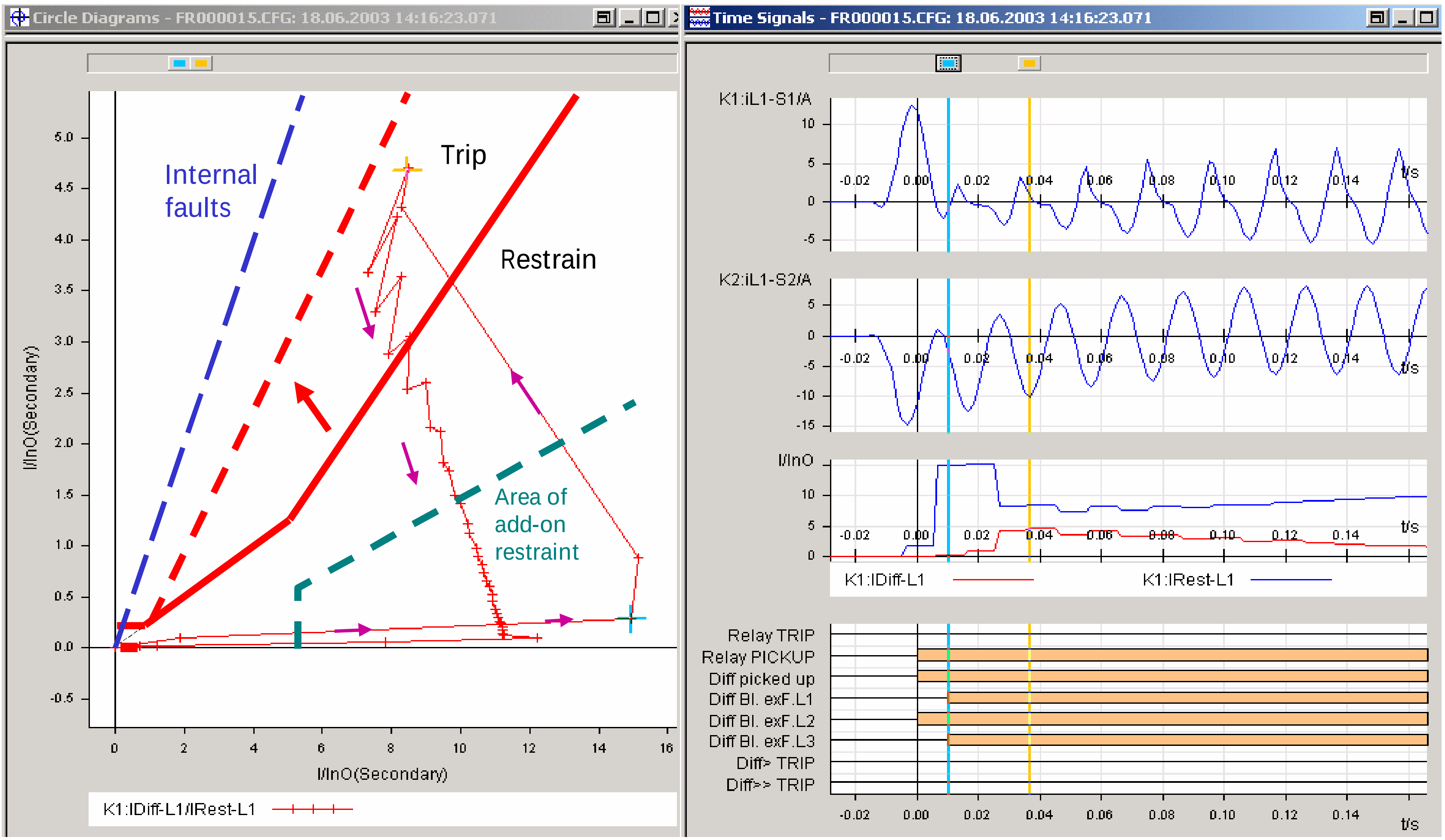
Transformer differential protection 7UT6: Saturation detection and automatic increase stabilisation



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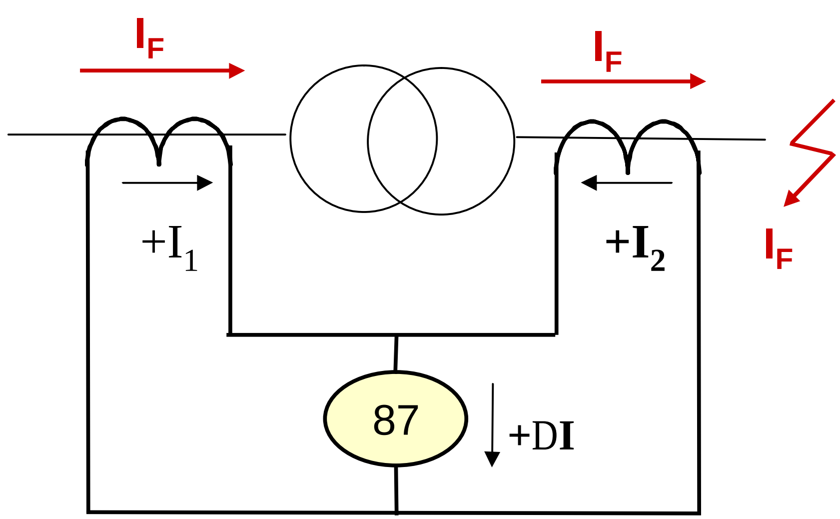
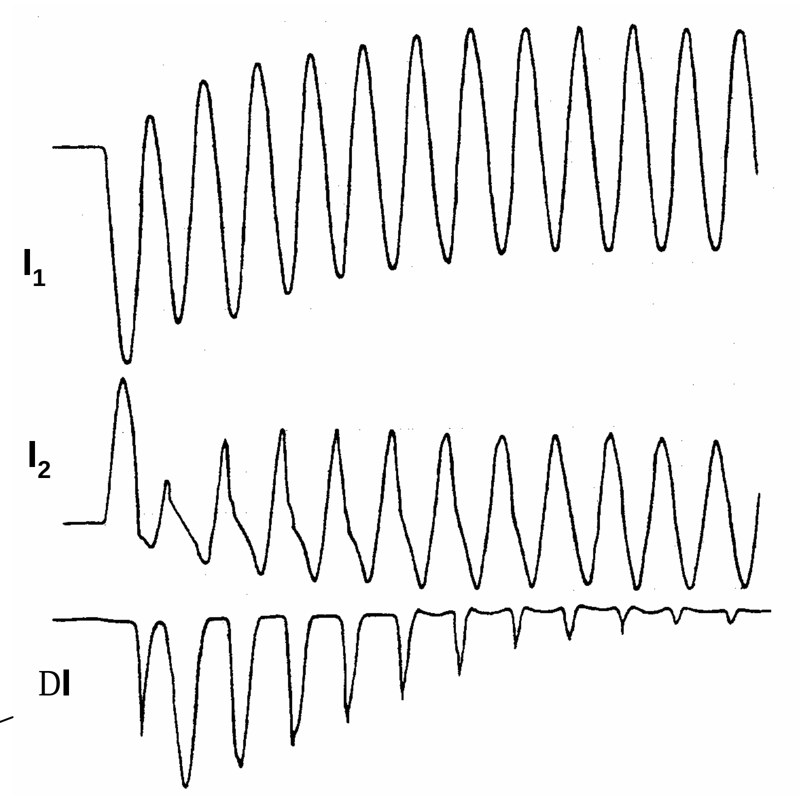
Transient CT saturation causes false differential currents





Wave shape similar to transformer inrush current ?

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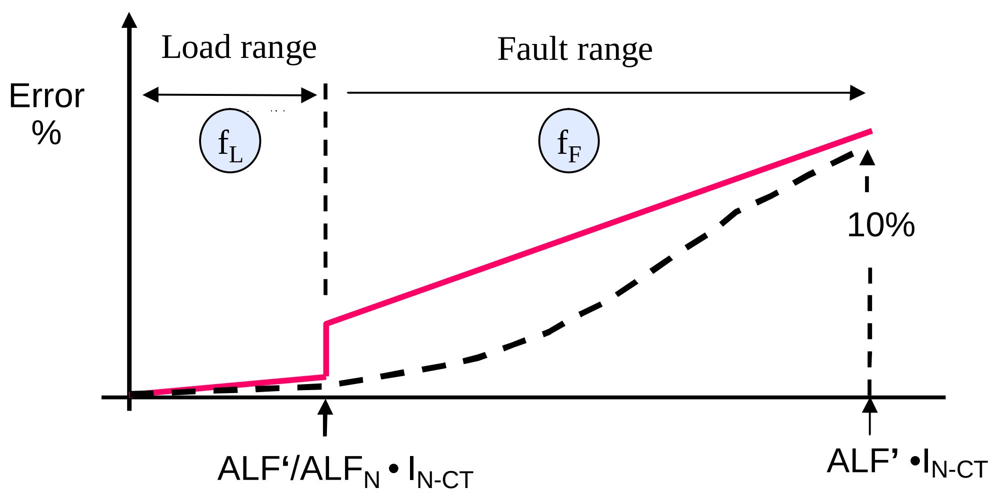
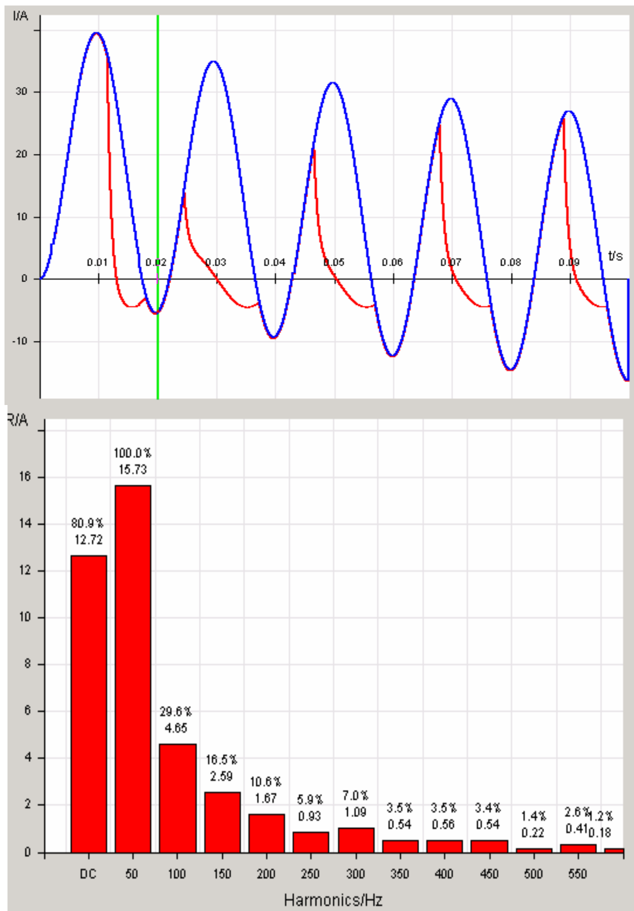
Adaptive restraint against CT errors (7SD52/61)

CT Error approximation (no-saturation)



Detection of CT saturation
(wave shape analysis)



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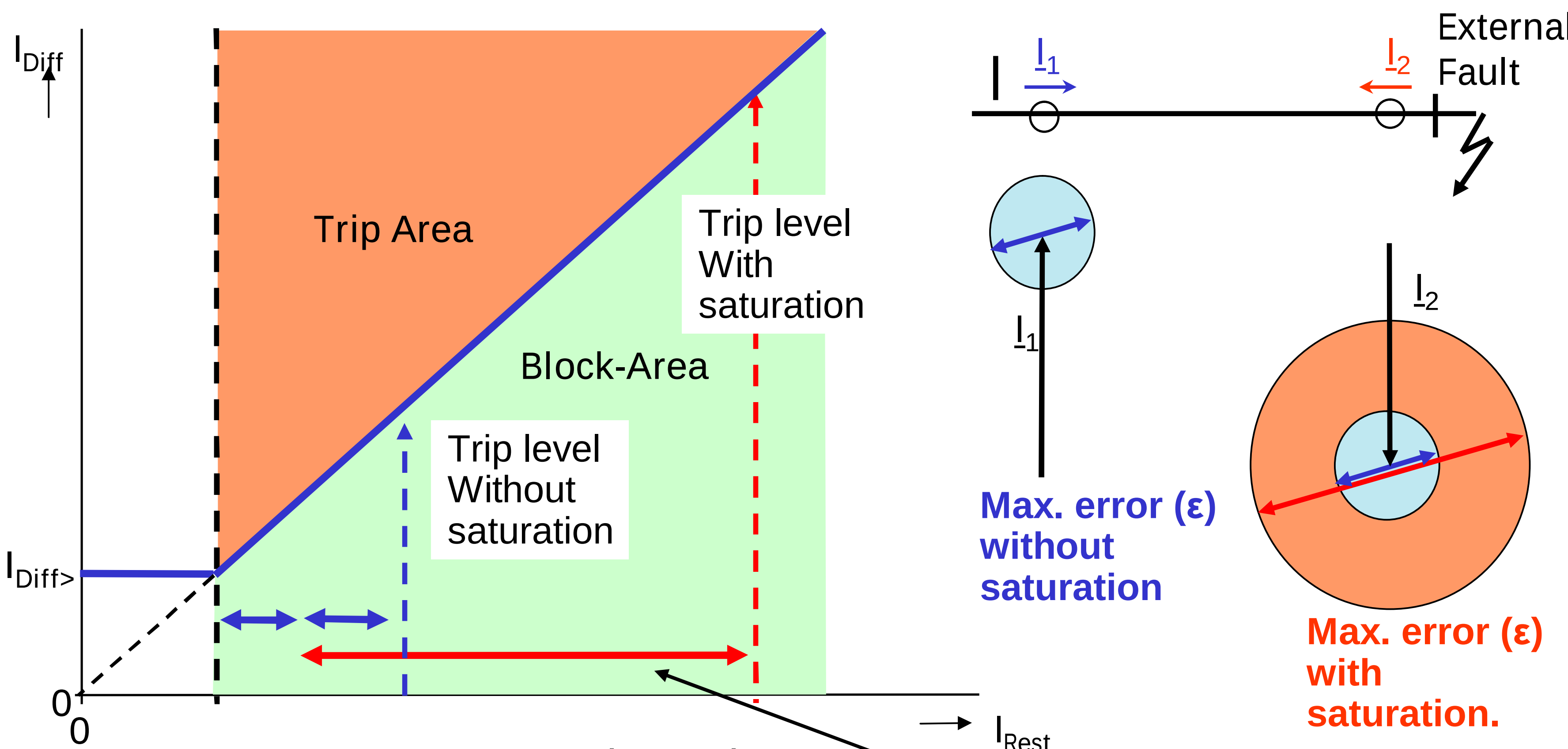
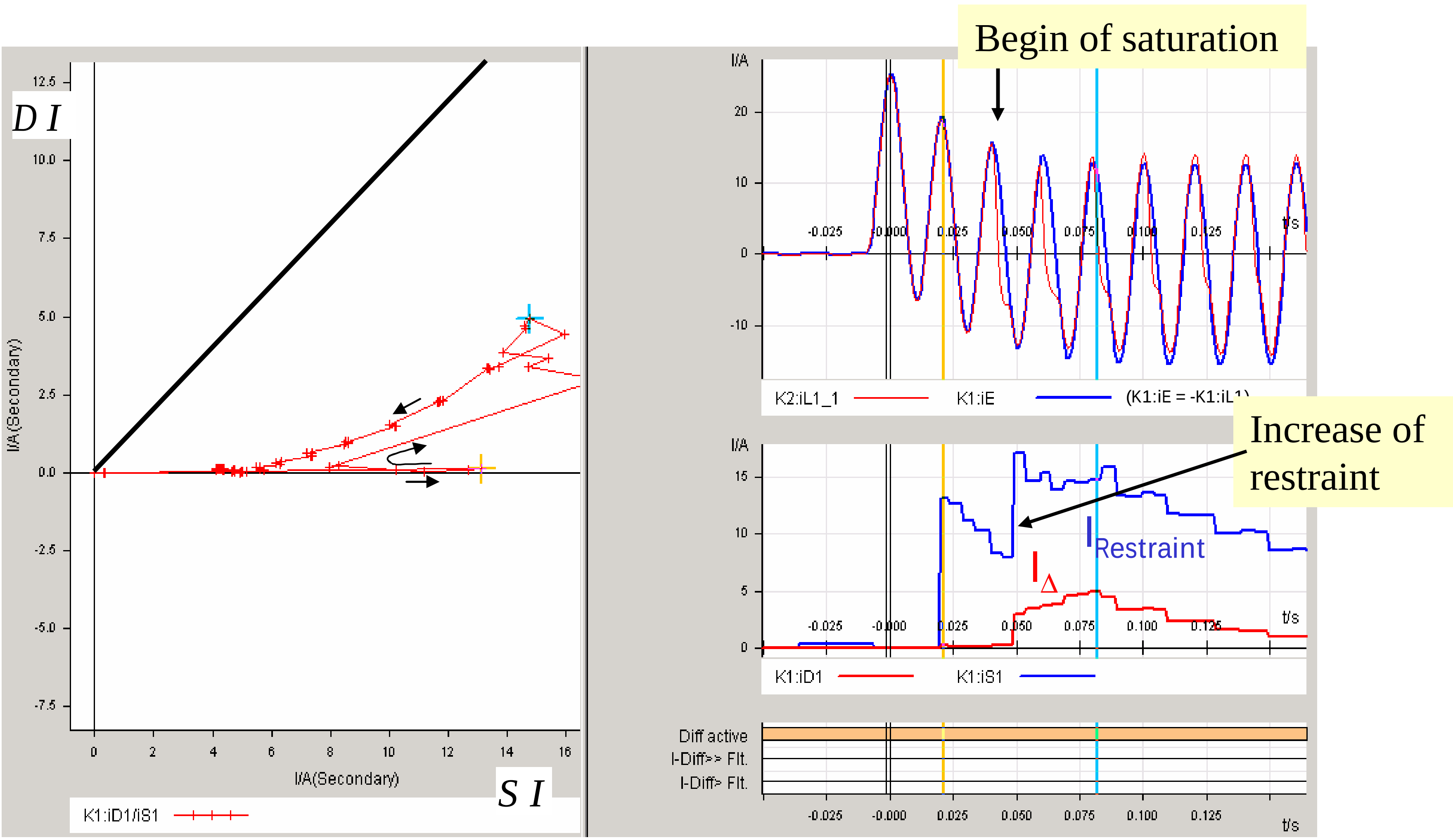
Adaptive 87 restraint (7SD52/61) considers current CT- errors



Current summation: $I_{Diff} = \left| \underline{I}_1 + \underline{I}_2 \right|$

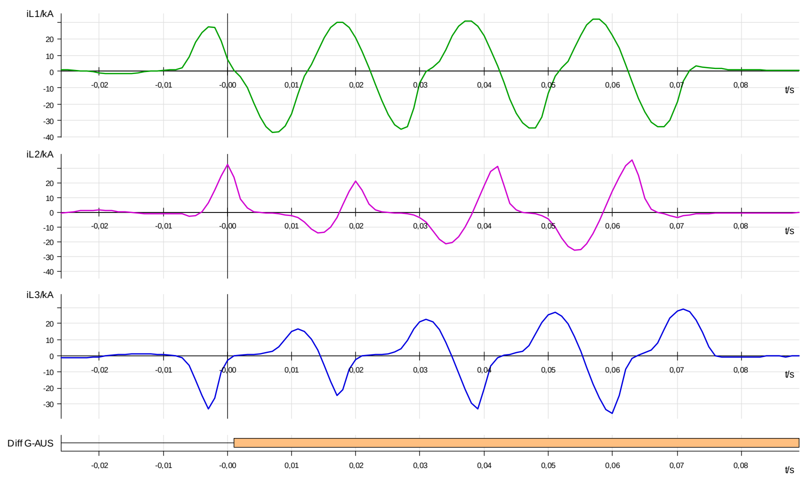
Max. error summation: $I_{Restraint} = \Sigma I_{Error} = I_{Diff>} + \varepsilon_{CT1} \cdot I_1 + f_{Sat} \cdot \varepsilon_{CT2} \cdot I_2$

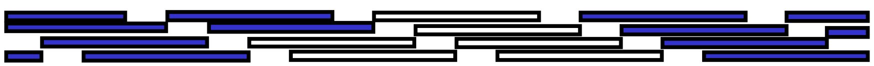
External fault
Increase of stabilisation after detection of saturation



Fast charge comparison supplement

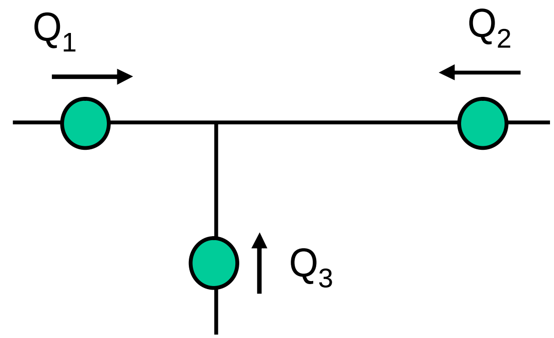
speeds up phasor based line differential protection (7SD52/61)

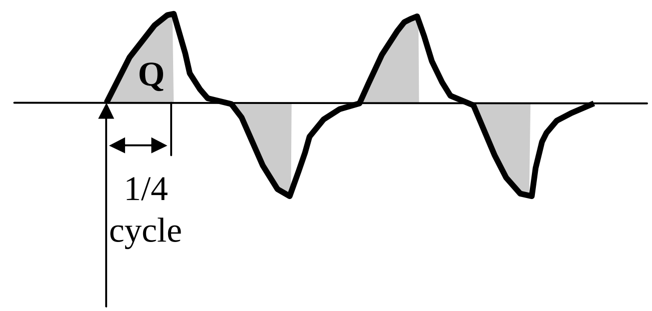




1 cycle data windows for phasor comparison

¼ cycle data windows of fast charge comparison





- Synchronized with fault inception
- Released by I_{diff} >>

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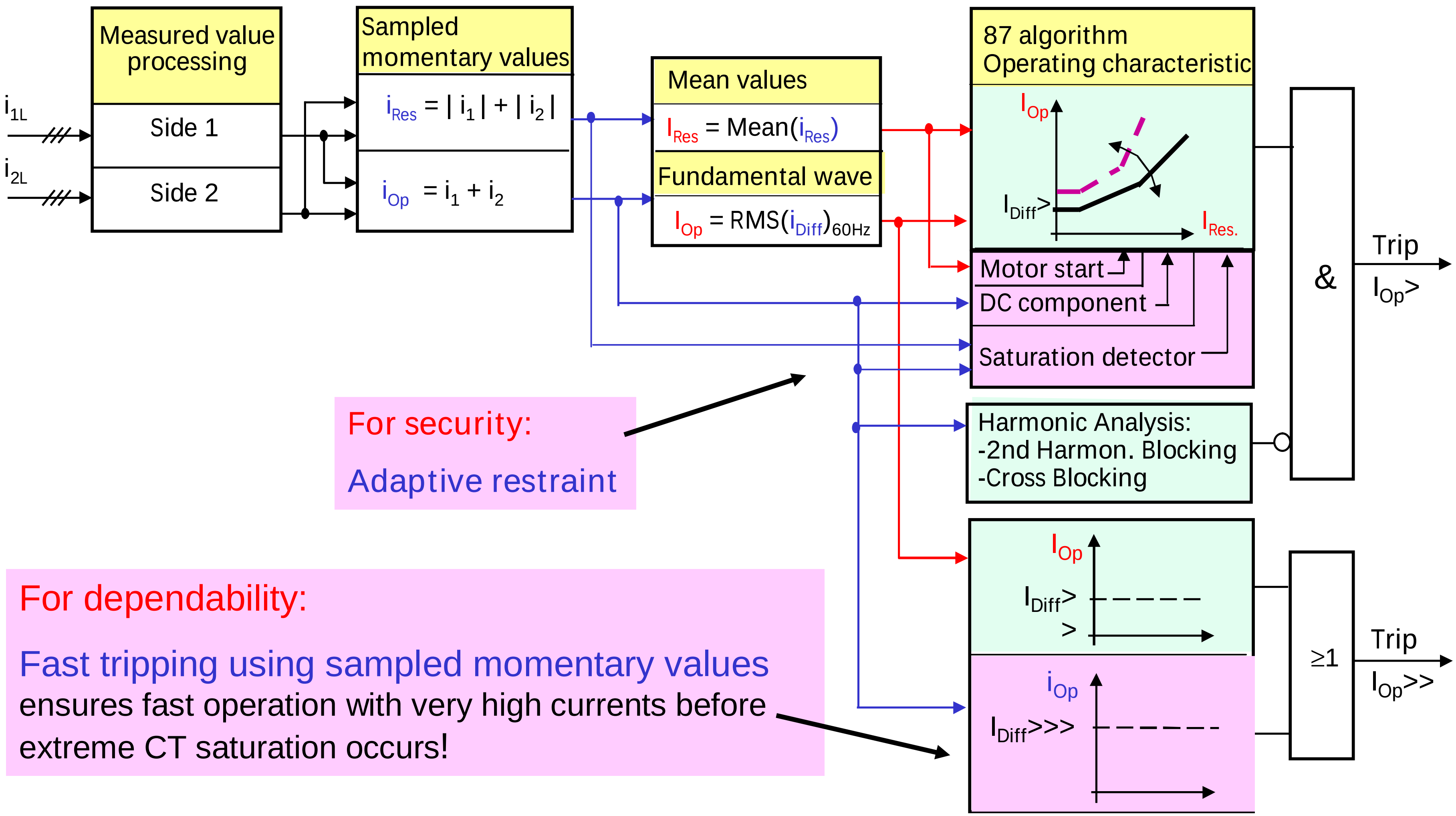
Generator, Motor and Transformer protection: Adaptive algorithms to upgrade relay stability and dependability with CT saturation (7UT6)



Current Transformers for Differential Relaying
Requirements and Dimensioning

Gerhard Ziegler

SIEMENS

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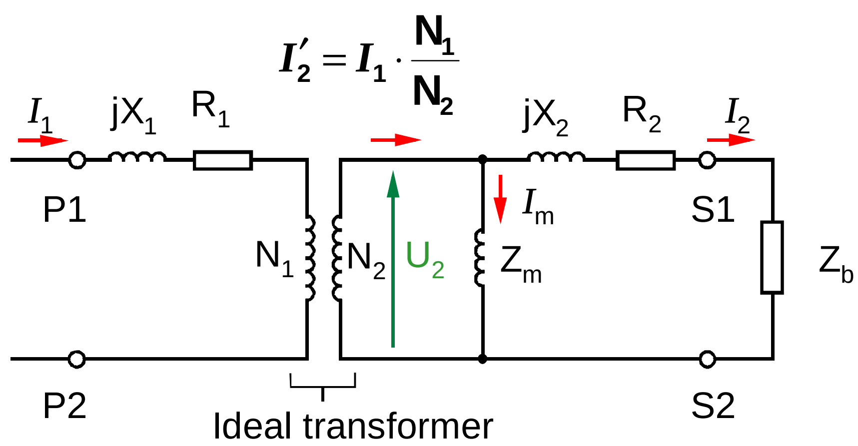
Equivalent current transformer circuit



X_1 = Primary leakage reactance
R_1 = Primary winding resistance
X_2 = Secondary leakage reactance
Z_0 = Magnetising impedance
R_2 = Secondary winding resistance
Z_b = Secondary load

Note: **Normally the leakage fluxes X_1 and X_2 can be neglected**

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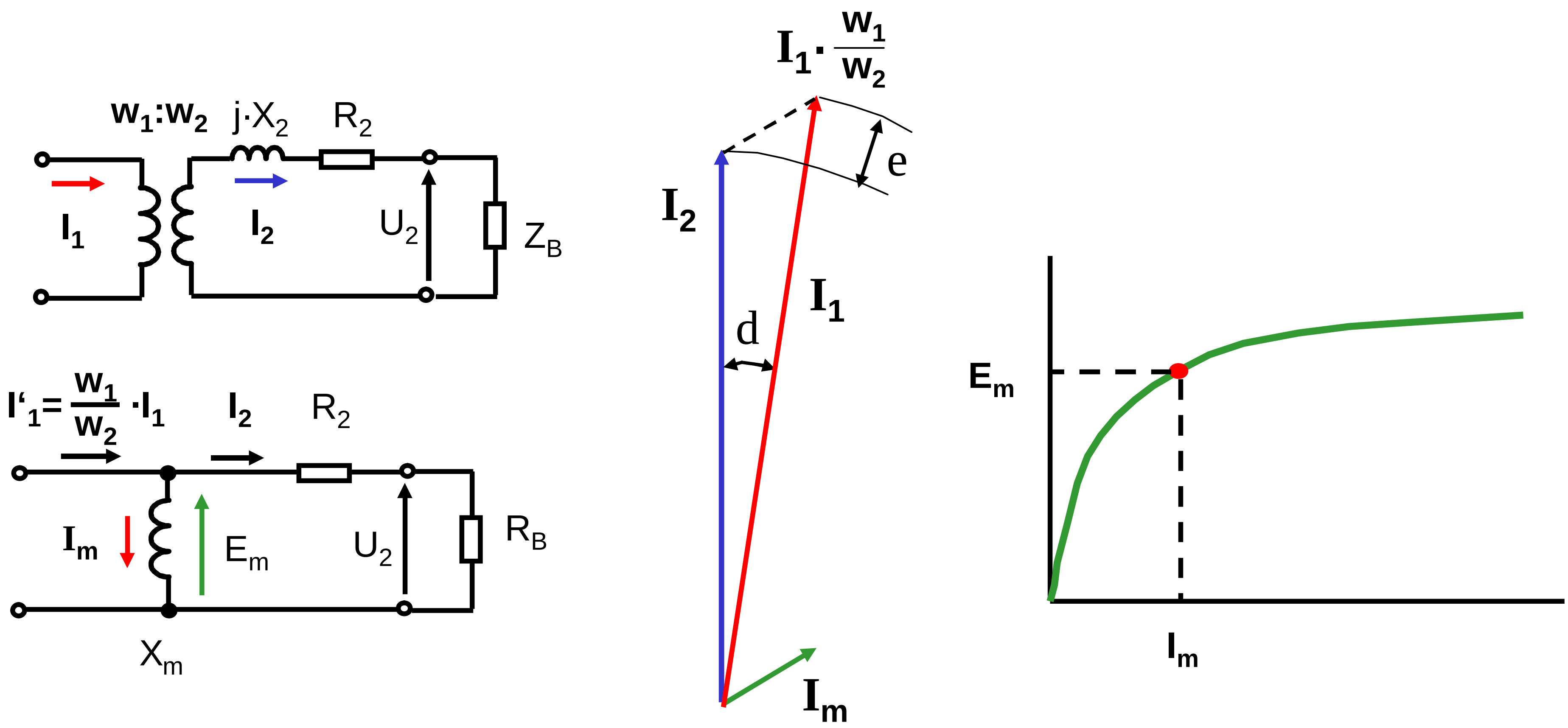
Current transformer:
Phase displacement (δ) and current ratio error (ε)



Dimensioning of CTs for differential protection

CT classes to IEC 60044-1: 5P or 10P

$P_i = I_{sec.}^2 \times R_{CT}$

Specification: 300/1 A 5P10, 30 VA R_{CT} £ 5 Ohm

Ratio $I_{n\text{-Prim}} / I_{n\text{-Sek.}}$

Rated burden (nominal power) P_N

5% accuracy at I= n x In

Accuracy limit factor ALF

Actual accuracy limit factor in operation is higher as the CT is normally under-burdened :
Operating ALF: ALF‘

$$ALF' = ALF \times \frac{P_i + P_N}{P_i + P_B}$$

Dimension criterium:

$$ALF' \geq \frac{I_{SC-\max}}{I_n} \times K_{TF}$$

K_{TF} (over-dimensioning factor) considers the single sided CT over-magnetising due to the d.c. component in short circuit current I_{SC}.
K_{TF} values required in practice depend on relay type and design.
Recommendations are provided by manufacturers (see Application Guide)

Current transformer, Standard for steady-state performance

IEC 60044-1 specifies the following classes:

Accuracy class	Current error at nominal current (In)	Angle error d at rated current In	Total error at n x In (rated accuracy limit)
5P	± 1 %	± 60 minutes	5 %
10P	± 5%	———	10 %

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Current transformers, Standard for transient performance

IEC 60044-6 specifies four classes:

Class	Error at rated current: Ratio error	Error at rated current: Angle error	Maximum error at rated accuracy limit	Remanence
TPX (closed iron core)	± 0,5 %	± 30 min	$\hat{e} \leq 10\%$	no limit
TPY with anti-remanence air-gap	± 1,0 %	± 30 min	$\hat{e} \leq 10\%$	< 10 %
TPZ linear core	± 1,0 %	± 180 ± 18 min	$\hat{e} \leq 10\%$ (a.c. current only)	negligible
TPS closed iron core	Special version for high impedance protection (Knee point voltage, internal secondary resistance)			No limit

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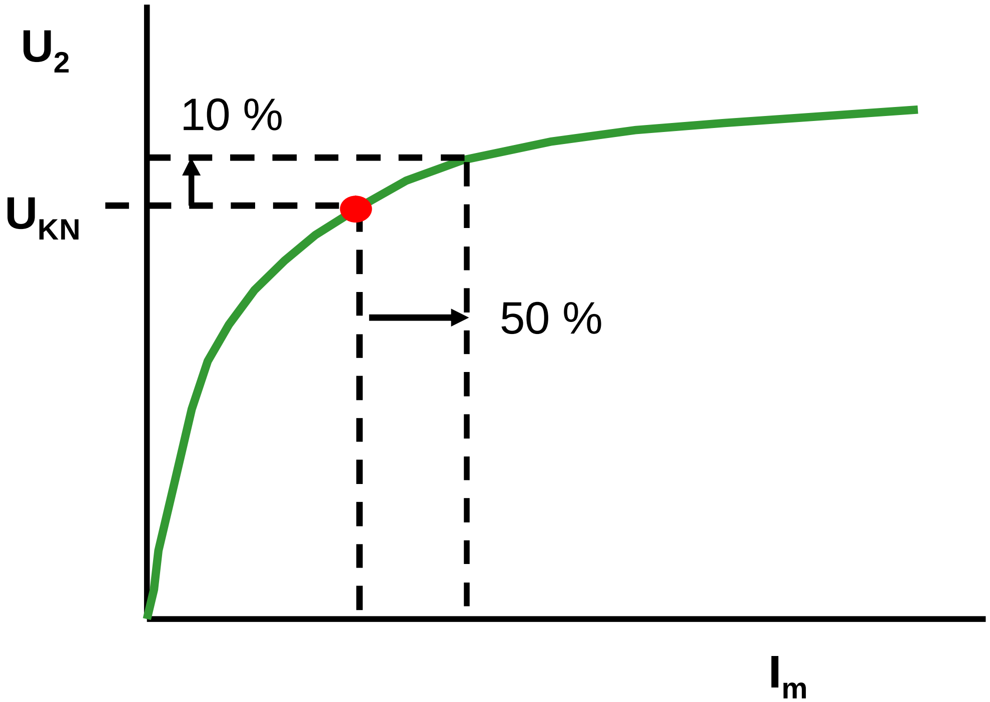
Definition of the CT knee-point voltage (BS and IEC)



British Standard BS3938: Class X

or

IEC 60044-1 Amendment 2000/07: Class PX

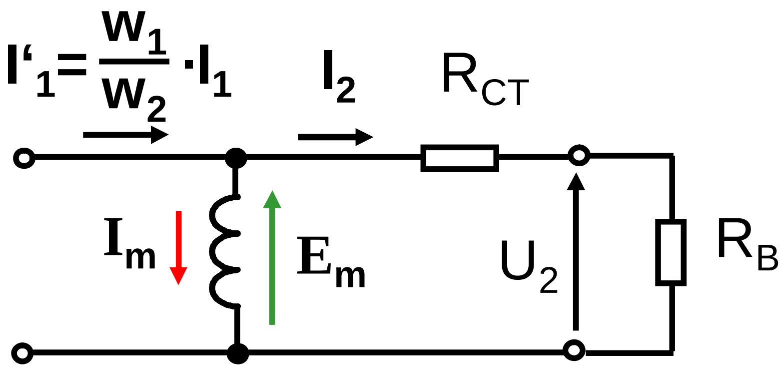
Specify:

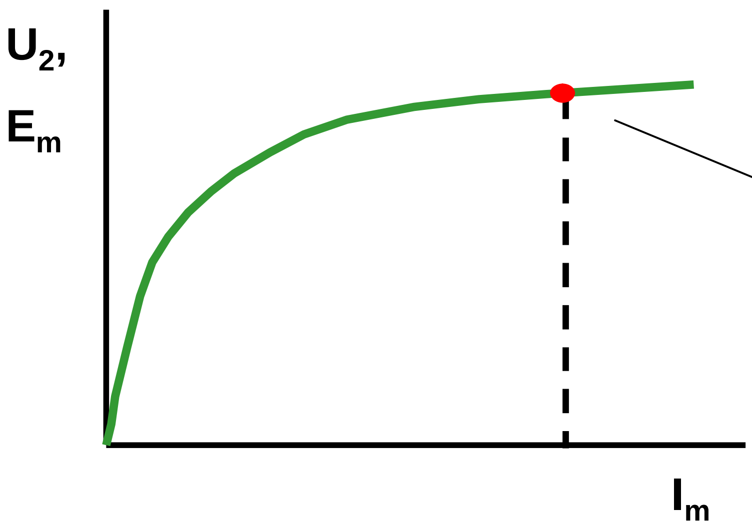
Knee point voltage

Secondary resistance R_{CT}

$$U_{KN} \geq K_{TF} \cdot (R_{CT} + R_{B-connected}) \cdot \frac{I_{SC-max.}}{I_{n-CT}}$$

CT specification according to ANSI C57.13





ANSI C57.13 specifies:

- Secondary terminal voltage U_2 at 20 times rated current (20x5=100 A) and rated burden
- Error <10%

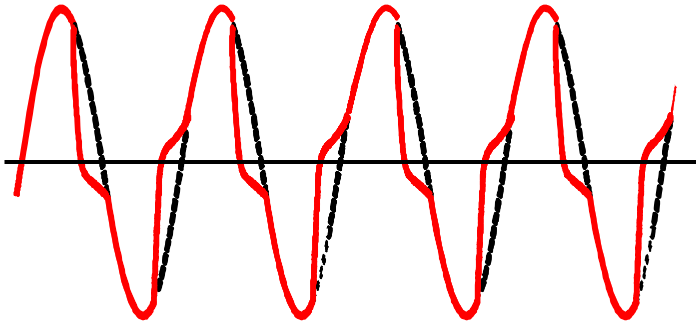
Example:

800/5 A, C400 (R_B= 4 Ω)

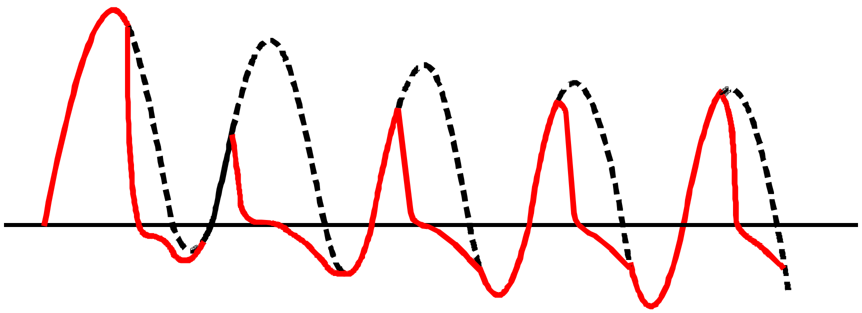
Resulting magnetising voltage:

$$E_{al} \approx (U_{ANSI} + 20 \cdot 5 \cdot R_{CT}) = (20 \cdot 5 \cdot Z_{B-rated} + 20 \cdot 5 \cdot R_{CT})$$

Current transformer saturation



Steady-state saturation with a.c. current



Transient saturation with offset current

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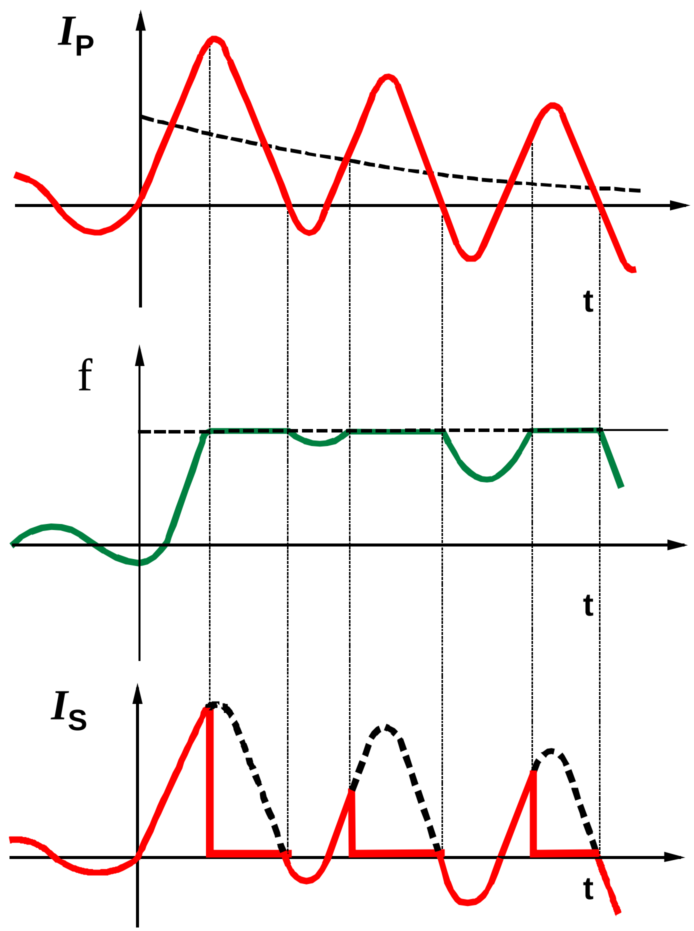
CT saturation
Currents and magnetising



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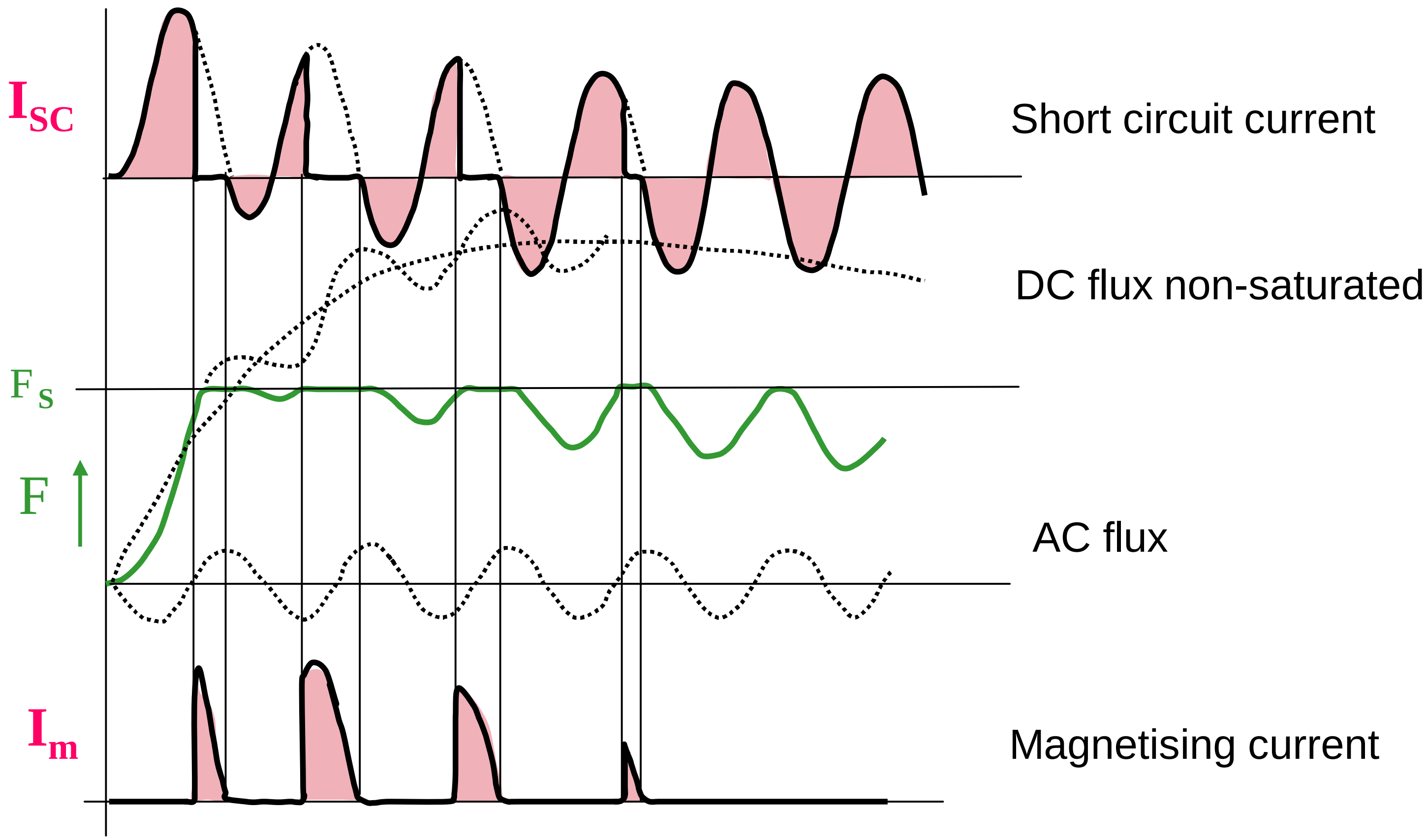
Transient CT saturation due to DC component



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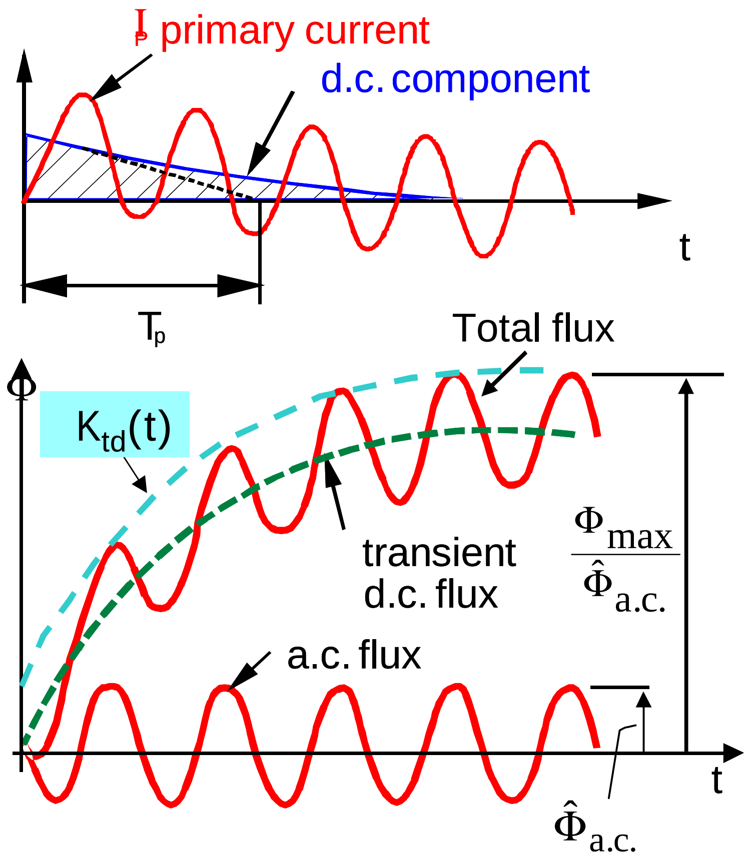
Course of CT-flux during off-set short-circuit current



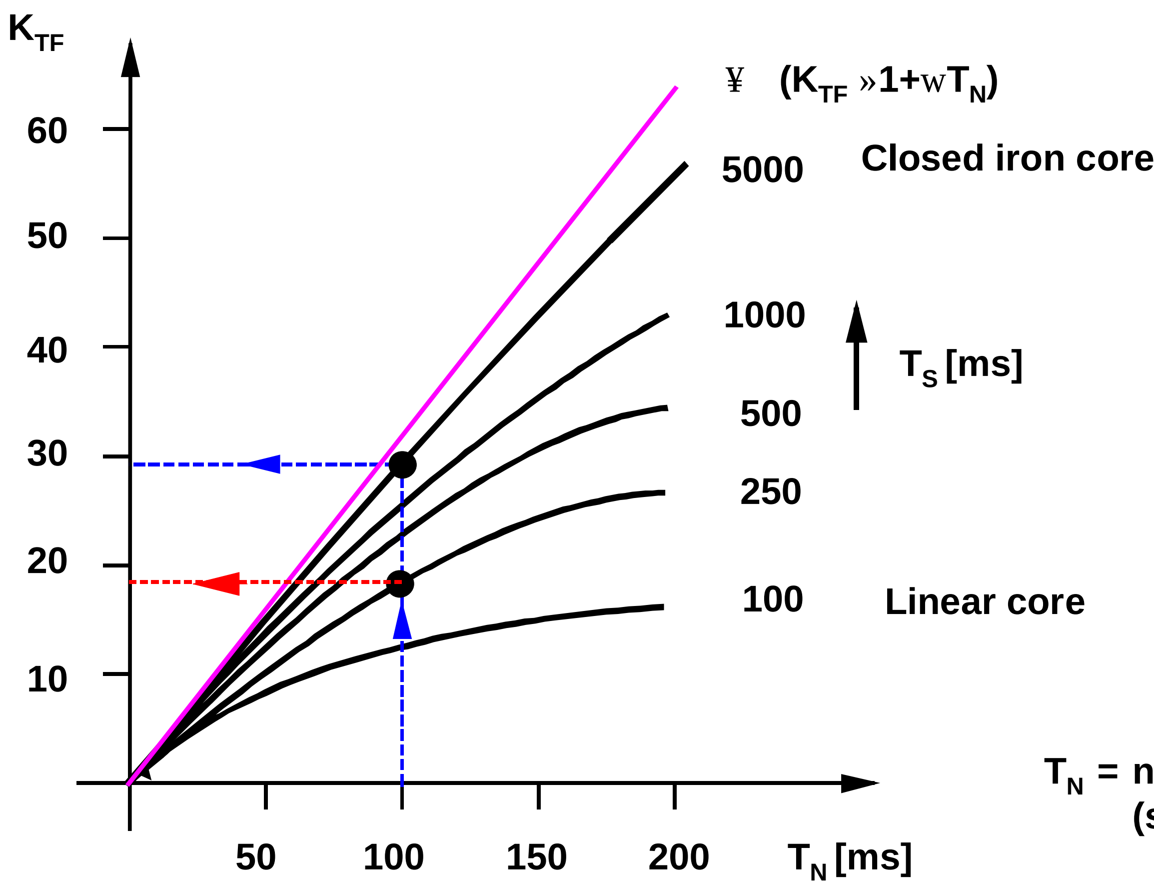
$$i_p(t) = \sqrt{2} \cdot I_p \cdot \left[e^{-\frac{t}{Tp}} - \cos(\omega t) \right]$$

$$\frac{\Phi}{\hat{\Phi}_{a.c.}} = \frac{\omega T_p T_s}{T_p - T_s} \left(e^{-\frac{t}{Tp}} - e^{-\frac{t}{Ts}}\right) - \sin \omega t$$

$$K_{td}(t) = \frac{\Phi_{max}}{\hat{\Phi}_{a.c.}} = \frac{\omega T_p T_s}{T_p - T_s} \left(e^{-\frac{t}{Tp}} - e^{-\frac{t}{Ts}}\right) + 1$$

$$K_{td-max} = 1 + \omega T_p = 1 + \frac{X_p}{R_p}$$

Theoretical CT over-dimensioning factor K_{TF}



$$K_{TF} = 1 + \omega T_S \left(\frac{T_N}{T_S}\right)^{\frac{T_S}{T_S - T_N}}$$

T_N = network time constant (short-circuit time constant)

T_S = CT secondary time constant

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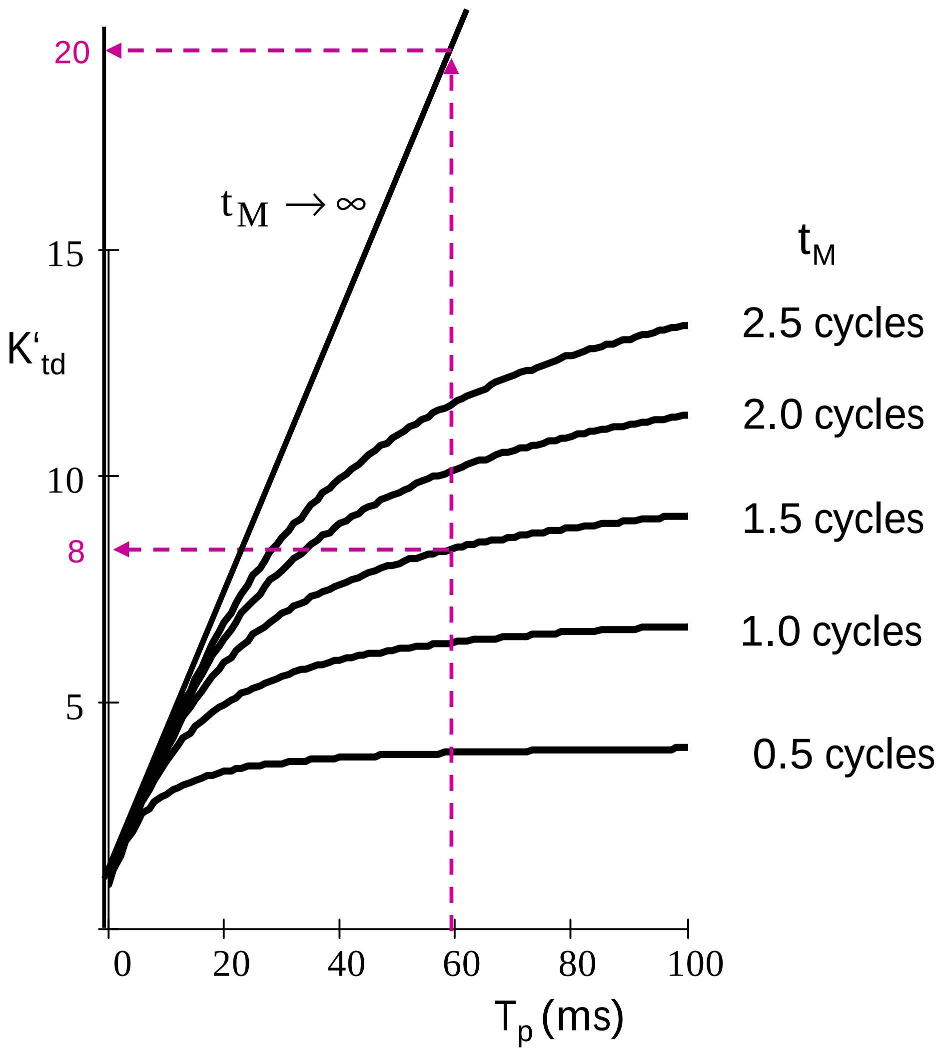
CT with closed iron core,
Over-dimensioning factor K_{TF}‘ for specified time to saturation (t_M)

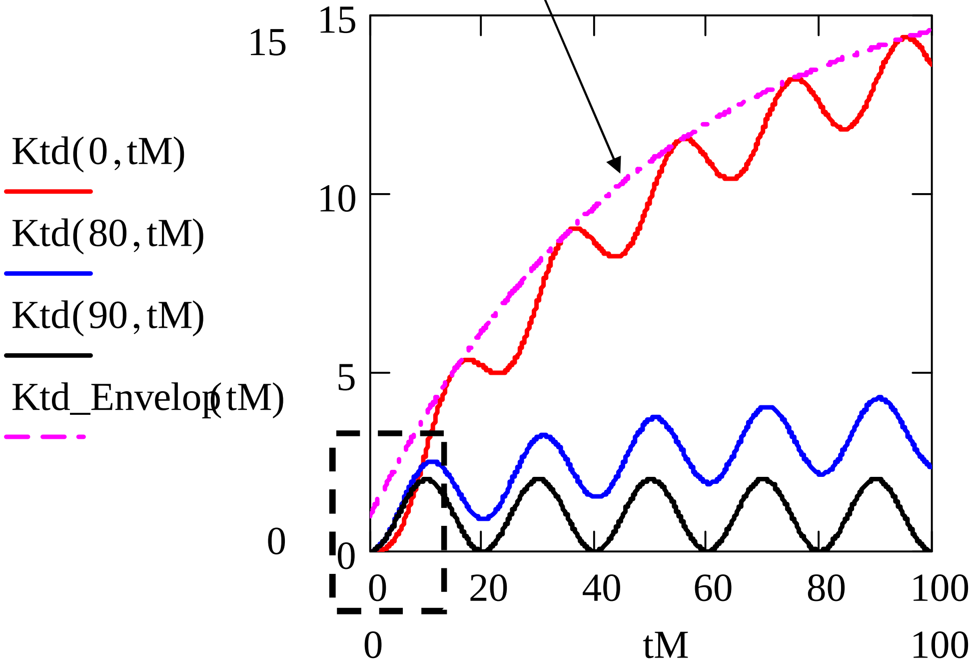


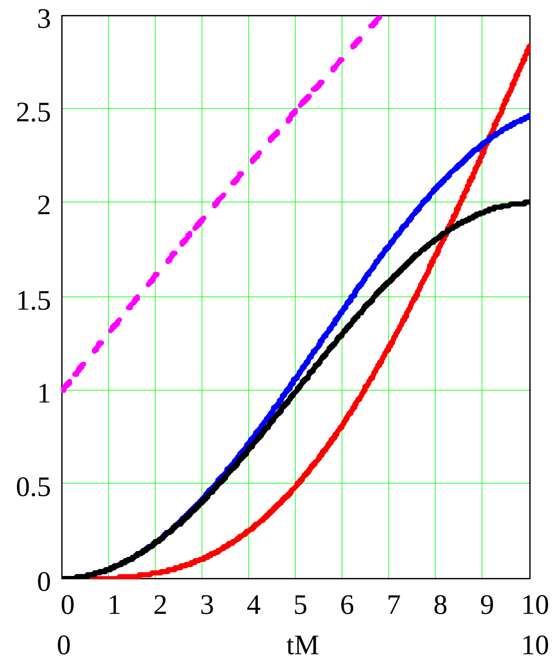
$$K'_{td} = 1 + wT_p \cdot \left(1 - e^{-\frac{t_M}{T_p}} \right)$$

Transient dimensioning factor K''_{td} for short time to saturation t_M

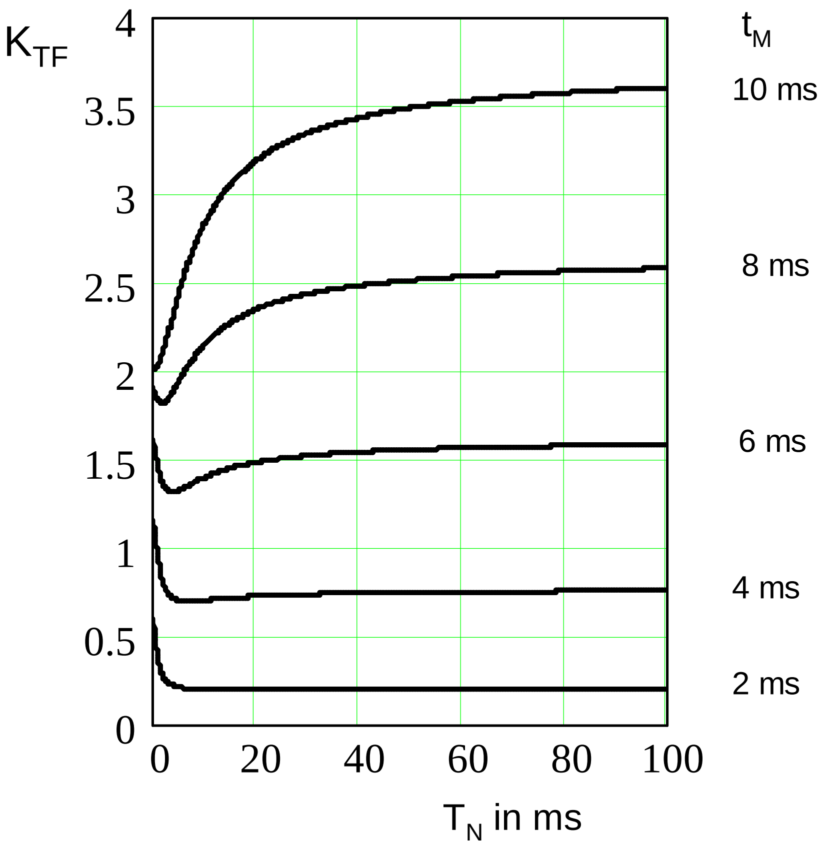
$$K_{td-Envelop} = 1 + \omega T_p \cdot \left(1 - e^{-\frac{t_M}{T_p}}\right)$$

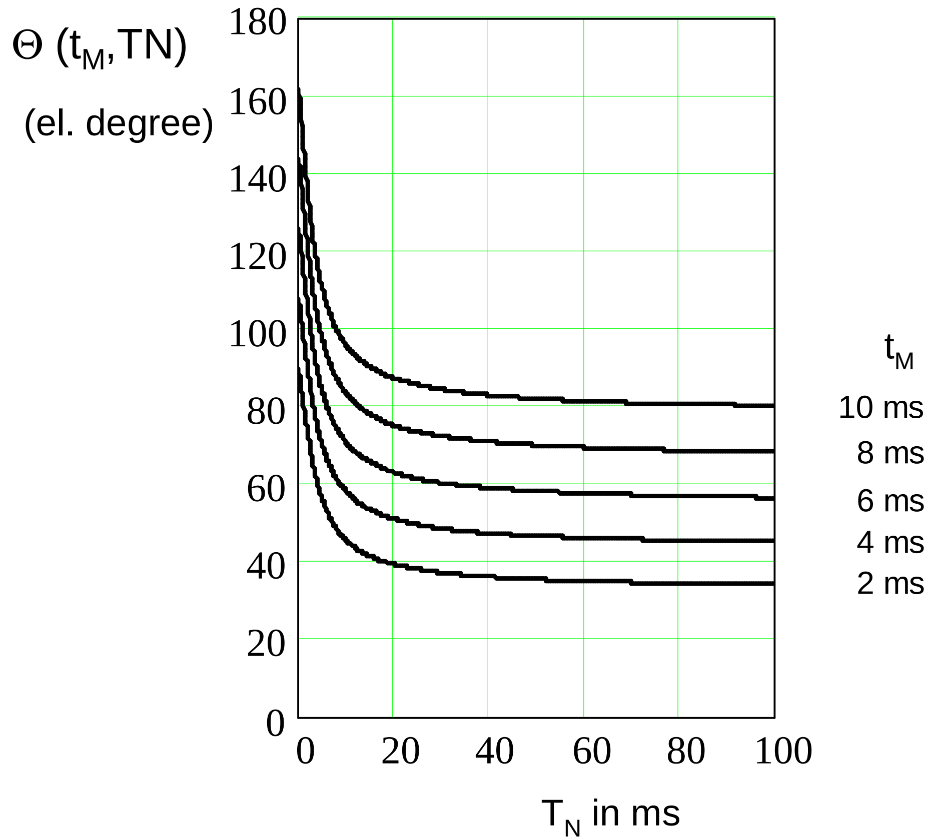
$$K''_{td}(\Theta, t_M) = \omega \cdot T_p \cdot \cos\theta \cdot \left(1 - e^{-\frac{t_M}{T_p}}\right) + \sin\Theta - \sin(\omega t_M + \Theta)$$





CT over-dimensioning factor K_{TF} (t_M,T_N) in the case of short time to saturation (t_M)





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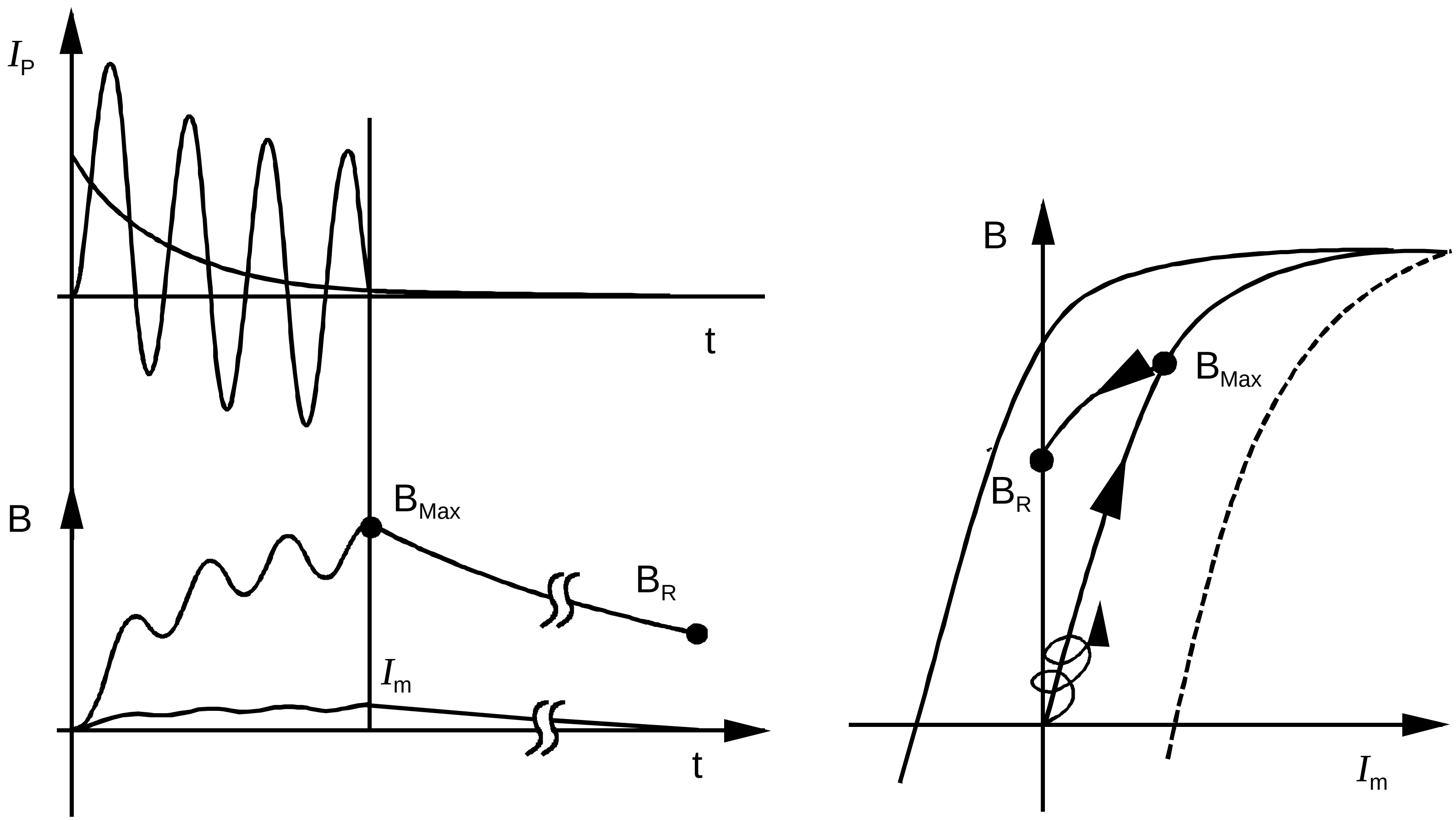
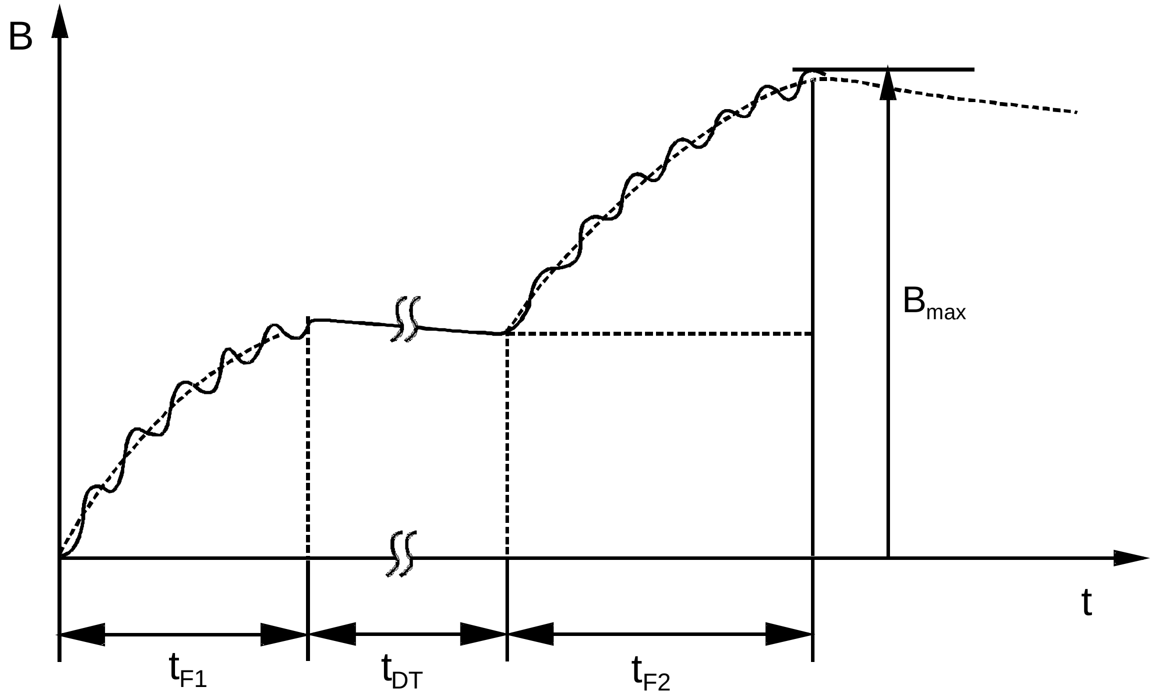
Current transformer
Magnetising and de-magnetising



Current transformer
Course of flux in the case of non-successful auto-reclosure



t_{F1} = duration of 1st fault

t_{DT} dead time

t_{F2} =duration of 2nd fault

$$\frac{B_{max}}{\hat{B}_{\sim}} = \left[1+\frac{\omega \cdot T_N \cdot T_S}{T_N - T_S}\left(e^{-\frac{tF1}{T_N}} - e^{-\frac{tF1}{T_S}}\right)\right] \cdot e^{-\frac{tDT+tF2}{T_S}} + \left[1+\frac{\omega \cdot T_N \cdot T_S}{T_N - T_S}\left(e^{-\frac{tF2}{T_N}} - e^{-\frac{tF2}{T_S}}\right)\right]$$

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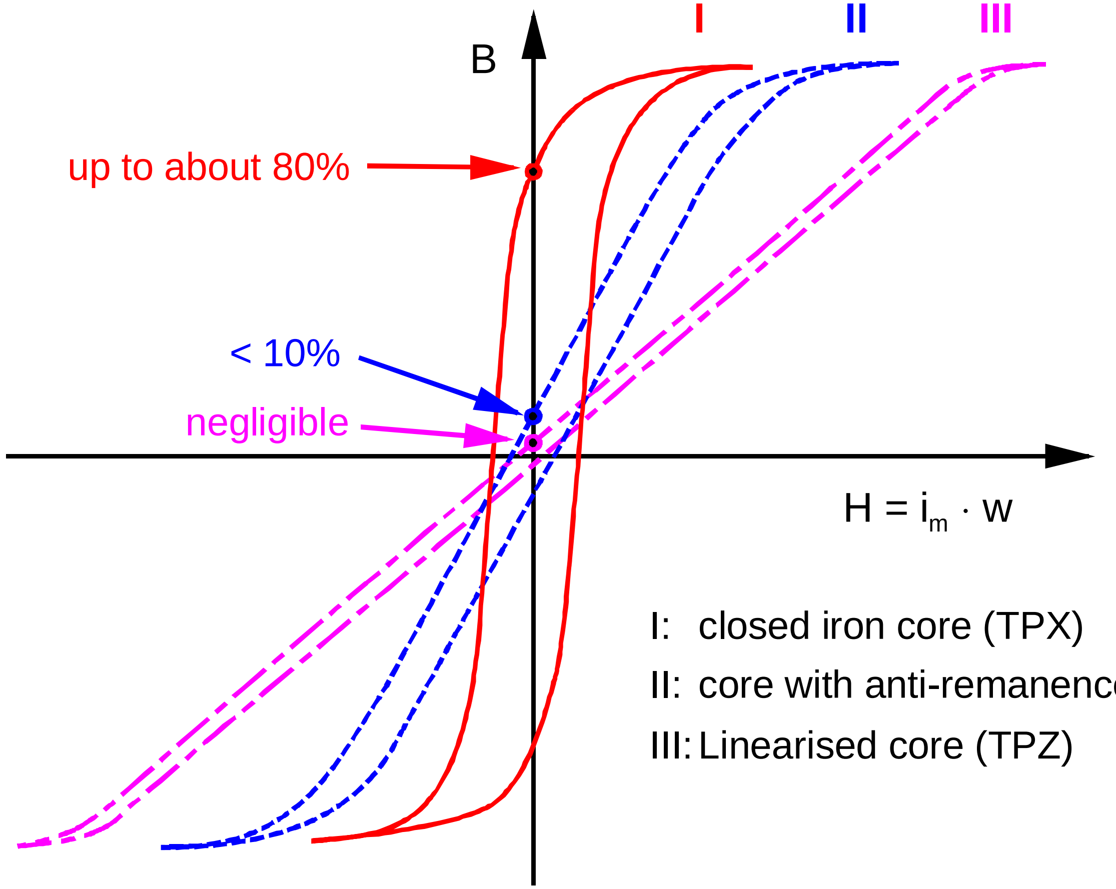
Current transformer
Magnetising curve and point of remanence



I: closed iron core (TPX)

II: core with anti-remanence air-gaps (TPY)

III: Linearised core (TPZ)

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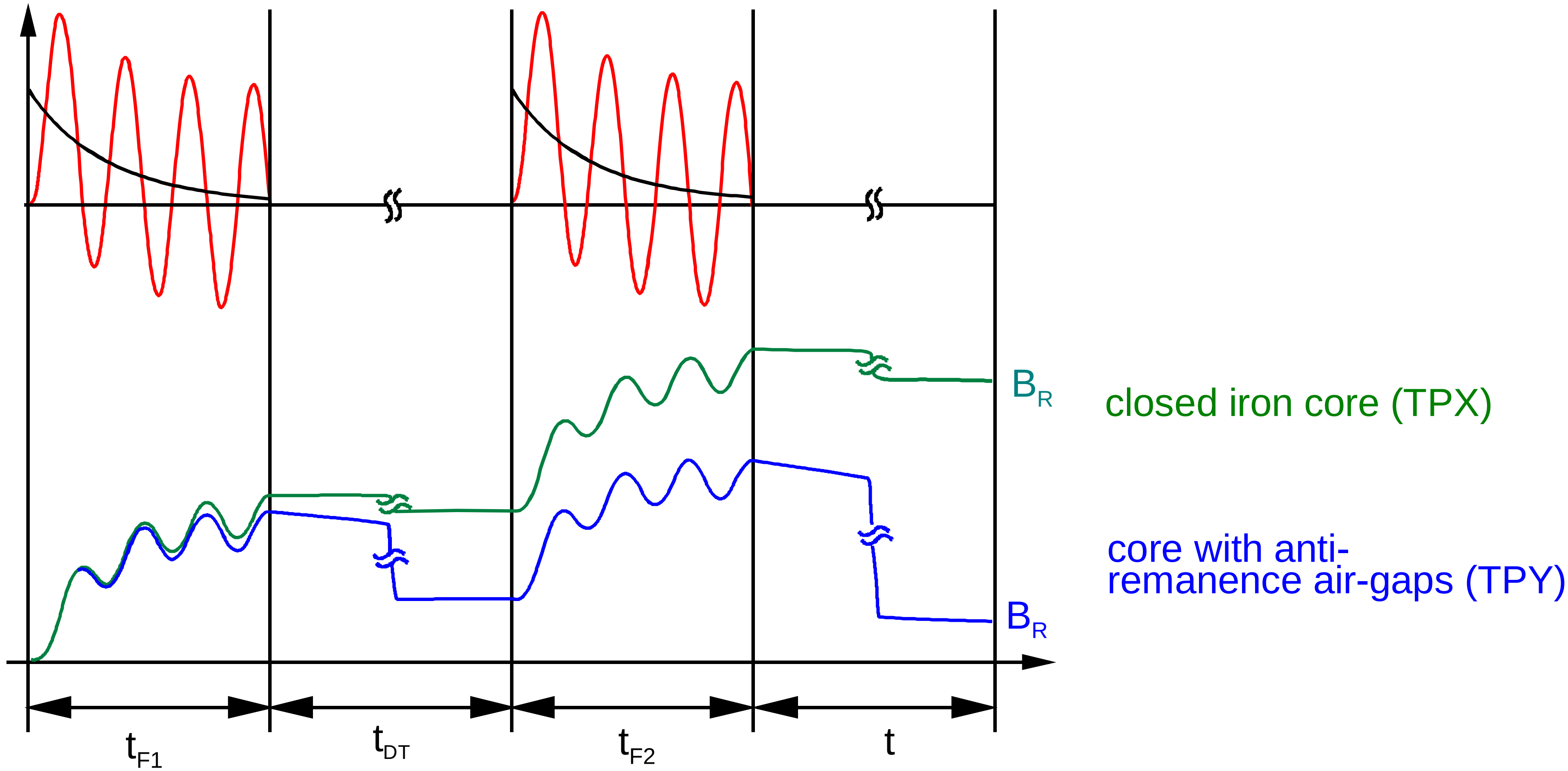
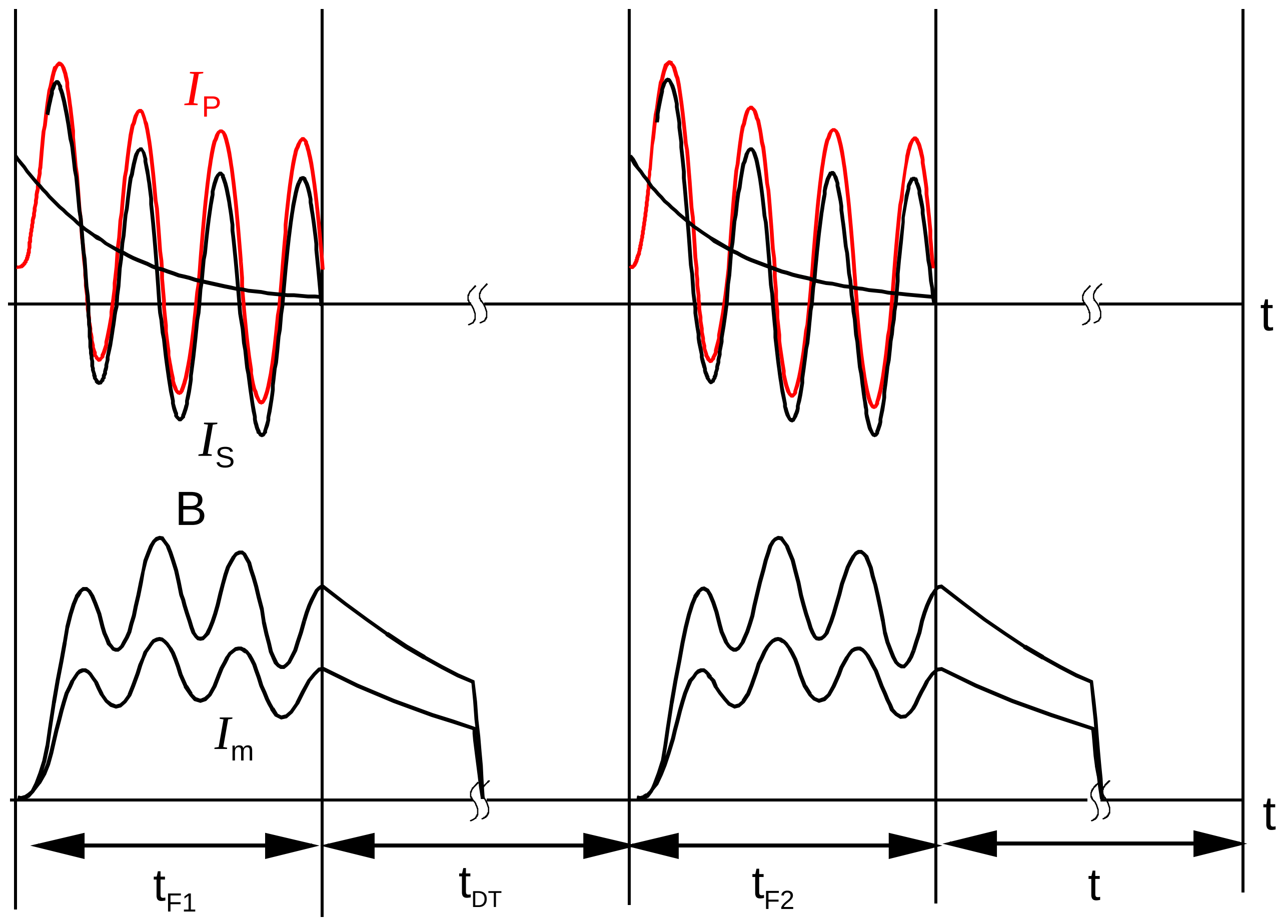
Current transformers TPX und TPY
Course of the flux with non-successful auto-reclosure



Current transformer with linear core (TPZ),
Course of the flux with non-successful auto-reclosure



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Dimensioning of CTs for protection application

$$ALF' = ALF \cdot \frac{P_i + P_N}{P_i + P_B} = n \cdot \frac{R_i + R_N}{R_i + R_B}$$

$$ALF = ALF' \cdot \frac{P_i + P_B}{P_i + P_N} = ALF' \cdot \frac{R_i + R_B}{R_i + R_N}$$

Rated CT burden: P_N

Internal CT burden: $P_i = R_i \cdot I_{2N}^2$

Actually connected burden : $P_B = R_B \cdot I_{2N}^2$

with: $R_B = R_L + R_R$ = total burden resistance
R_L = resistance of connecting cable
R_R = relay burden resistance

with $ALF' \geq K_{OD} \cdot \frac{I_{SC}}{I_N}$

Where K_{OD} is the total over-dimensioning factor:

$$K_{OD} \geq K_{TF} \cdot K_{Rem}$$

$$K_{Rem} = 1 + \frac{\%\ \text{remanence}}{100}$$

Theory:

No saturation during total fault duration: $K'_{TF} = \frac{B_{Max}}{\hat{B}_{\sim}} = 1 + wT_N = 1 + \frac{X_N}{R_N}$

No saturation for the specified time t_M: $K''_{TF} = \left[1 + \frac{\omega \cdot T_N \cdot T_S}{T_N - T_S}\left(e^{-\frac{t_M}{T_N}} - e^{-\frac{t_M}{T_S}}\right)\right]$

Practice:

$$K_{OD} = K_{TF}$$

Remanence only considered in extra high voltage systems (EHV)

K_{TF}-values acc. to relay manufacturers' guides

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Practical CT dimensioning using dimensioning factors K_{td} (required minimum time to saturation)

IEC 60044-1 and 60044-6

300/5 A, 5P20, VA (Rb= 1.0 Ω),
R_{ct}= 0.15 Ω

$$ALF' \geq K_{SSC} \cdot K_{td}$$

$$ALF' = \frac{R_{ct} + R_{b-rated}}{R_{ct} + R_{b-connected}} \cdot ALF$$

$$ALF \geq K_{td} \cdot \frac{I_{F-max}}{I_{pn}} \cdot \frac{R_{ct} + R_{b-connected}}{R_{ct} + R_{b-rated}}$$

BS 3839 (IEC: 60044-1 addendum)

$$E_{al} = \frac{I_{F-max}}{I_{pn}} \cdot K_{td} \cdot (R_{ct} + R_{b-con.}) \cdot I_{sn-CT}$$

$$U_{KN} \approx (0.8...0.85) \cdot E_{al}$$

ANSI C57.13

300/5 A, C100 (Rb= 1 Ω)

$$E_{al} \approx (U_{ANSI} + 20 \cdot 5 \cdot R_{ct}) = (20 \cdot 5 \cdot Z_{b-rated} + 20 \cdot 5 \cdot R_{ct})$$

$$20 \geq K_{td} \cdot \frac{I_{F-max}}{I_{pn}} \cdot \frac{R_{ct} + R_{b-connected}}{R_{ct} + R_{b-rated}}$$

Transient dim. factor: K_{td}

No saturation:	$1+X/R = 1+\omega \cdot T_p$
Differential relays:	1 (87BB: 0.5)
Distance relays:	2 to 4 close-in faults 5 to 10 zone end faults

O/C relays: I>> ALF' > ($I>>_{set}$ / I_n)

Coordination of CTs and digital relays
Summary

- Digital relays use intelligent algorithms and are therefore highly tolerant against CT saturation.
- In particular differential relays allow short time to saturation of ¼ cycle and below.
- Determination of transient dimensioning factors for short time to saturation must consider the real flux course after fault inception.
- With time to saturation < 10 ms, the critical point on wave of fault inception is not close to voltage zero-crossing (fully offset current), but varies and is closer to voltage maximum (a.c. current).
- CT dimensioning is normally based on relay specific K_{td} factors provided by manufacturers
- In practice, fully offset s.c. current has been assumed while remanence has been widely neglected for CT dimensioning.
- A new dimensioning factor is discussed in CIGRE WG B5.02, composed of more probable transient and remanence factors.

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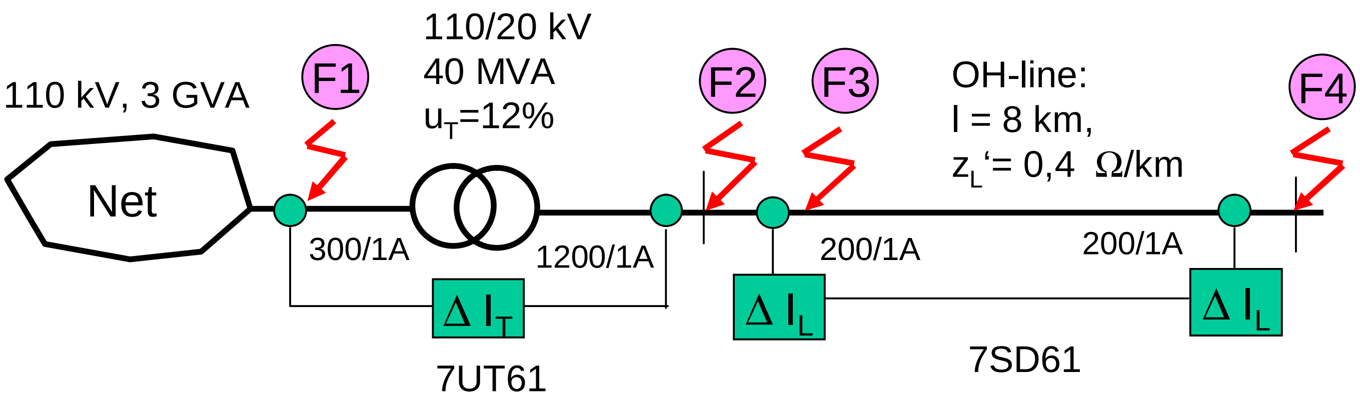
CT dimensioning for differential protection (1)

1. Calculation of fault currents



Impedances related to 110 kV:

$$\text{Net}: \quad Z_N = \frac{U_N^2[kV^2]}{S_{SC}''[MVA]} = \frac{110^2}{3000} = 4.03\ \Omega$$

$$\text{Transf.}: \quad Z_T = \frac{U_N^2[kV^2]}{P_{N-T}[MVA]} \cdot \frac{u_T[\%]}{100} = \frac{110^2}{40} \cdot \frac{12\%}{100} = 36.3\ \Omega$$

Impedances related to 20 kV:

$$\text{Net}: \quad Z_N = \frac{U_N^2[kV^2]}{S_{SC}''[MVA]} = \frac{20^2}{3000} = 0.13\ \Omega$$

$$\text{Transf.}: \quad Z_T = \frac{U_N^2[kV^2]}{P_{N-T}[MVA]} \cdot \frac{u_T[\%]}{100} = \frac{20^2}{40} \cdot \frac{12\%}{100} = 1.2\ \Omega$$

$$\text{Line}: \quad Z_L = l[km] \cdot z_L'[\Omega/km] = 8 \cdot 0{,}4 = 3{,}2\ \Omega$$

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CT dimensioning for differential protection (2)

F1 $$I_{F1} = \frac{1.1 \cdot U_N / \sqrt{3}}{Z_N} = \frac{1.1 \cdot 110kV/\sqrt{3}}{4.03\Omega} = 17.3\ kA$$

F3 $$I_{F3} = \frac{1.1 \cdot U_N / \sqrt{3}}{Z_N + Z_T} = \frac{1.1 \cdot 20kV/\sqrt{3}}{0.13\Omega + 1.2\Omega} = 9.55\ kA$$

F2 $$I_{F2} = \frac{1.1 \cdot U_N / \sqrt{3}}{Z_N + Z_T} = \frac{1,1 \cdot 110kV/\sqrt{3}}{4.03\Omega + 36.3\Omega} = 1.73\ kA$$

F4 $$I_{F4} = \frac{1.1 \cdot U_N / \sqrt{3}}{Z_N + Z_T + Z_L} = \frac{1,1 \cdot 20kV/\sqrt{3}}{0.13\Omega + 1.2\Omega + 3.2\Omega} = 2.8\ kA$$

Dimensioning of the 110 kV CTs for the transformer differential protection:

Manufacturer recommends for relay 7UT61:

1) Saturation free time ^{3} 4ms for internal faults

2) Over-dimensioning factor K_{TF} ^{3} 1,2 for through flowing currents (external faults)

The saturation free time of 3 ms corresponds to $K_{TF} \geq 0,75$

See diagram, page 59

Criterion 1) therefore reads:

$$ALF' \geq K_{TF} \cdot \frac{I_{F1}}{I_N} = 0,75 \cdot \frac{17300}{300} = 43$$

For criterion 2) we get:

$$ALF' \geq K_{TF} \cdot \frac{I_{F2}}{I_N} = 1,2 \cdot \frac{1730}{300} = 7$$

The 110 kV CTs must be dimensioned according to criterion 1).

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CT dimensioning for differential protection (3)

We try to use a CT type: 300/1, 10 VA, 5P?, internal burden 2 VA.

$$ALF \geq \frac{P_i + P_{operation}}{P_i + P_{rated}} \cdot ALF' = \frac{2+2.5}{2+10} \cdot 43 = 16.1$$ (Connected burden estimated to about 2.5 VA)

Chosen, with a security margin : 300 /1 A, 5P20, 10 VA, $R_2 \leq$ 2 Ohm ($P_i \leq$ 2VA)

Specification of the CTs at the 20 kV side of the transformer:

It is good relaying practice to choose the same dimensioning as for the CTs on the 110 kV side:

1200/1, 10 VA, 5P20, $R_2 \leq$ 2 Ohm ($P_i \leq$ 2VA)

Dimensioning of the 20 kV CTs for line protection:

For relay 7SD61, it is required:

1') Saturation free time ^{3} 3ms for internal faults
2') Over-dimensioning factor K_{TF} ^{3} 1.2
for through flowing currents (external faults)

The saturation free time of **3** ms corresponds to $K_{TF} \geq 0.5$
See diagram, page 59

Criterion 1') therefore reads:

$$ALF' \geq K_{TF} \cdot \frac{I_{F3}}{I_N} = 0.5 \cdot \frac{9550}{200} = 24$$

For criterion 2') we get:

$$ALF' \geq K_{TF} \cdot \frac{I_{F4}}{I_N} = 1.2 \cdot \frac{2800}{200} = 16.8$$

The 20 kV line CTs must be dimensioned according to criterion 1').

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CT dimensioning for differential protection (4)

For the 20 kV line we have considered the CT type: 200/5 A, 5 VA, 5P?, internal burden ca. 1 VA

$$ALF \geq \frac{P_i + P_{operation}}{P_i + P_{rated}} \cdot ALF' = \frac{1+1}{1+5} \cdot 24 = 8$$

(Connected burden about 1 VA)

Specification of line CTs:

We choose the next higher standard accuracy limit factor ALF=10 :
Herewith, we can specify: CT Type TPX, 200/5 A, 5 VA, 5P10, $R_2 \leq 0.04$ Ohm ($P_i \leq 1$ VA)

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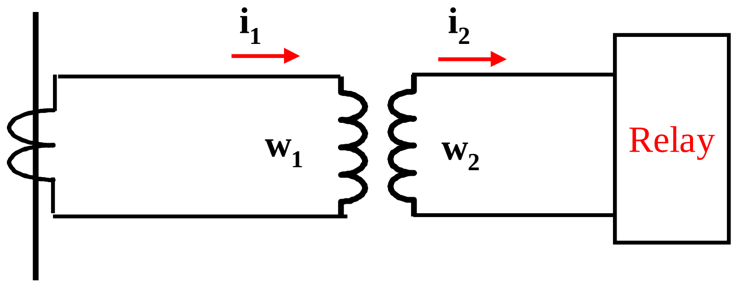
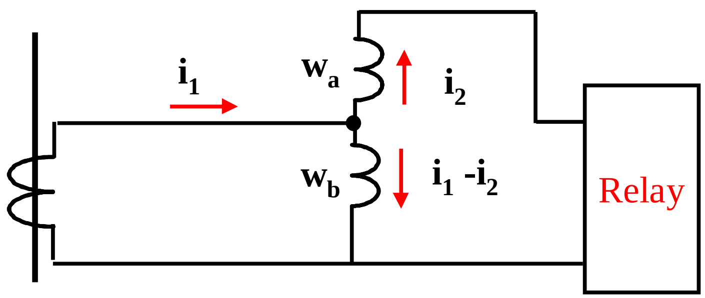
Interposing CTs, Basic versions



separate winding connection

$$i_2 = \frac{w_1}{w_2} \cdot i_1$$



auto-transformer connection

$$i_2 = \frac{w_b}{w_a + w_b} \cdot i_1$$

No galvanic separation!

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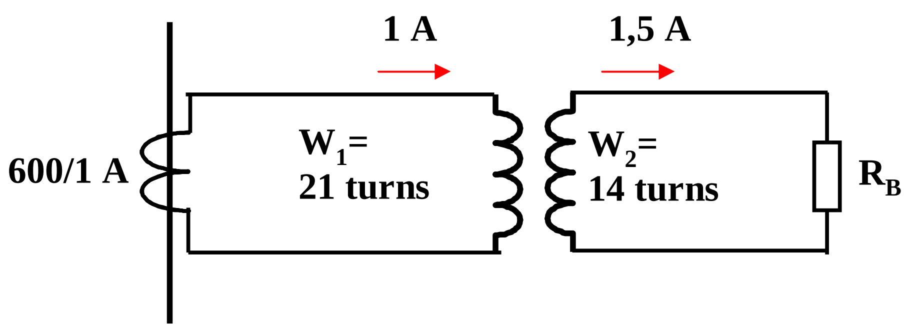
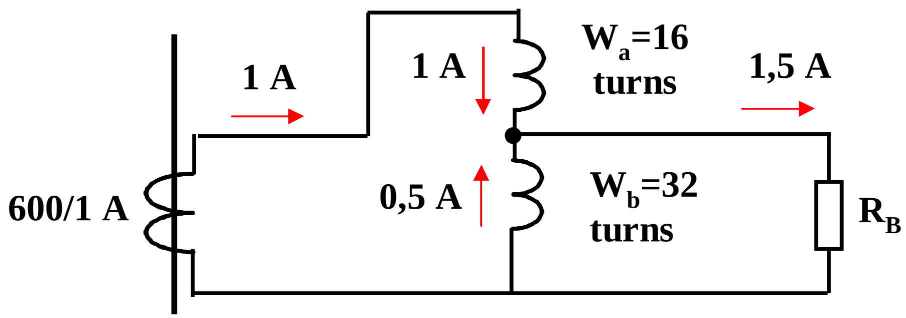
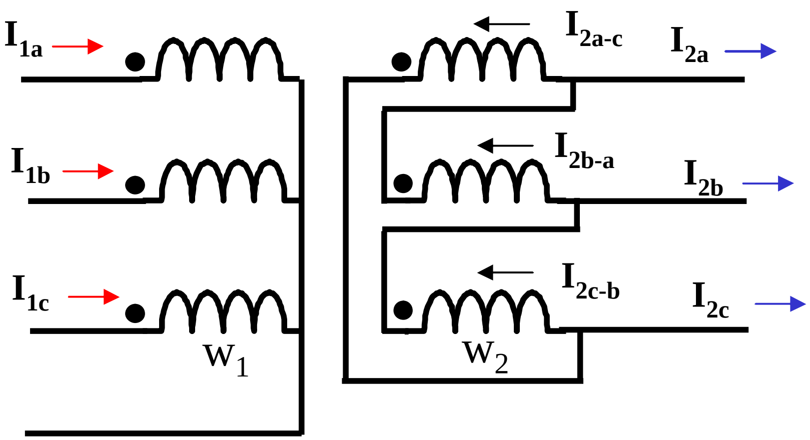
Interposing CTs, Example

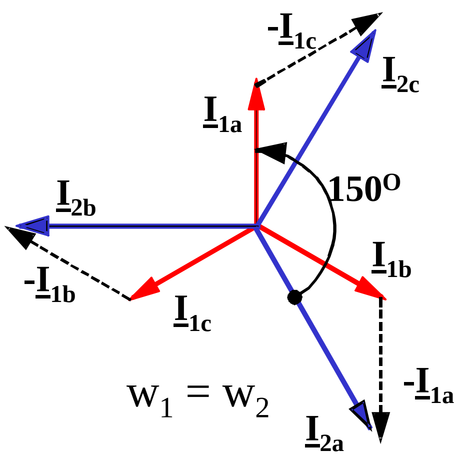




Interposing CTs in Y-Δ-connection

Yd5





$$\underline{I}_1 = \frac{1}{\sqrt{3}} \cdot \underline{I}_2 \cdot \frac{w_2}{w_1} \cdot e^{j \cdot (n \cdot 30^o)}$$

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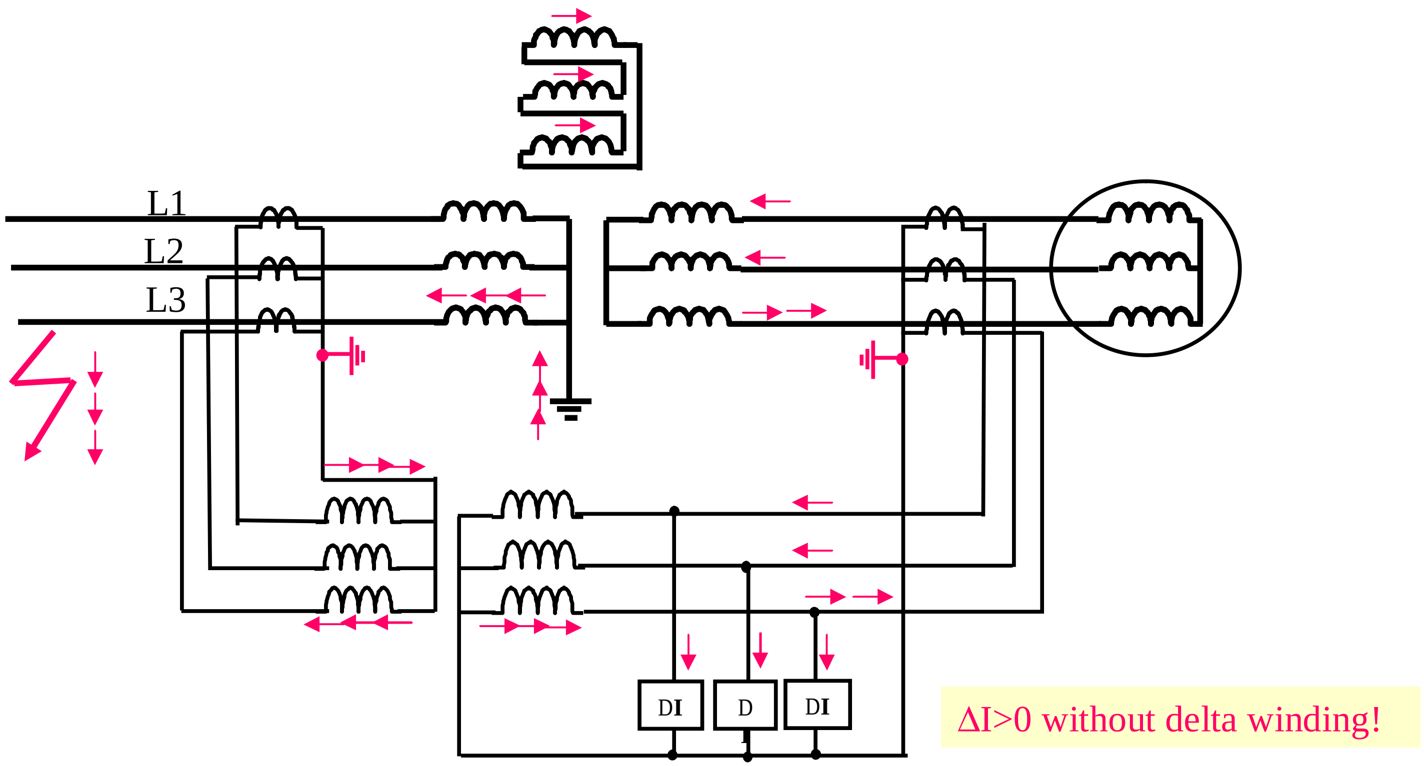
False operation during external fault of transformer differential protection without zero-sequence current filter



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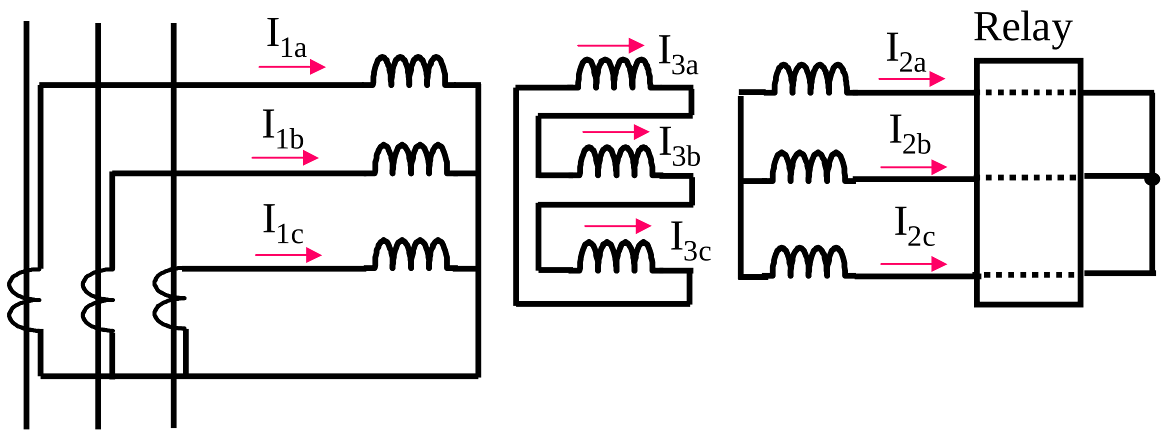
Zero-sequence current filter



$$\underline{I}_{1a} \cdot w_1 + \underline{I}_{2a} \cdot w_{w2} + \underline{I}_{3a} \cdot w_3 = 0$$
$$\underline{I}_{1b} \cdot w_1 + \underline{I}_{2b} \cdot w_{w2} + \underline{I}_{3b} \cdot w_3 = 0$$
$$\underline{I}_{1c} \cdot w_1 + \underline{I}_{2c} \cdot w_{w2} + \underline{I}_{3c} \cdot w_3 = 0$$
$$\underline{I}_{3a} = \underline{I}_{3b} = \underline{I}_{3c}$$
$$\underline{I}_{2a} + \underline{I}_{2b} + \underline{I}_{2c} = 0$$

$$\underline{I}_{3a} = \underline{I}_{3b} = \underline{I}_{3c} = \frac{w_1}{w_3} \cdot \frac{\underline{I}_{1a} + \underline{I}_{1b} + \underline{I}_{1c}}{3} = \frac{\underline{I}_E}{3}$$
$$\underline{I}_{2a} = \frac{w_1}{w_2}\left(\underline{I}_{1a} - \frac{\underline{I}_{1a} + \underline{I}_{1b} + \underline{I}_{1c}}{3}\right)$$
$$\underline{I}_{2b} = \frac{w_1}{w_2}\left(\underline{I}_{1b} - \frac{\underline{I}_{1a} + \underline{I}_{1b} + \underline{I}_{1c}}{3}\right)$$
$$\underline{I}_{2c} = \frac{w_1}{w_2}\left(\underline{I}_{1c} - \frac{\underline{I}_{1a} + \underline{I}_{1b} + \underline{I}_{1c}}{3}\right)$$

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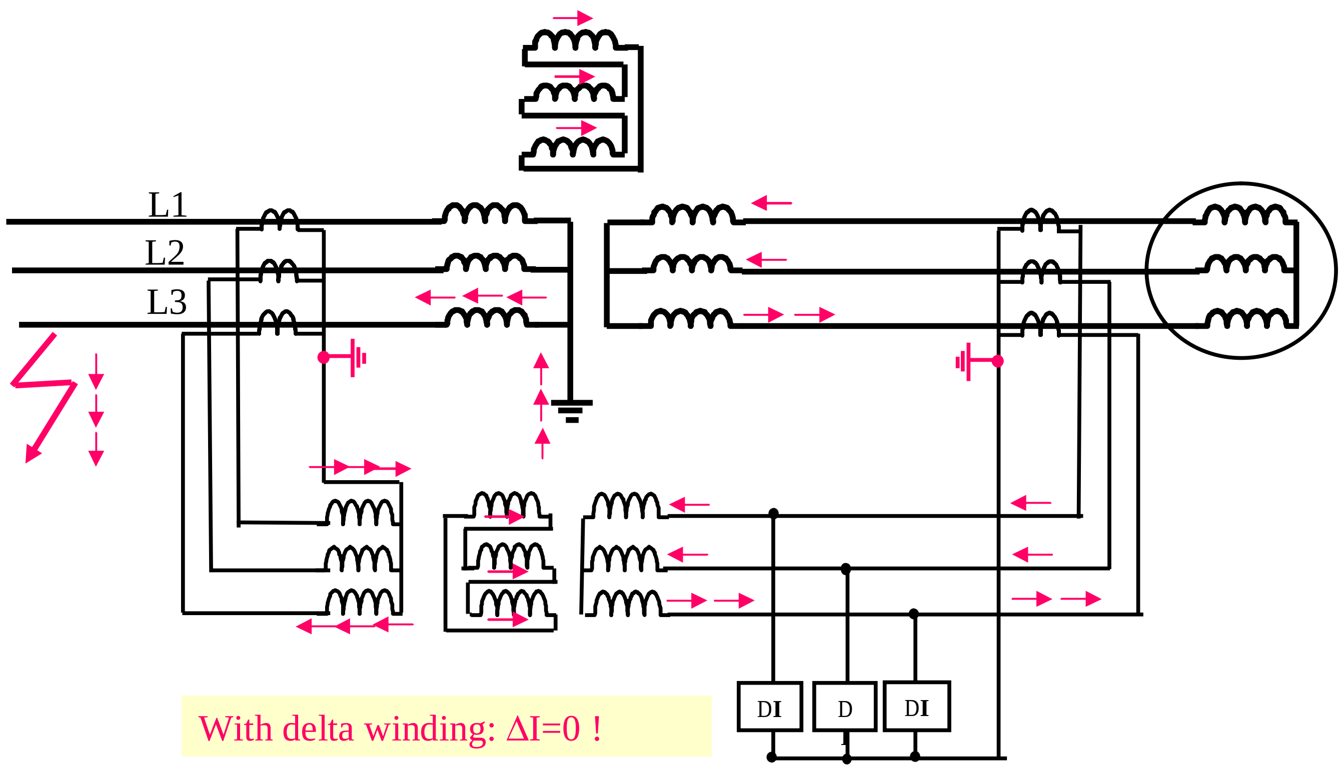
Biasing of transformer differential protection during external earth fault with zero-sequence current filter (closed delta winding)



With delta winding: ΔI=0 !

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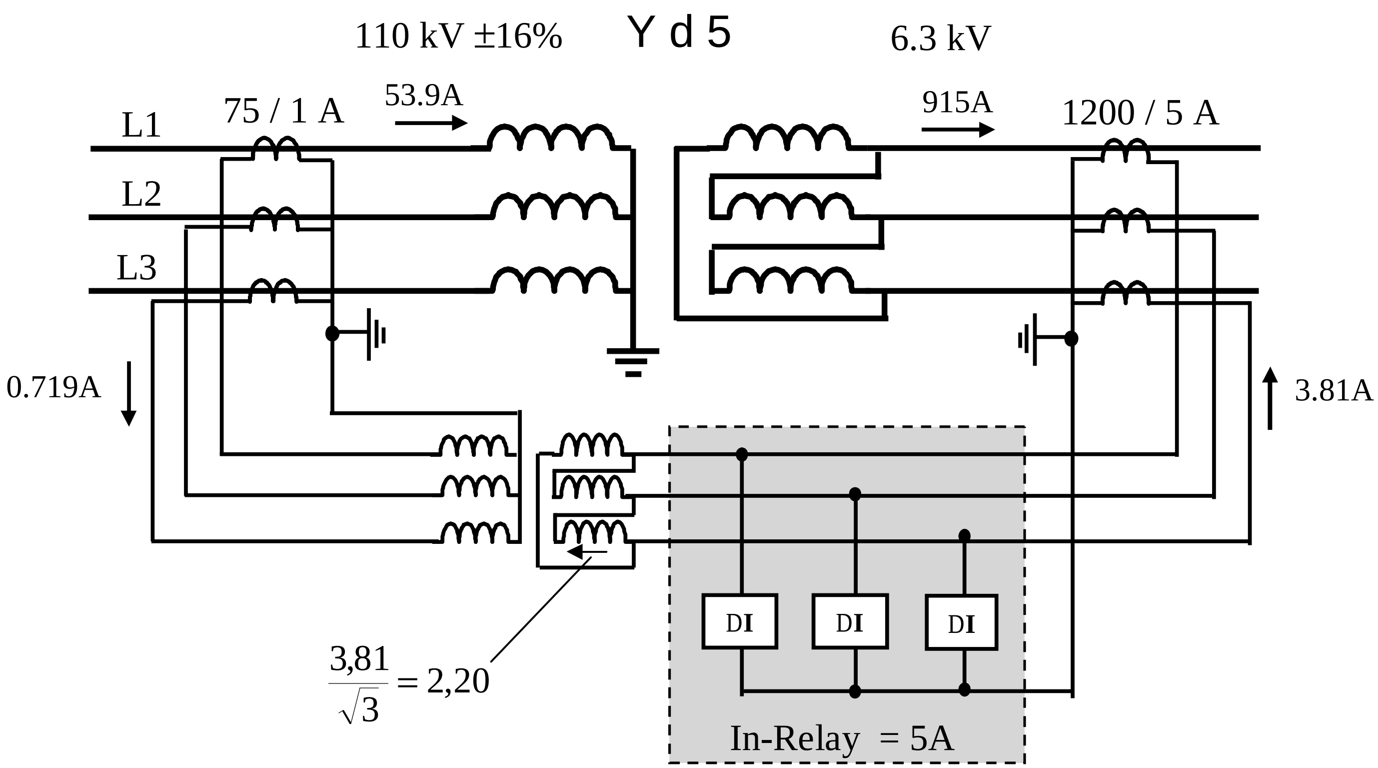
Current matching with interposing CTs (1)
Calculation example



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Current matching with interposing CTs (2)
Calculation example

<u>Current transformation ratio:</u>
We take through flowing rated current as reference:
:
<u>110kV-side:</u>
Mean current value of upper and lower tap changer position:

$$I_1 = \frac{10{,}000\text{kVA}}{\sqrt{3}\cdot(110\text{kV}+16\%} = 45.2\text{A} \qquad I_1' = \frac{10{,}000\text{kVA}}{\sqrt{3}\cdot(110\text{kV}-16\%} = 62.5\text{A} \qquad I_{1-\text{mean}} = \frac{45.2+62.5}{2} = 53.9\text{A}$$

<u>6 kV-side:</u>

$$I_2 = \frac{10.000\text{kVA}}{\sqrt{3}\cdot 6.3\text{kV}} = 915\text{A}$$

The corresponding secondary currents are:

$$i_1 = 53.9 \cdot \frac{1}{75} = 0.719\text{ A}$$ and $$i_2 = 915 \cdot \frac{5}{1200} = 3.813$$

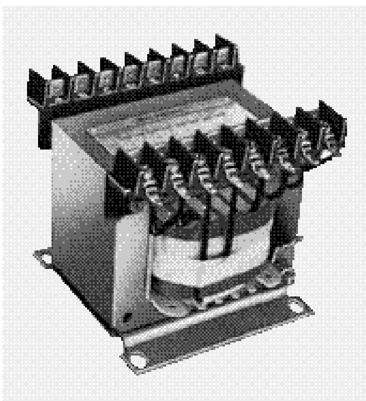
The current in the star connected winding of the interposing transformer is i_1

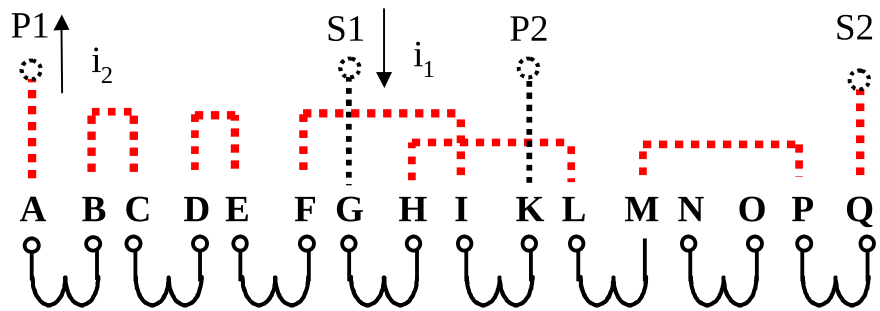
The current in the delta connected winding is: $i_2/\sqrt{3}$.

The ratio of the interposing CT must be :

$$\frac{w_1}{w_2} = \frac{i_2/\sqrt{3}}{i_1} = \frac{3.813/\sqrt{3}}{0.719} = \frac{2.202}{0.719} = 3.06$$

Link selectable interposing CT 4AM5170-7AA





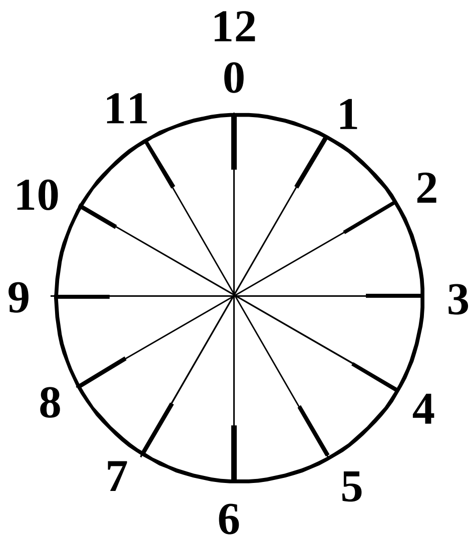
1	2	7	16	1	2	7	16	**Windings**
0,013	0,025	0,08	0,75	0,013	0,025	0,08	0,75	**R in Ohm**
2	4	14	32	2	4	14	32	**U-max. in V**
5	5	5	1	5	5	5	1	**Rated current in A**

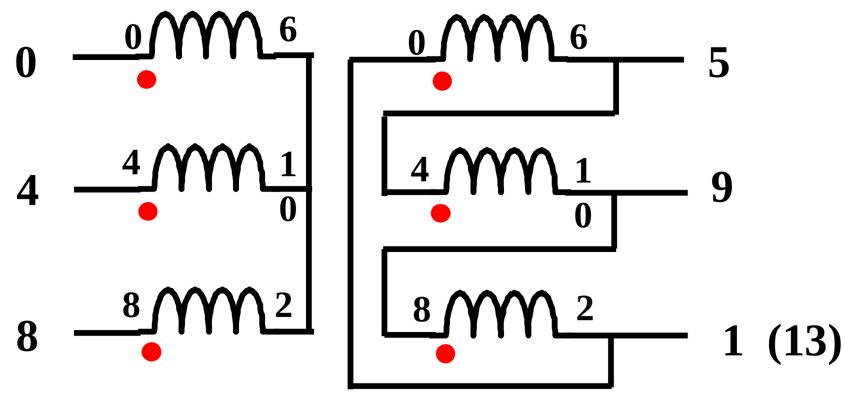
$$\frac{w_1}{w_2} = \frac{i_2/\sqrt{3}}{i_1} = \frac{3{,}813/\sqrt{3}}{0{,}719} = \frac{2{,}202}{0{,}719} = 3.06$$

$$\text{chosen}: \frac{w_1}{w_2} = \frac{16+16+2}{7+2+1+1} = \frac{34}{11} = 3{,}09$$

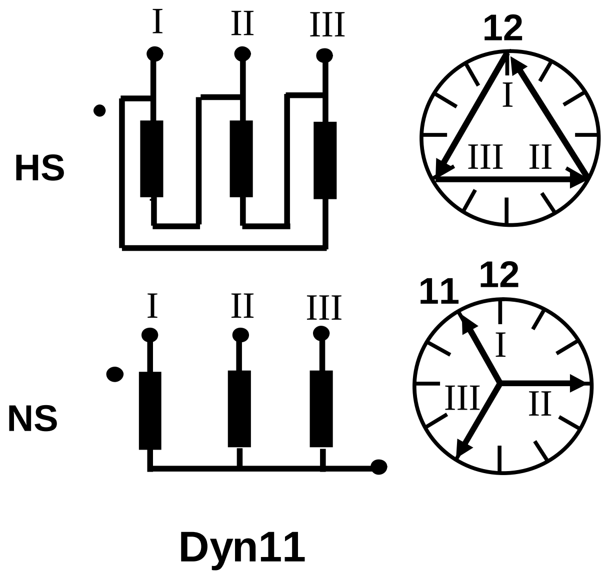
Connection and links as shown.

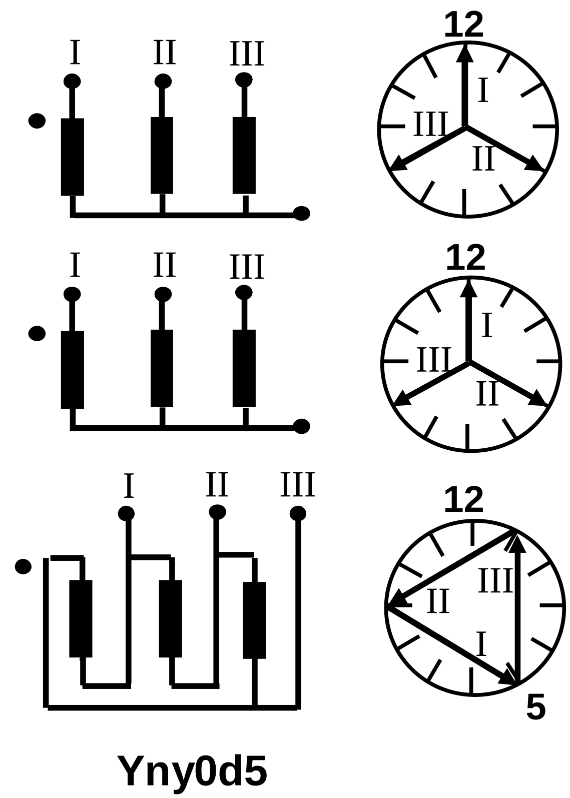
Designation of transformer or CT vector groups (1)
Clock-wise notation according to IEC 60076-1



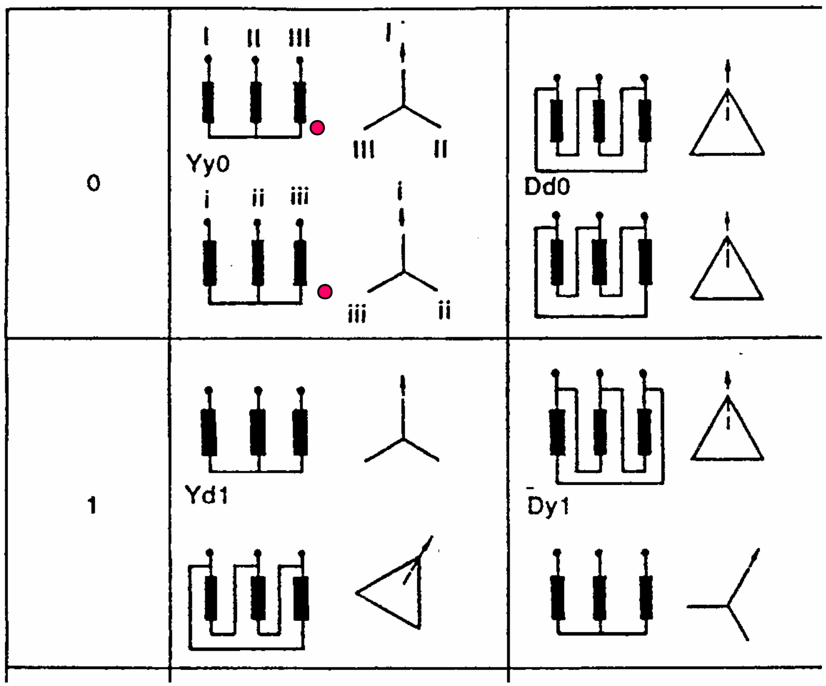


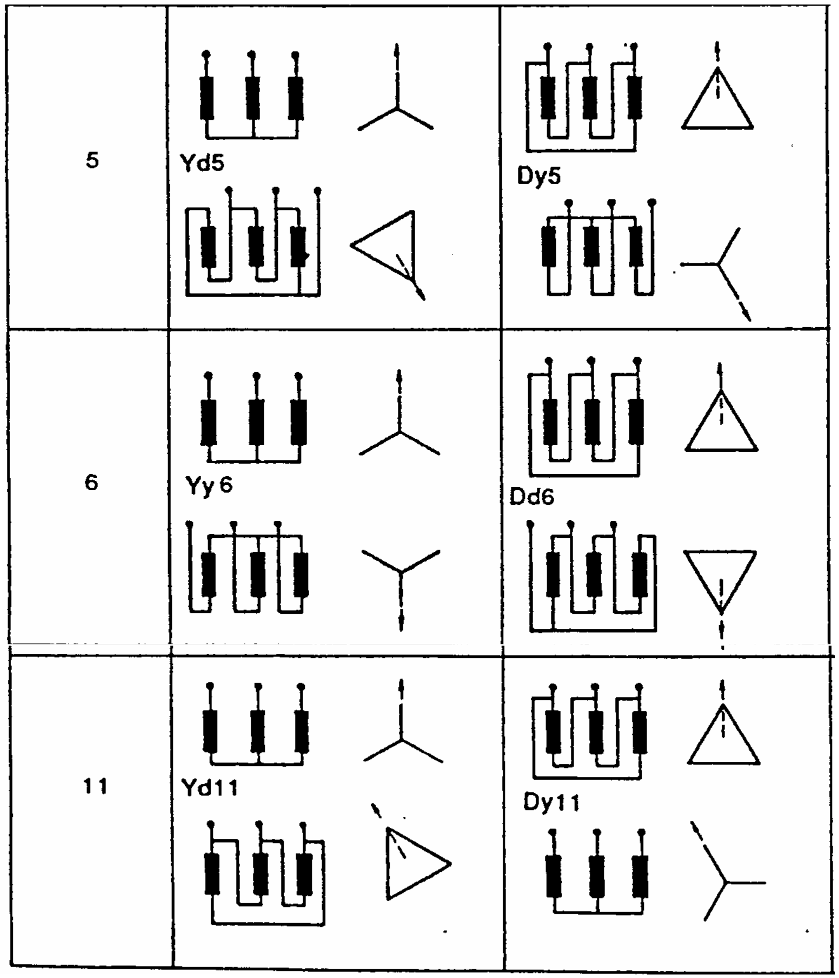
Designation of transformer or CT vector groups (2)
Clock-wise notation according to IEC 60076-1, examples





Frequently used vector groups (IEC 60076-1)





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Finding the vector group by using the clock principle

Proceed in the following steps:

1. Starting on the high voltage winding, the phase connection terminals are numbered with 0, 4, 8 (always $4 \times 30^{O}= 120^{O}$ phase shift).

2. The opposite end of each winding is labelled with a number incremented by +6 relative to the phase connection ($6x\ 30^{O} =180^{O}$).

3. The secondary windings are numbered the same. In this context it is assumed that the polarity of the windings is the same in the diagram. (If in doubt, polarity marks may also be applied.)

4. The phase connection is labelled with the average value of the corresponding terminal designations belonging to the winding terminals connected to this phase terminal, e.g. (6+4)/2= 5

5. The difference between the high and low voltage side terminal numbers of same phases corresponds each with the vector group number, being Yd5 in this case.

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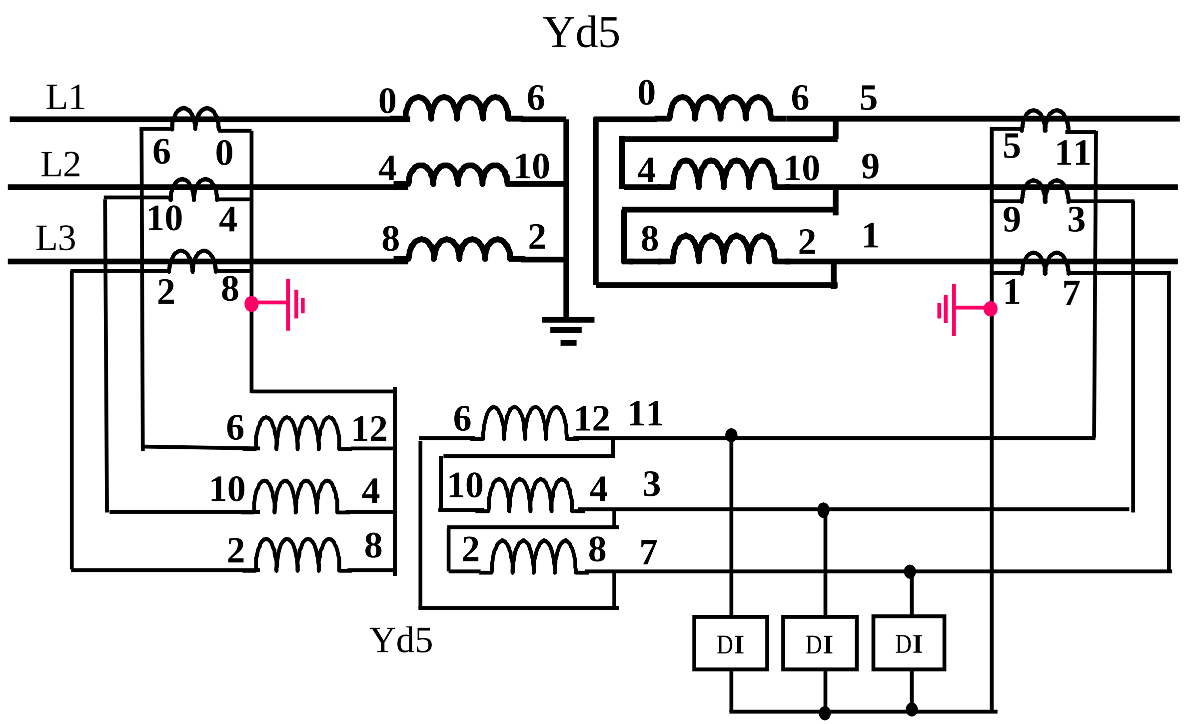
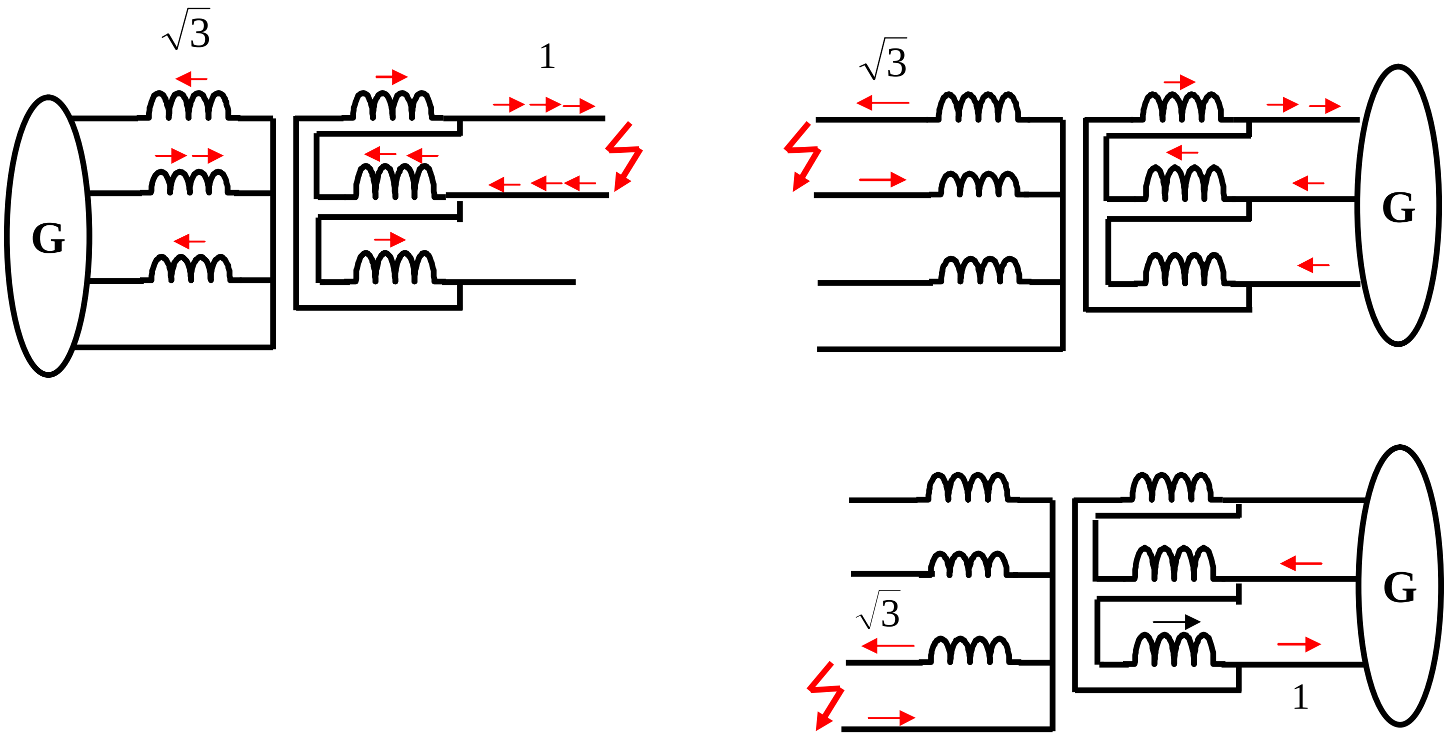
Checking the connections of transformer differential protection using the clock-wise notation method



Current distribution in Y-Δ-transformer circuits for different external fault types



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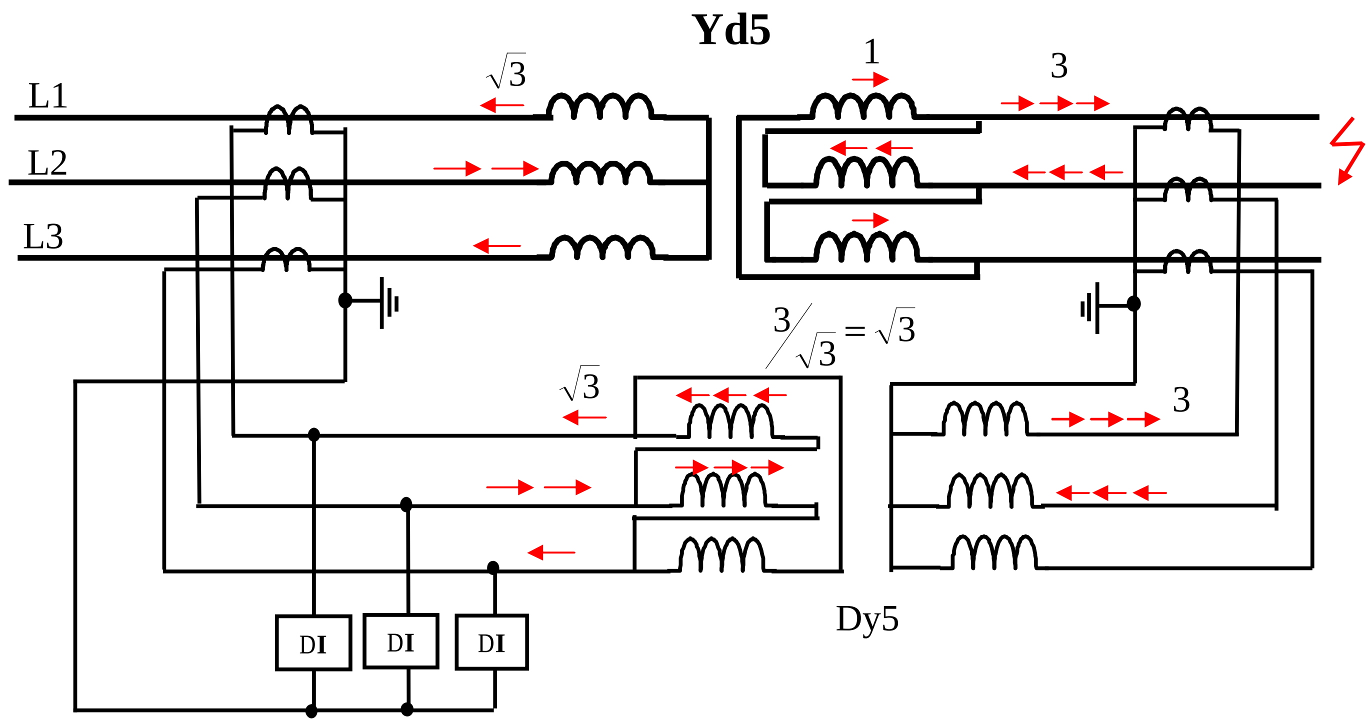
Checking the connections of transformer differential protection using the arrow method (two-phase fault)



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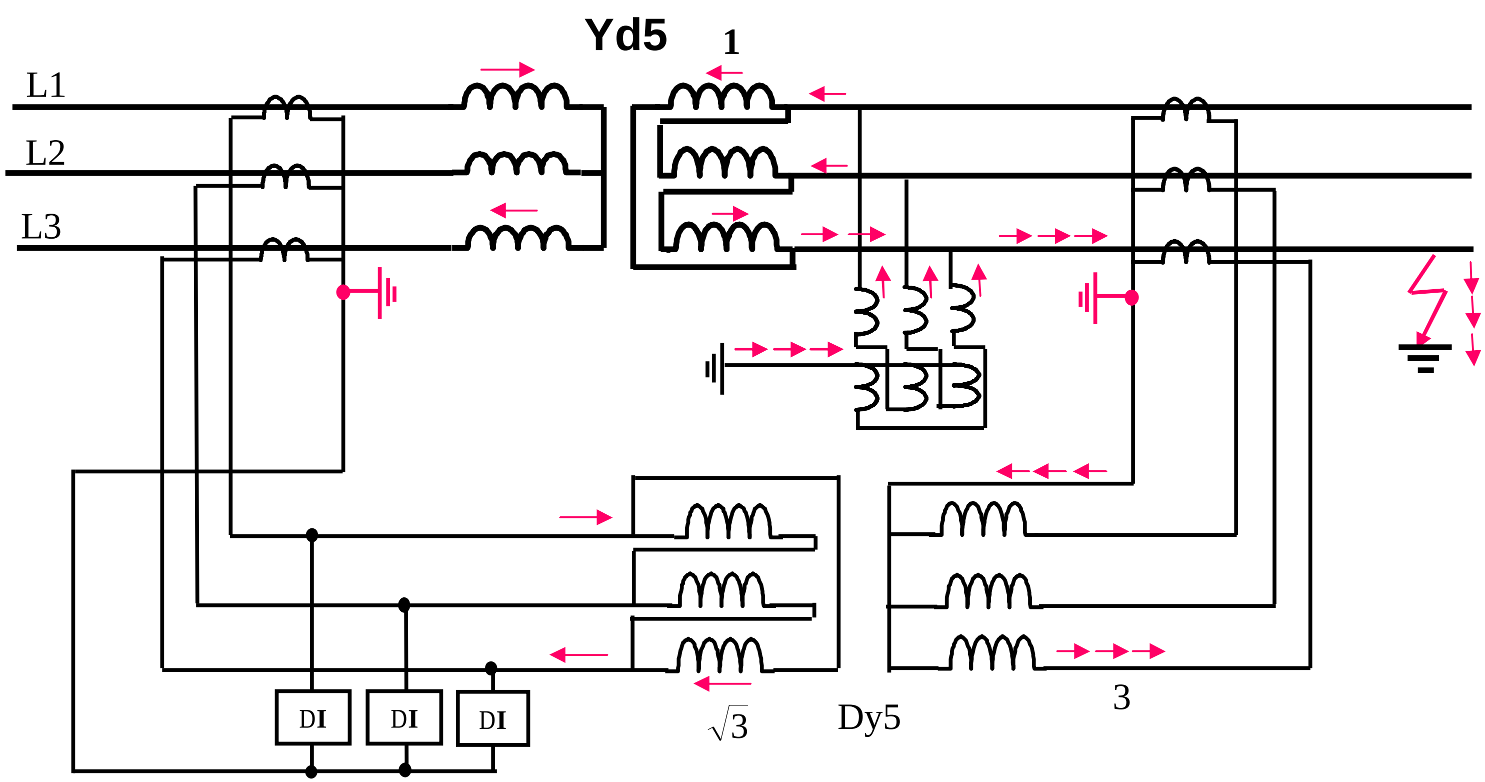
Checking the connections of transformer differential protection using the arrow method (single-phase earth fault)



Digital Differential Protection

Communications

Gerhard Ziegler

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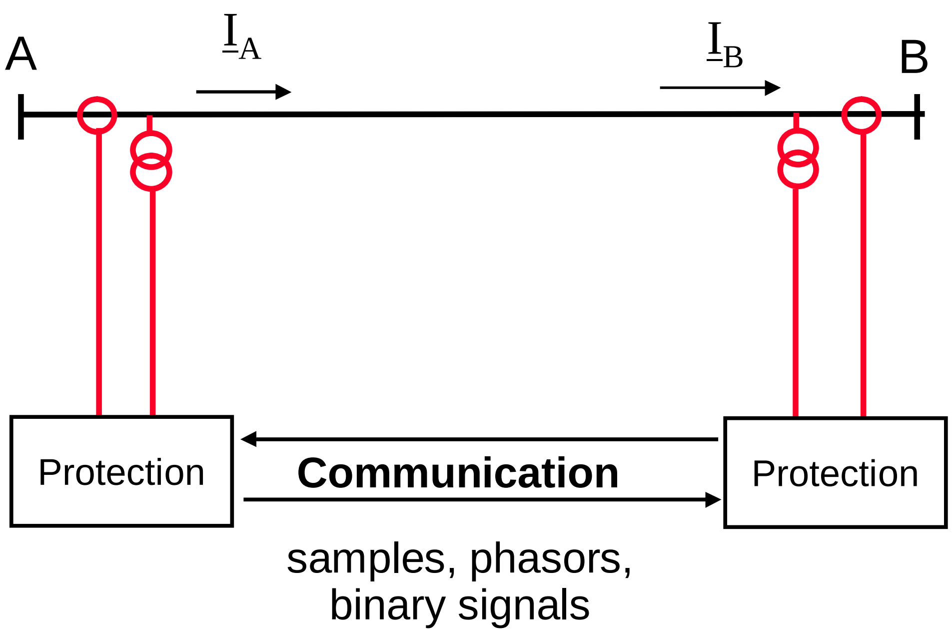
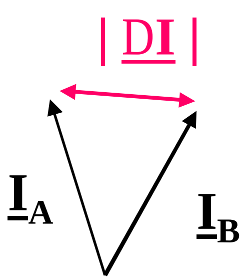
Comparison protection

Absolute selectivity by using communication



- Directial comparison
  distance protection
  Exchange of YES/NO signals
  (e.g. fault forward / reverse)

- Current comparison (phasors)
  differential protection



$$| \underline{\Delta I} | = | \underline{I}_A - \underline{I}_B | > I_{pick\text{-}up}$$

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Signal transmission channels for differential relaying

Pilot wires

- AC (50/60 Hz), voice frequency and digital communication (128 - kbit/s)
- for short distances (< about 20 km)
- influenced by earth short-circuit currents!

Optical fibres

- wide-band communication (n · 64 kbit/s)
- digital signal transmission (PCM)
- up to about 150 km without repeater stations
- noise proof

Digital microwave channels 2 - 10 GHz

- wide-band communication (n · 64 kbit/s)
- digital signal transmission (PCM)
- up to about 50 km (sight connection)
- dependent on weather conditions (fading)

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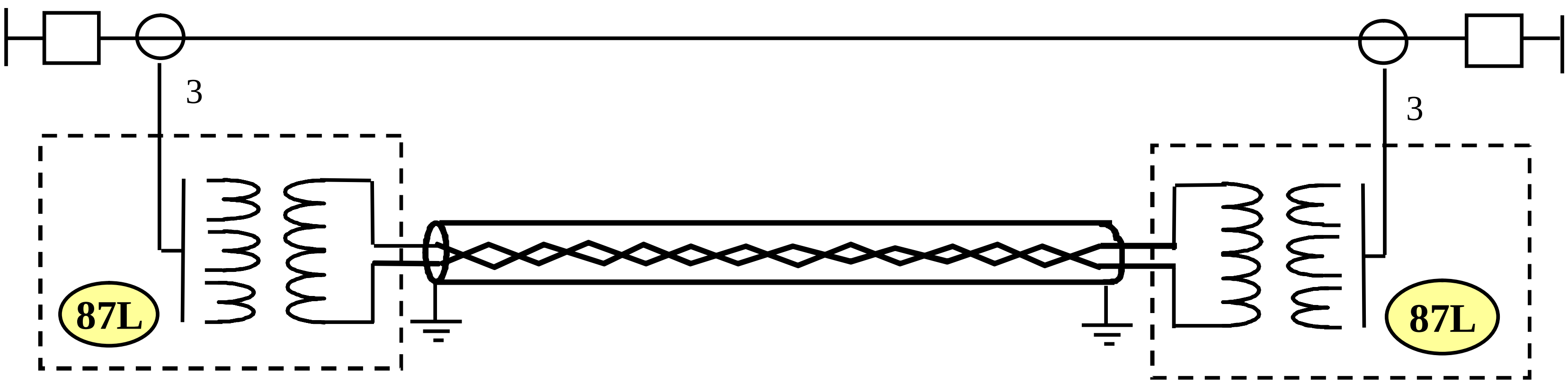
Analog pilot wire differential relaying



- Pilot wires are normally operated insulated form earth
- Voltage limiters (glow dischargers) connected to earth , as used with telephone lines, are not allowed!

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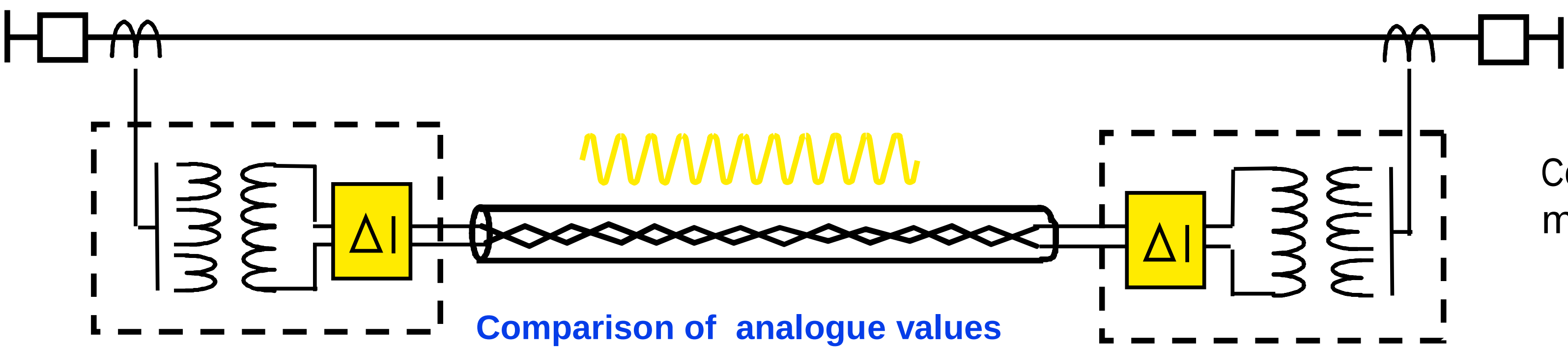
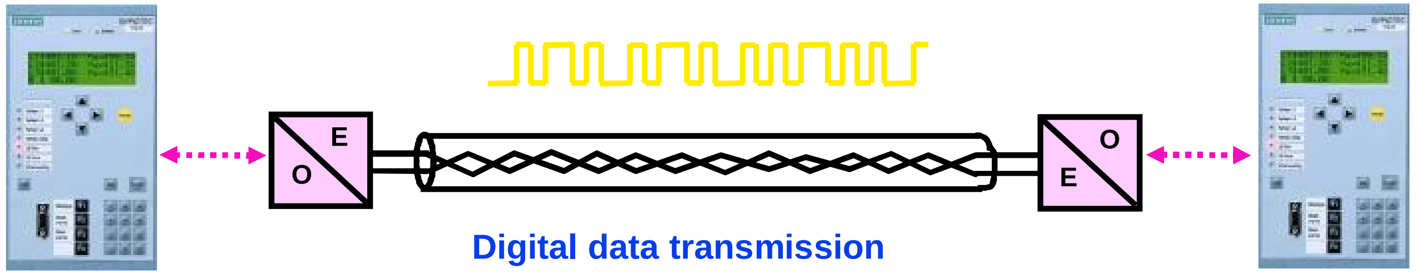
Relay-to-Relay pilot wires communication
New technology on existing (copper-) pilots

Traditional:



Composed current measurement

Modern:



Phase segregated measurement

64 kbps bi-directional
4 value digital code (2B1Q)
Amplitude and phase modulation
Spectrum mid frequency: 80 kHz

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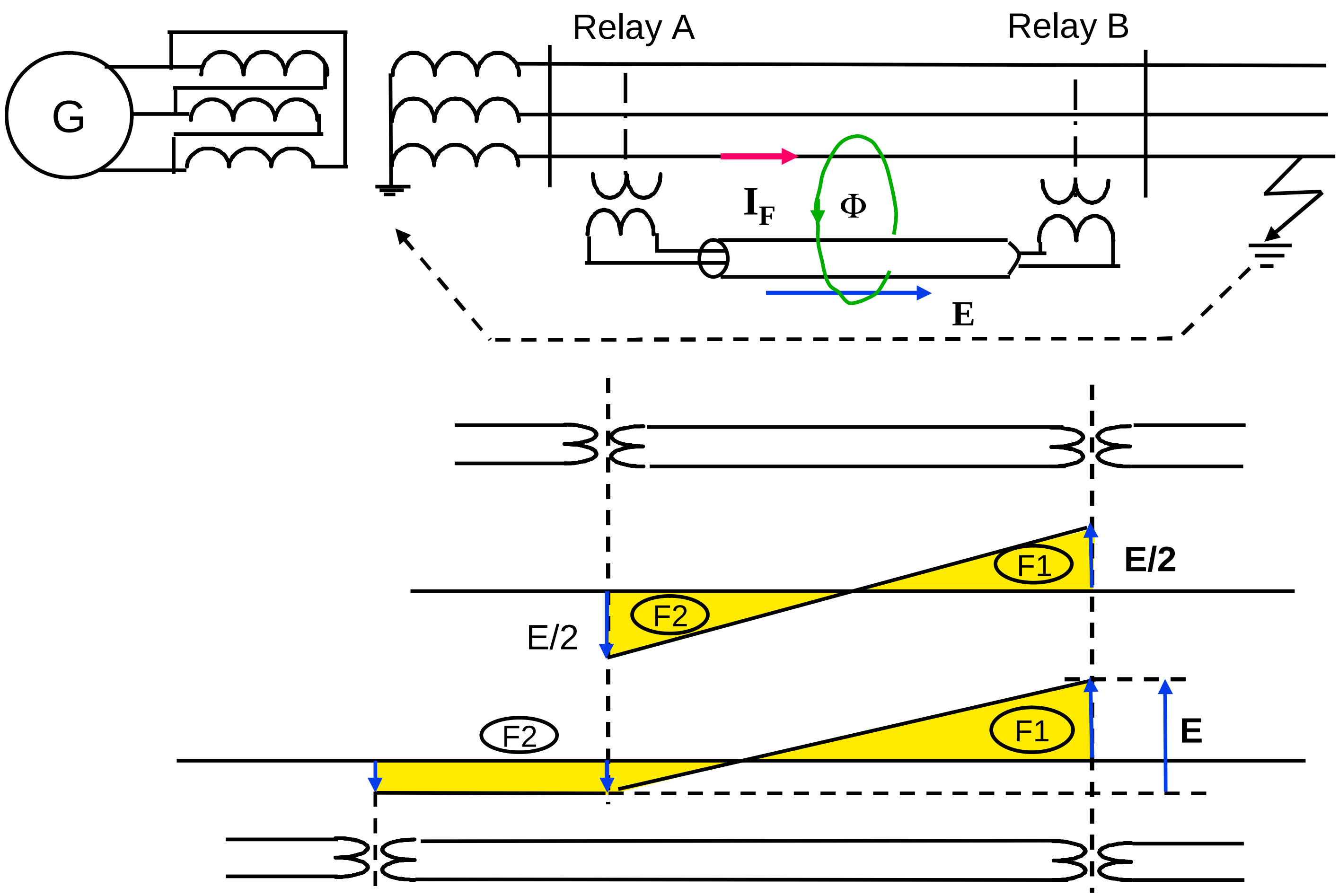
Wire pilot cables
Longitudinal voltage induced by earth currents



A) Symmetrical coupling along the pilot cable

B) Unsymmetrical Coupling along the pilot cable

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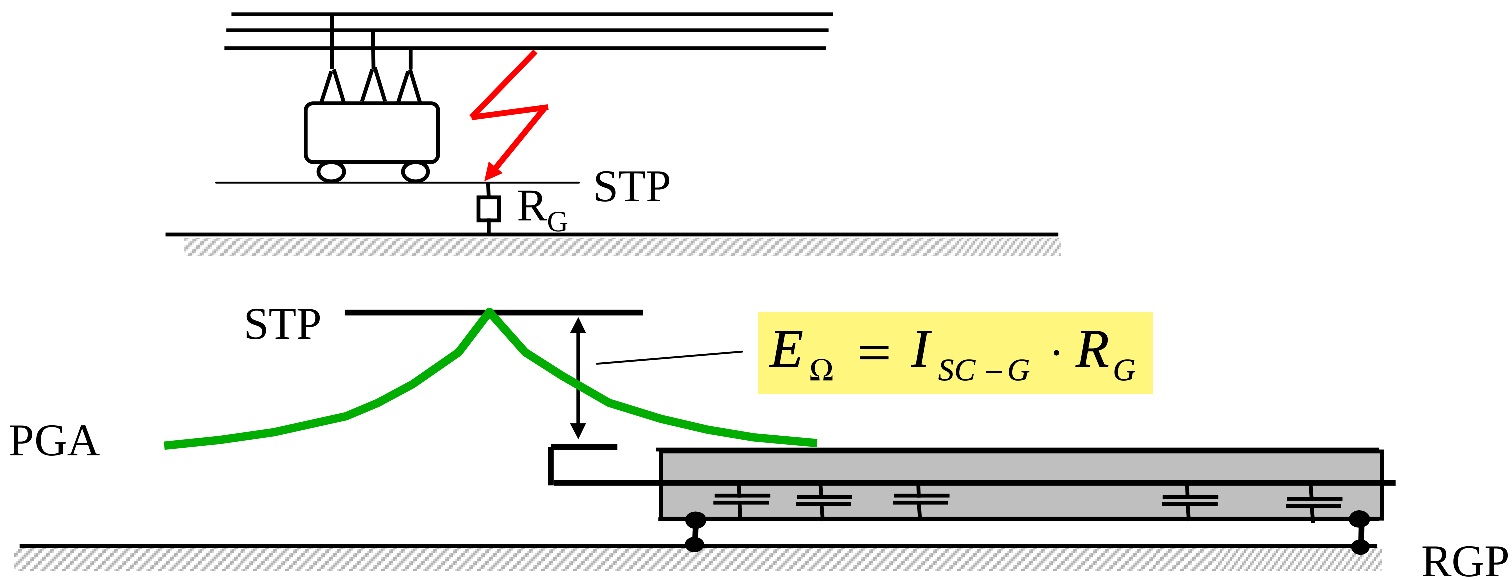
Disturbance voltage caused by rise in station potential

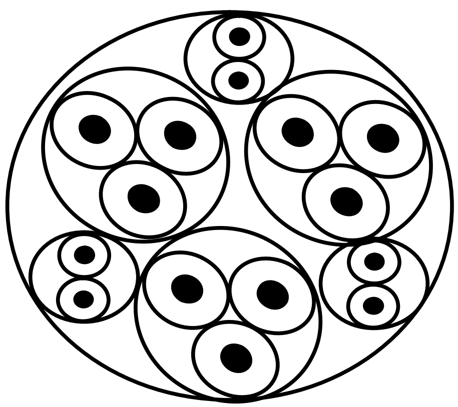


Legend:

R_G	station grounding resistance
STP	station potential
PGA	potential gradient area
RGP	remote ground potential
E	station potential rise against remote ground (ohmic coupled disturbance voltage)

HV insulated protection pilot cable (example)

core diameter	pilot resistance		pilot capacitance	test voltage (r.m.s. value)				
mm	Core Ω/km	Loop Ω/km	nF/km	core-core kV	core-shield kV	triple core to triple core kV	pair to pair kV	pair to triple core kV
1,4	11,9	---	---	2,5	8	8		
0,8	---	73,2	60	2	2		2	8



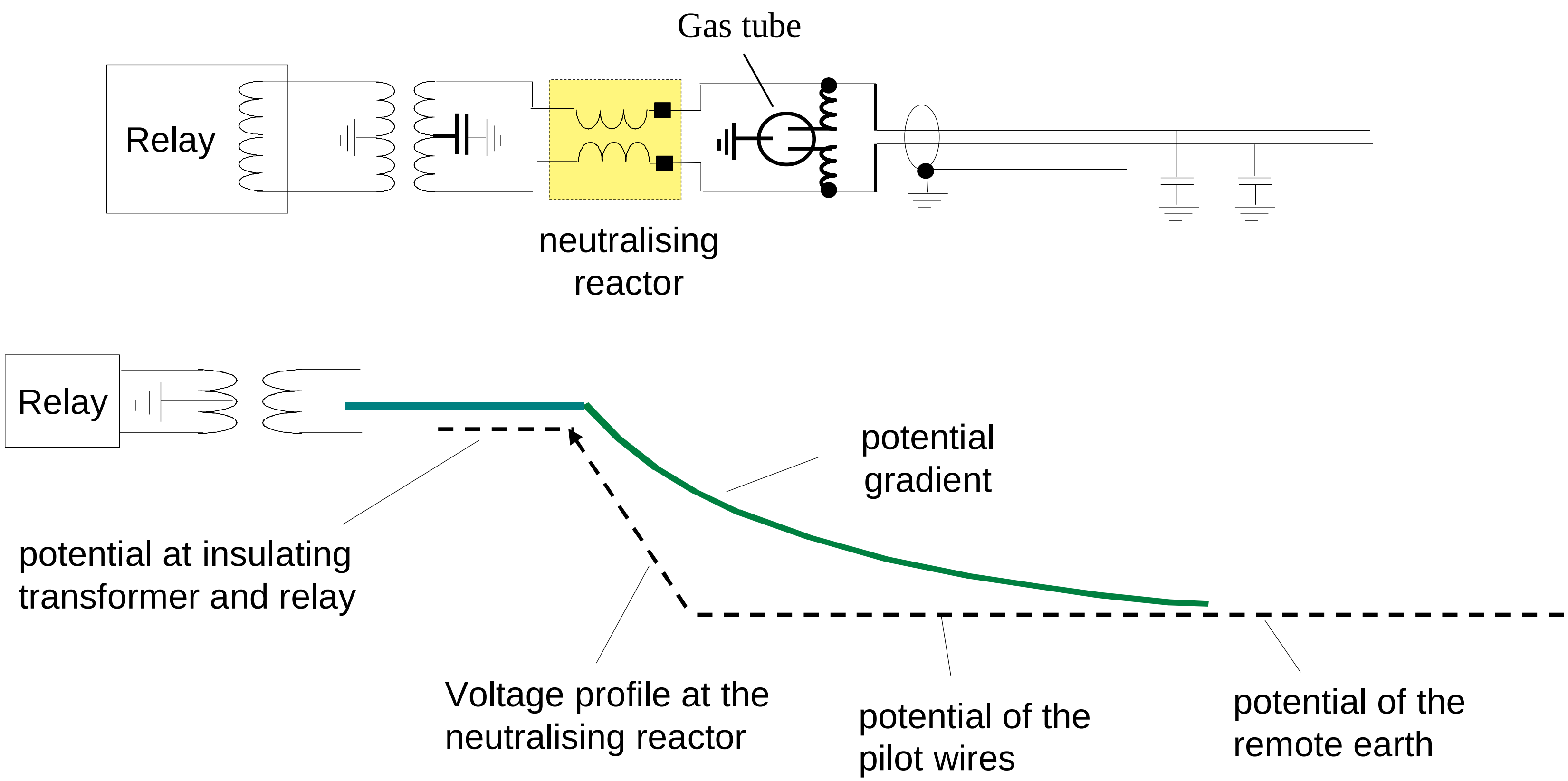
Symmetry: better 10^{-3} (60 db) at 800/1000 Hz

better 10^{-4} (80 db) at 50/60 Hz

$(U_q < 10^{-4} \cdot U_l)$

American practice

Neutralising reactor to compensate potential rise at the station



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Optic fibre (OF) Cable

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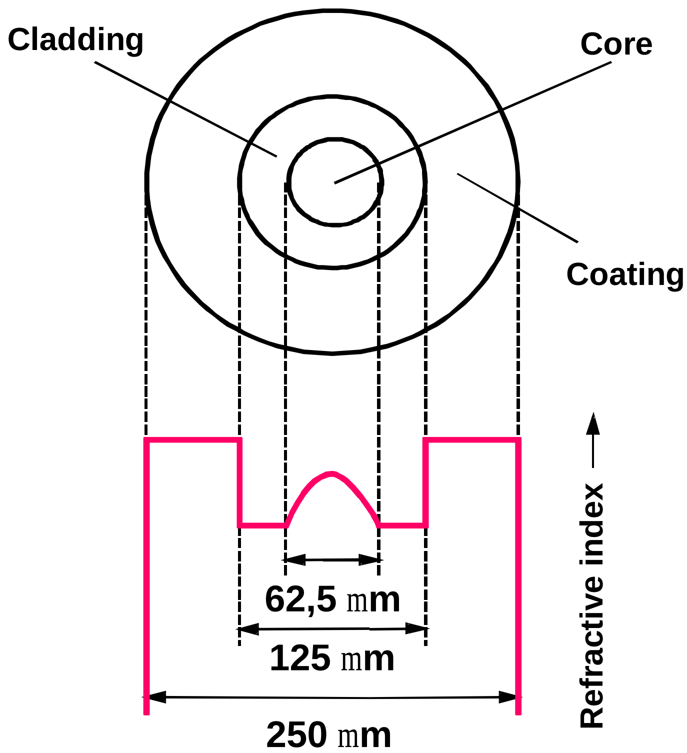
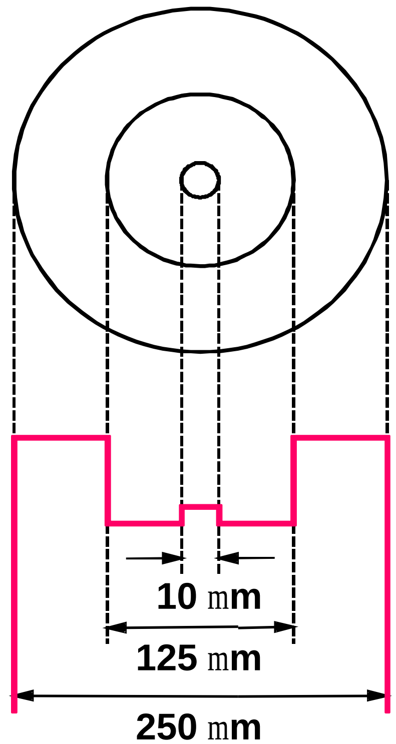
Optic fibers and connectors

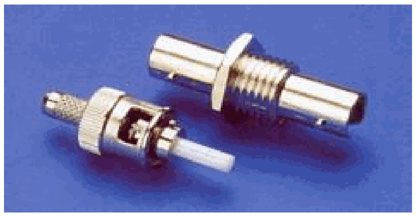
Multi-mode fiber (IEC 793-2)
Type 62.5 / 125 μm
for 850 and 1300 nm

Mono-mode fiber (IEC 793-2)
Type 10/125 μm
for 1300 and 1550 nm

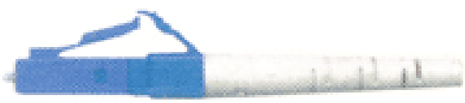




ST connector



LC connector



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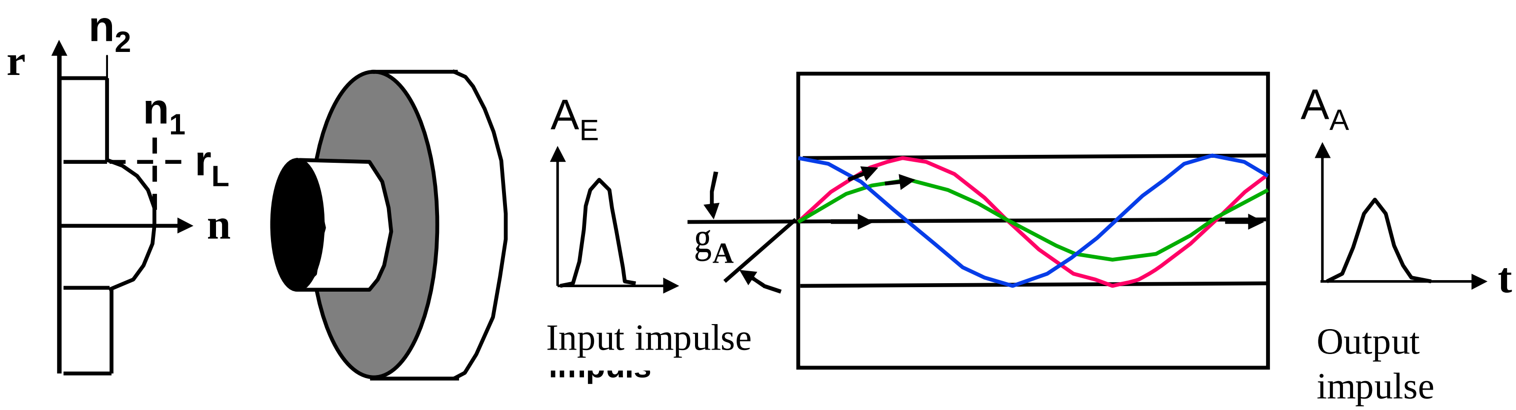
Optic fibres: Principle of light wave propagation

A) Graded index fibre

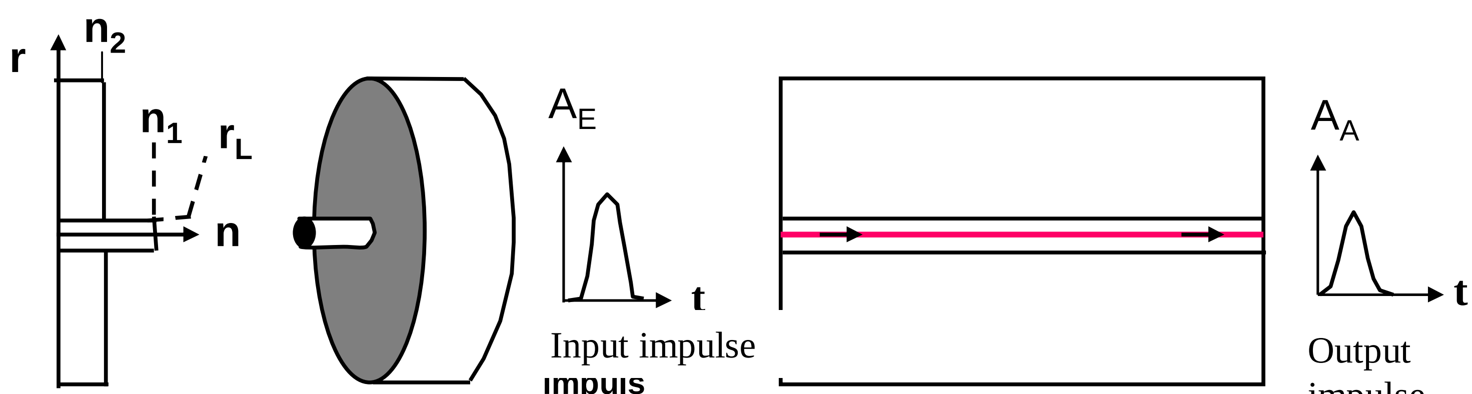


Refractive index profile

Geometric design

Wave propagation

B) Mono-mode fibre



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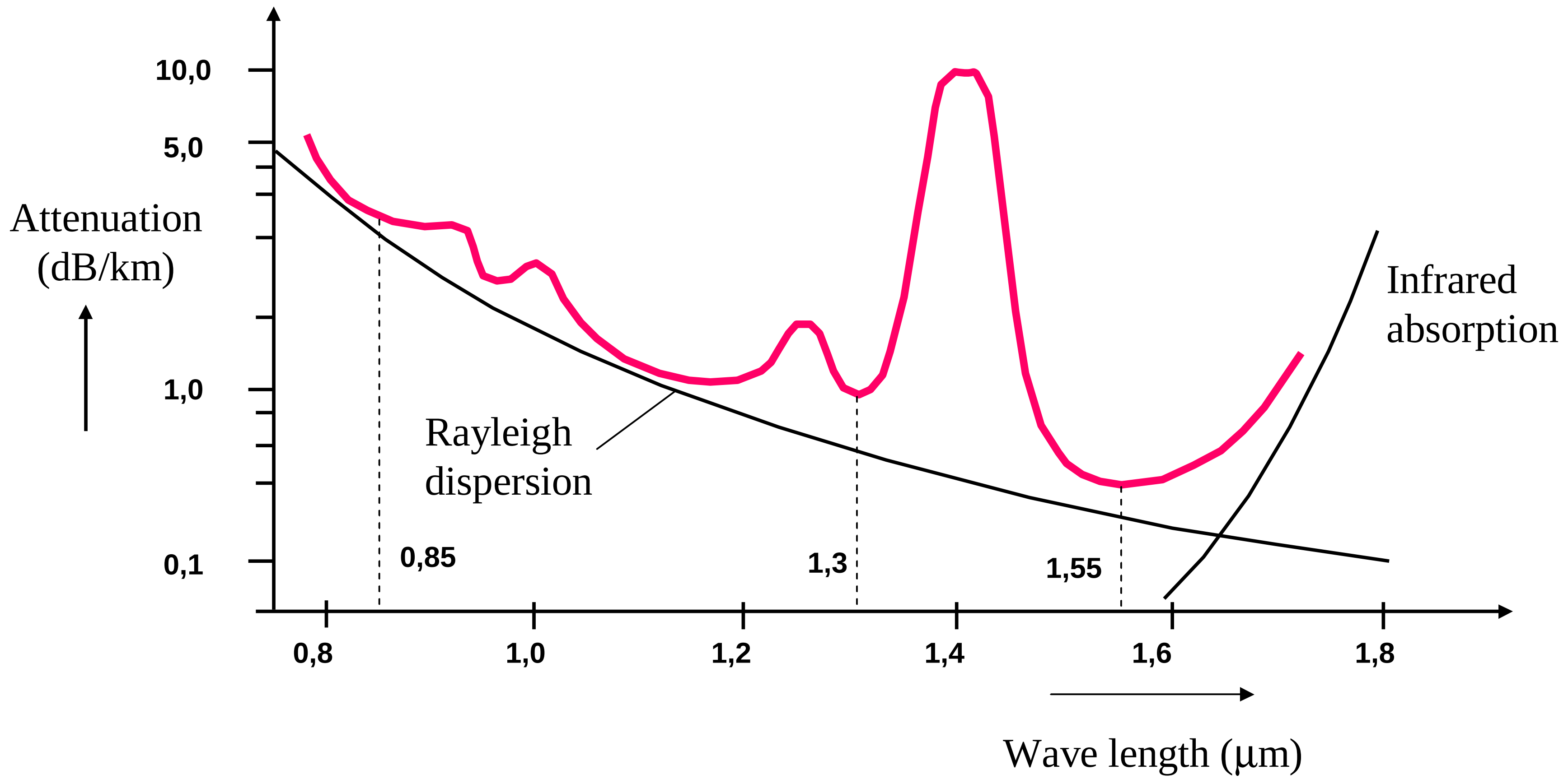
Optic attenuation of a mono-mode fibre



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Optic fibre connections: Coarse planning rules

Optic component:		Attenuation:
Mono-mode fibre	at 1300 nm	α_{OFC} = 0.45 dB/km
	at 1550 nm	α_{OFC} = 0.30 dB/km
Gradient fibre	at 850 nm	α_{OFC} = 2,5 to 3,5 dB/km
	at 1300 nm	α_{OFC} = 0.7 to 1.0 dB/km
Per splice		α_{SPL} = 0.1 dB
Per connector	FSMA	α_{CON} = 1.0 dB
	FC	α_{CON} = 0.5 dB
Reserve		α_{RES} = 0.1 to 0.4 dB/km

Total attenuation of the OF cable system:

$$a_{TOT} = l \cdot a_{OFC} + n \cdot a_{SPL} + 2 \cdot a_{CON} + l \cdot a_{RES}$$

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Optic Fibre signal transmission system: Calculation example

Task: Optic fibre signal transmission device 7VR500
Estimation of maximum reach

Given: Device data: Sending power of laser diode: α_S= –14 dB
Minimum reception power: α_E= -46 dB
Optic wave length: 1300 nm
The optic fibre cable is shipped in sections of each 2 km.
For reserve, 0.2 dB/km have been chosen.

Seached: Maximum distance that can be bridged

Solution: The cable length is: l=x·2 km
The number of splices is: n=x-1
The admissible system attenuation: –14– (–46)=32 dB
Therefore:

$$32dB = x \cdot 2km \cdot 0{,}45\frac{dB}{km} + (x-1) \cdot 0{,}1dB + 2 \cdot 0{,}5dB + x \cdot 2km \cdot 0{,}2\frac{dB}{km}$$

we get: x=22 and **l=44 km**

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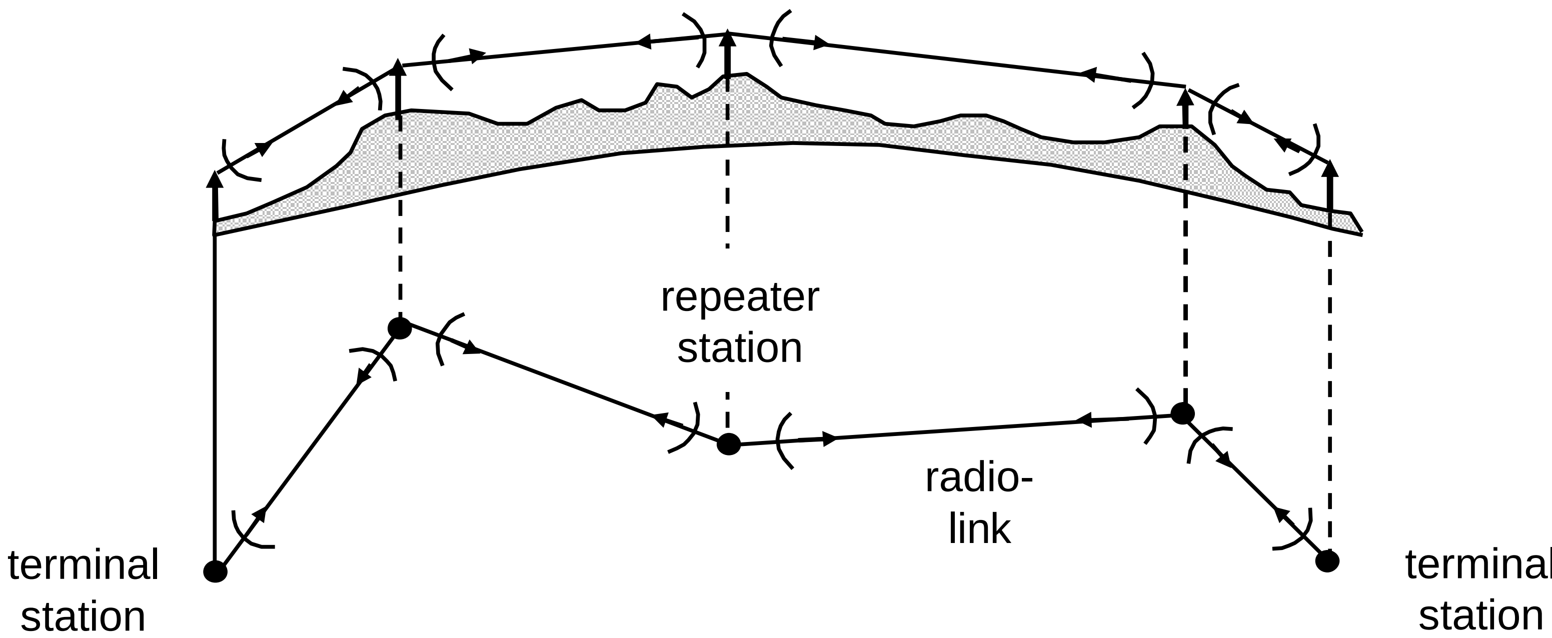
Radio (Micro-wave) Signalling

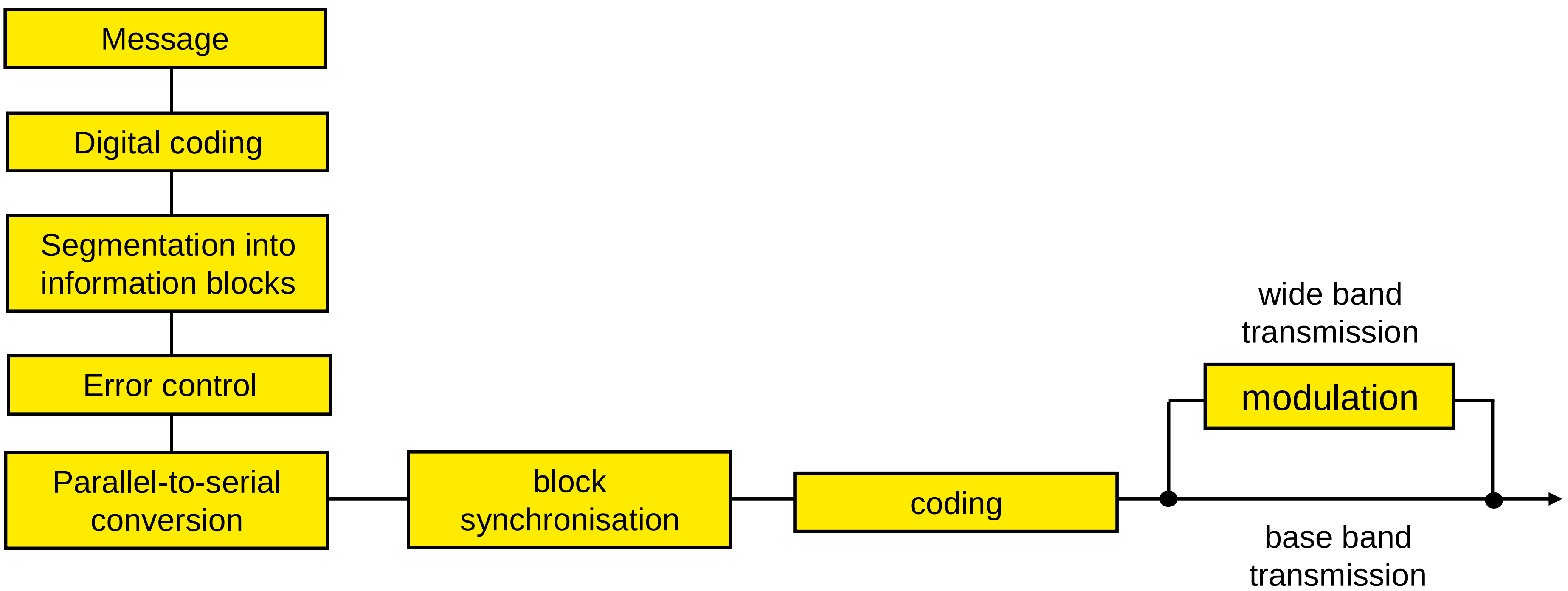


- Line-of-sight path (up to about 50 km without repeater)
- 150 MHz to 20 GHz, n times 4 kHz channels analog and n times 64 (56) kbit/s digital (PCM)
- Advantage: Independent of line short-circuit and switching disturbances
- Disadvantage: Fading and reflections during bad weather conditions
  Additional pilot links necessary to sending/receiver stations

Digital communication

- Wide-band communication via optic fibre or digital microwave
- n times 64 (56) kbit/s channels
- pulse code modulation (PCM)
- transmission via dedicated channels or communication network
- access through time division multiplexers
- interface standard for synchronous data transmission: CCITT G.703 or X.21 (wired connection)
- interface standard for asynchronous data transmission: V.24/V.28 to CCITT or RS485 to EIA (wired connection)

Function sequence of message transmission
Sending side



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Structure of a remote control telegram

Start	Control	Identification	Information	Error check	End
Start sign	**Kind of telegram**	**Address**	**User data**	**Checking**	**End sign**
Block limit	Transmission cause	Origin	Measuring values	Check bits	
	Telegram length	Destination	Status		
	etc.		Commands		
			etc.		

← Information field → (Control to Information)

← Block length → (Control to Error check)

← Transmitted frame → (Start to End)

Digital communication
Synchronous transmission mode

- all bits follow a fixed time frame
- synchronism between sending and receiving station. (separate clocking line or signal codes with clock regain)
- block (frame) synchronising by opening and closing flags
- suitable for high data rates
- used protocol: HDLC (high-level data link control)
- cyclic redundancy check (CRC) or frame check sequence (FCS) by 16 or 32 added check-bits (probability of non-detected telegram block errors: 10^{-5} (CRC-16) or 10^{-10} (CRC-32))
- used for high speed teleprotection

HDLC telegram frame format to ISO 3309:

Opening Flag	Address Field	Control Field	Information Field	Frame Check FCS	Closing Flag
01111110	8 or more bits	8 or 16 bits	any length	16 or 32 bits	01111110

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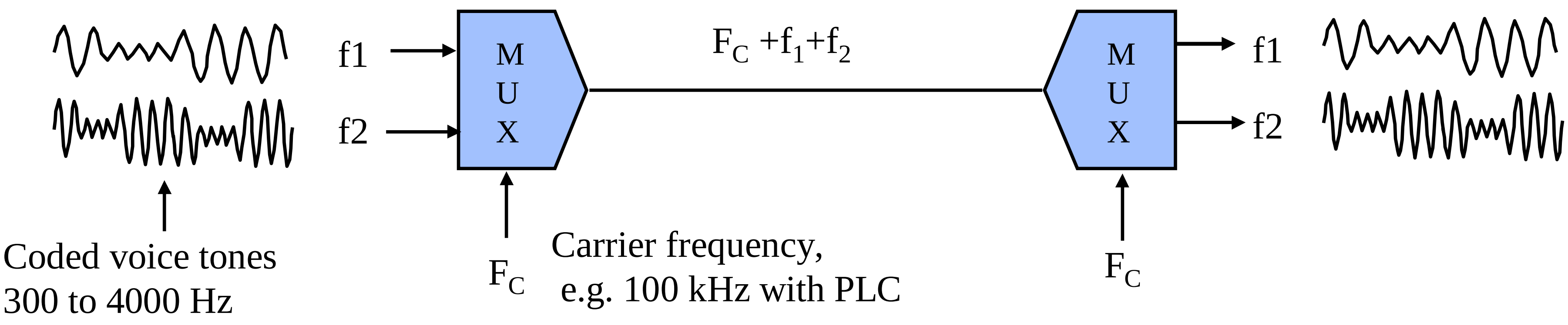
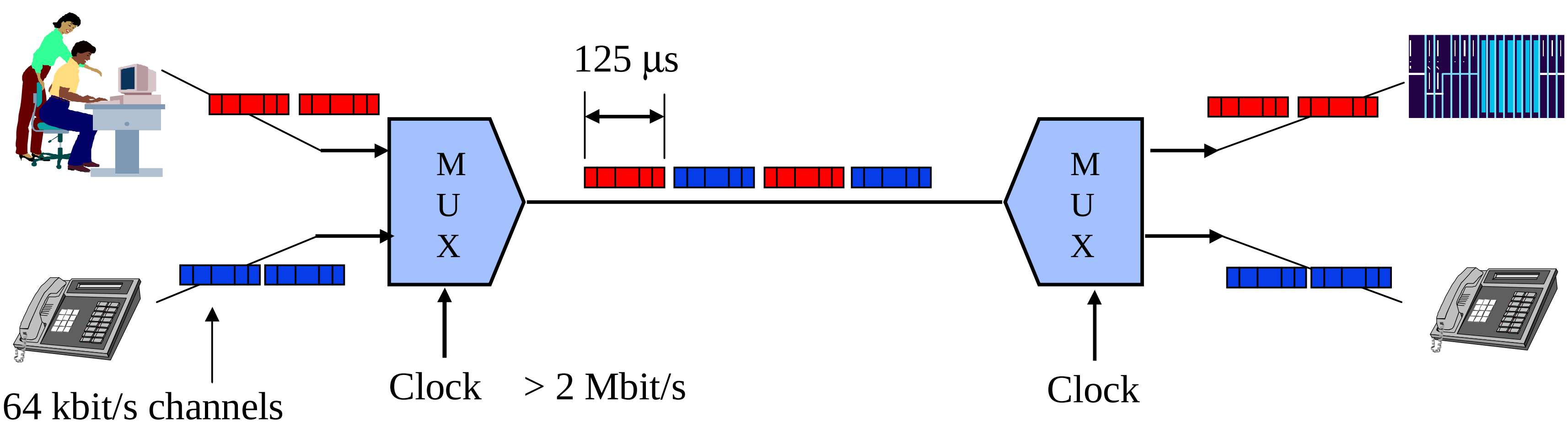
Multiplexing

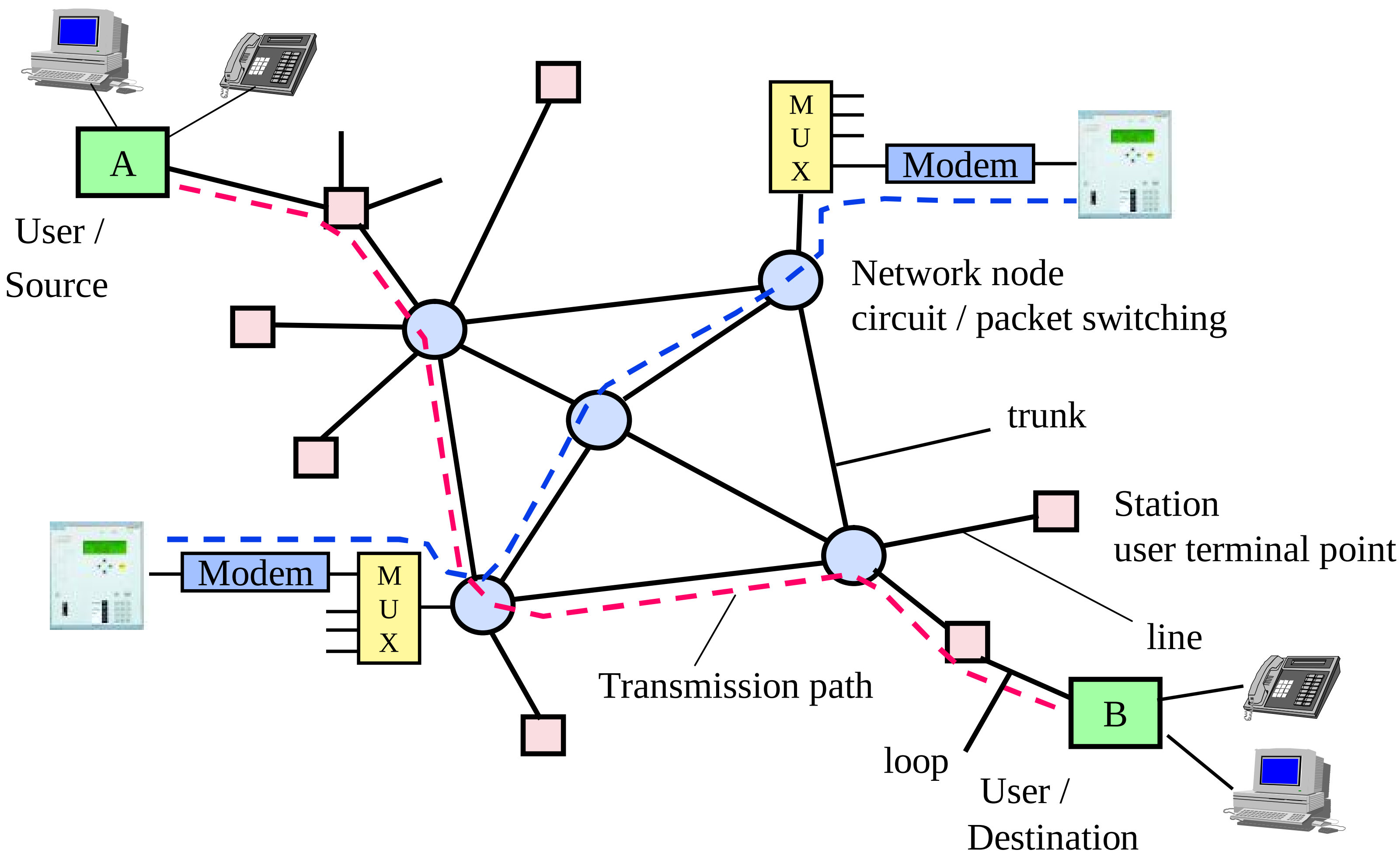
Frequency **M**ultiplexing



Time **D**ivison **M**ultiplexing (TDM)



Communication through transmission networks



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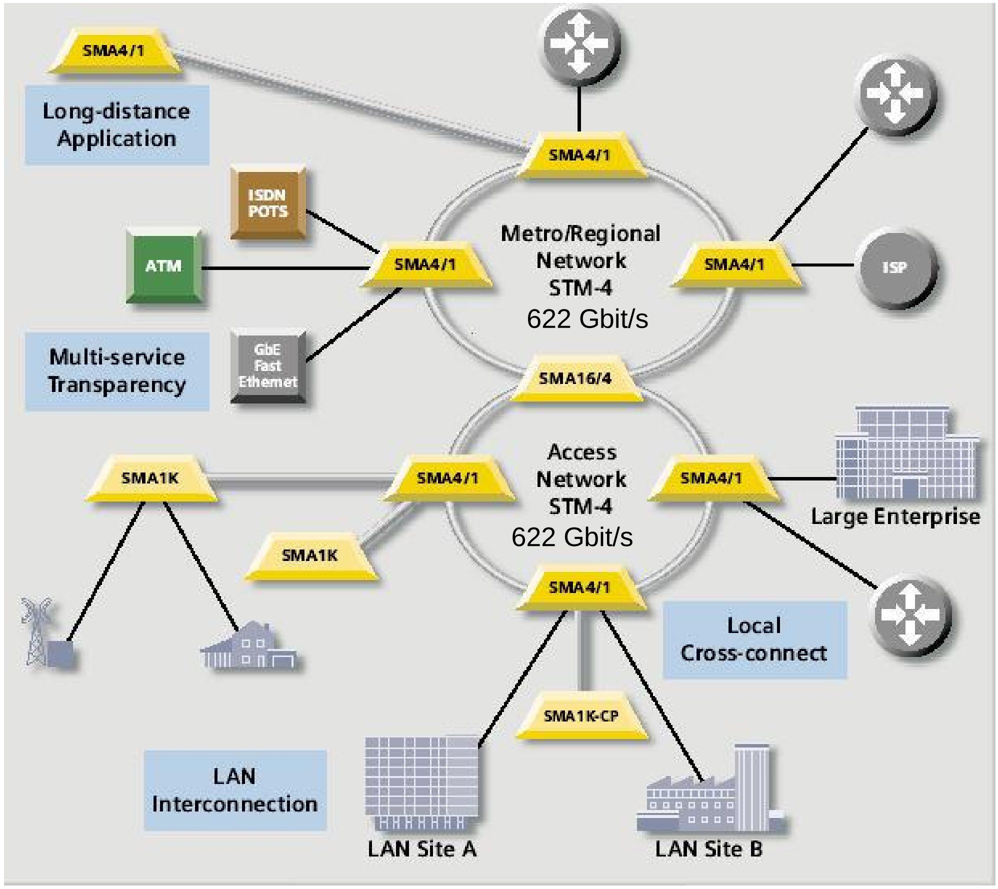
Structure of a modern data communication network



- Networks are plesiochronous (PDH), synchronous (SDH) or asynchronous (ATM)
- Data terminal devices (e.g. relays) are synchronised through the network
- Rings guarantee redundance.
- Data of different services (e.g. telephone and protection are commonly transmitted (time multiplexed)
- Protection relays must be adapted to the given network conditions (e.g. changing propagation time due to path witching.

POTS: Plain Old Telephone Services

ISDN: Integrated Services Digital Network

STM-n: Synchronous Transport Module level n

SMA: Synchronous Module Access

ATM: Asynchronous Transmission Mode

ISP: Internet Service Provider

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Comparison of Switching Methods

Circuit Switching

The physically assigned channel is established before and disconnected after communication

POT (Plain old telephony), ISDN

Digital networks on basis of PCM with plesiochronous digital hierarchy (PDH)

Reliable and fast transmission possible when connection is established.

Circuit establishment requires a free channel from A to B

Connection occupies channel also when no data is exchanged

Deterministic data transmission (fixed data transmission time per channel)

Packet switching

Data stream is segmented to packets

Transmission runs connection-oriented or connection-less

Synchronous digital hierarchy (SDH), ATM Backbone

Cannel not occupied during whole connection time

Channels can be used quasi-simultaneously

Data transmission by principle time is random.

SDH and ATM can provide virtual circuit-switched channels. However, **split path** signal routing may however result in unsymmetrical signal transmission times.

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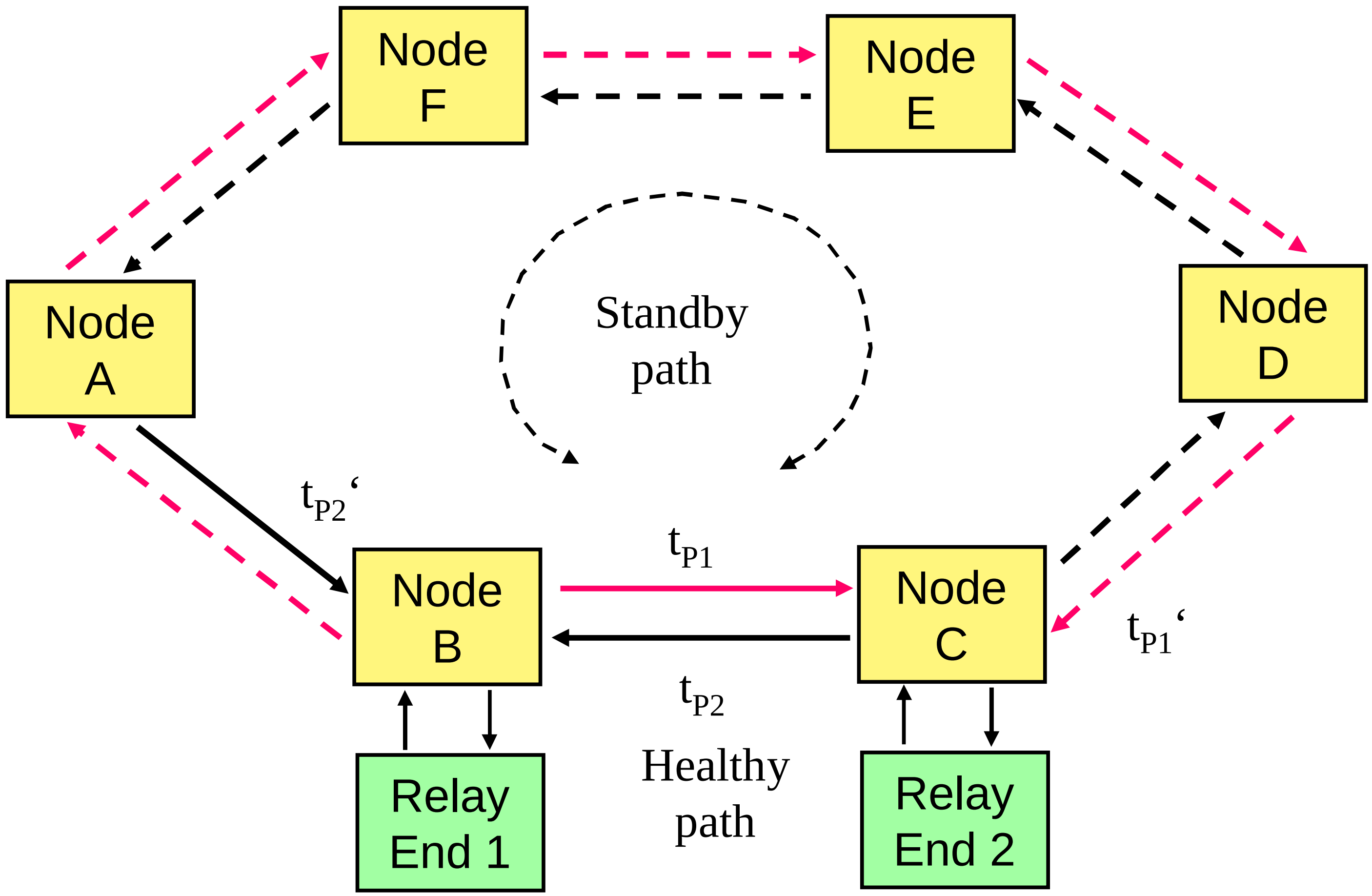
SDH network: Split path routing



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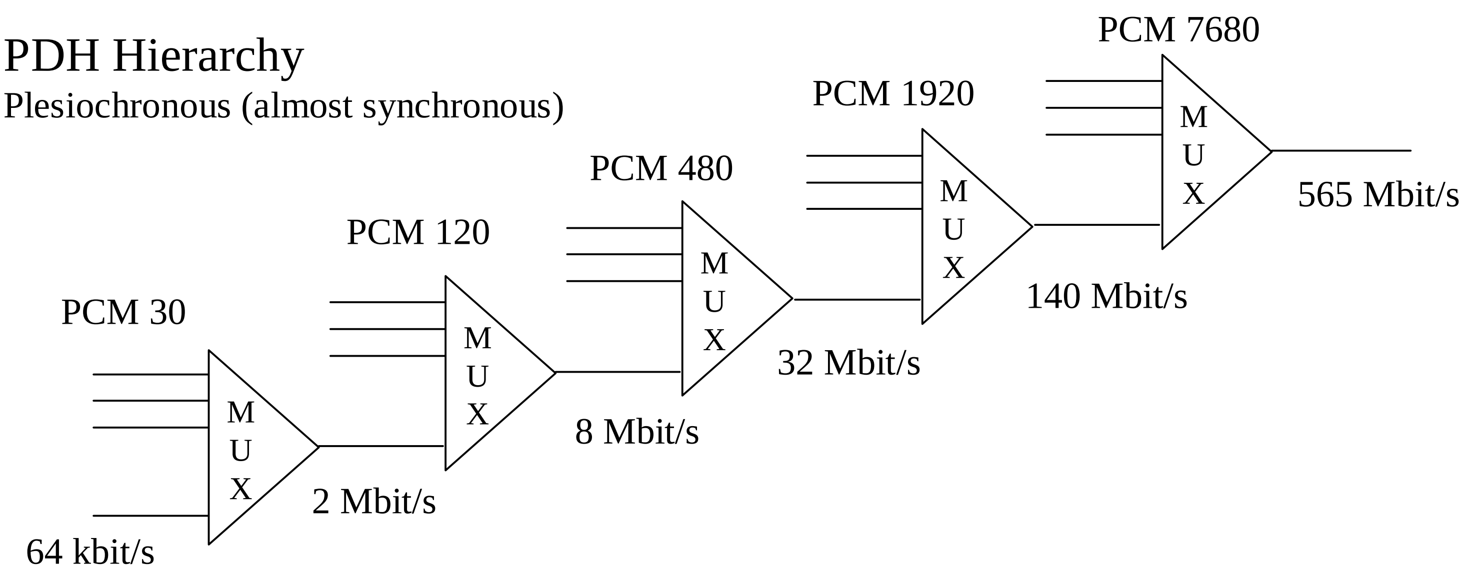
Digital Transport Systems: Bundling of channels

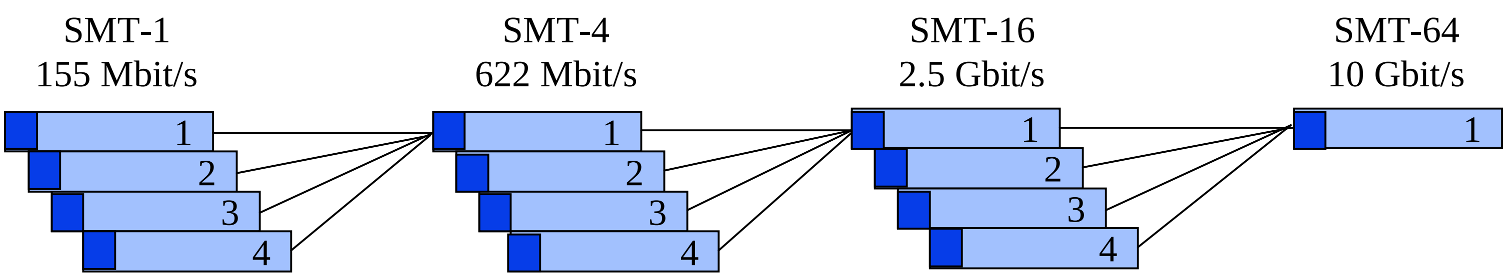
PDH Hierarchy

Plesiochronous (almost synchronous)



SDH Hierarchy

Synchronous



PDH (Plesiochronous Digital Hierarchy)

Multiplexing structure:

- Base rate 64 kbit/s (digital equivalent of analogue telephone channel)
- Equipments may generate slightly different bit rates due to independent internal clocks
- Bit stuffing is used to bring individual signals up to the same rate prior to multiplexing (Dummy bits are inserted at the sending side and removed at the receiving side)
- Intermediate inserting and extracting of individual channels is not possible, but the full multiplexing range has always to be run through.

Hierarchical level	Europe	USA
0	64 kbit/s	56 kbit/s
1	2‘048 Mbit/s	1‘544 Mbit/s
2	8‘448 Mbit/s	6‘312 Mbit/s
3	34‘368 Mbit/s	44‘736 Mbit/s
4	139‘264 Mbit/s	139‘264 Mbit/s

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SDH (Synchronous Digital Hierarchy)

Multiplexing structure

- SONET (Synchronous Optical Network) first appeared in USA (1985)
- ITU-T (formerly CCITT) issued B-ISDN as world wide standard (1988)
- All multiplexing functions operate synchronously using clocks derived from a common source
- Designed to carry also future ATM

SDH		SONET		
STM level	Aggregate Rate	OC level	STS level	Aggregate Rate
		OC-1	STS-1	51,840 Mbit/s
STM-1	155,520 Mbit/s	OC-3	STS-3	155,520 Mbit/s
STM-4	622,080 Mbit/s	OC-12	STS-12	622,080 Mbit/s
SZM-16	2‘488,320 Mbit/s	OC-48	STS-48	2‘488,320 Mbit/s
STM-64	9‘953,280 Mbit/s	OC-192	STS-192	9‘953,280 Mbit/s

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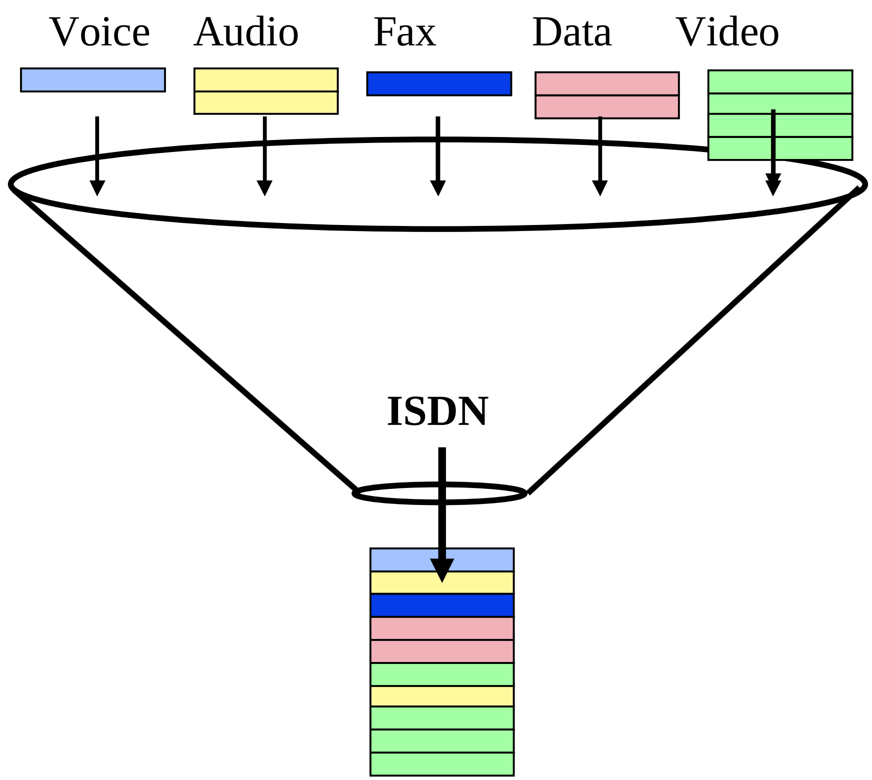
ATM (Asynchronous Transfer Mode) and Broadband B-ISDN

Features of ATM:

- Synchronisation individually per packet
- Packets carry each complete address of destination so that each can be separately delivered (Datagrams, here called Cells)
- Information stream is segmented into cells that are 53 octets long
- ATM sets up a virtual switched connection and sends data along a switched path from source to destination
- Requirements on bandwidth, bounded delay and delay variation can be set by the user
- Single cells can be inserted or removed at the nodes, as required
- The predominant use is for net backbones



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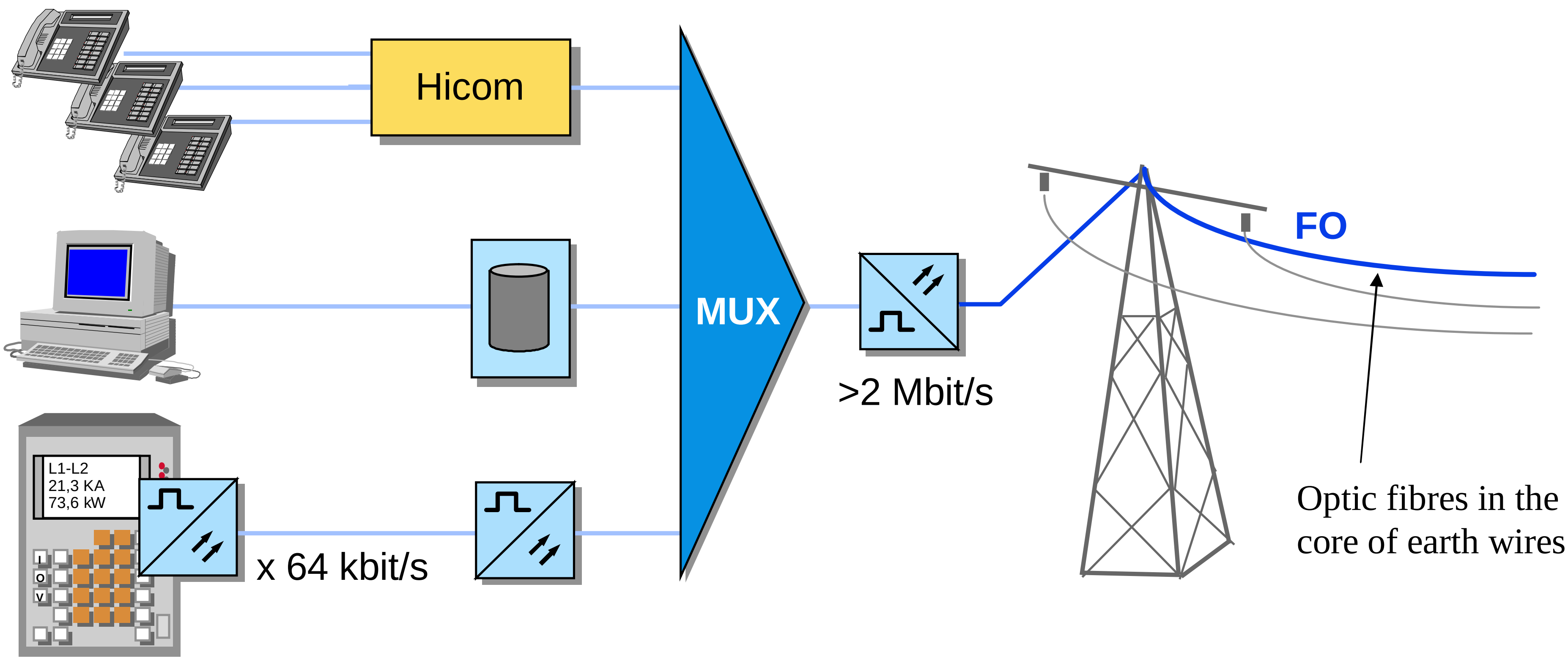
TDM over optical fiber



Bit error rate (of data channels)

Bit error rate: $$p = \frac{\text{number of faulty bits}}{\text{total number of sent bits}}$$

Typical bit error rates of public services:

Telephone circuits	ca. 10^{-5}
Digital data networks (Germany)	ca. 10^{-6} to 10^{-7}
Coaxial cables (LAN)	ca. 10^{-9}
Fiber optic communication	ca. 10^{-12}

Utility conditions (CIGRE SC34 Report 2001):

Fiber optic communication	ca. 10^{-6}
Data networks (PDH, SDH, ATM)	ca. 10^{-6}
Microwave	ca. 10^{-3}

Requirements acc. to CIGRE report:

Protection and control in general:	$< 10^{-6}$
Function guaranteed up to	$< 10^{-3}$ however downgraded (reduced operating speed)
Line differential protection	$< 10^{-6}$ and $< 10^{-5}$ during power system faults

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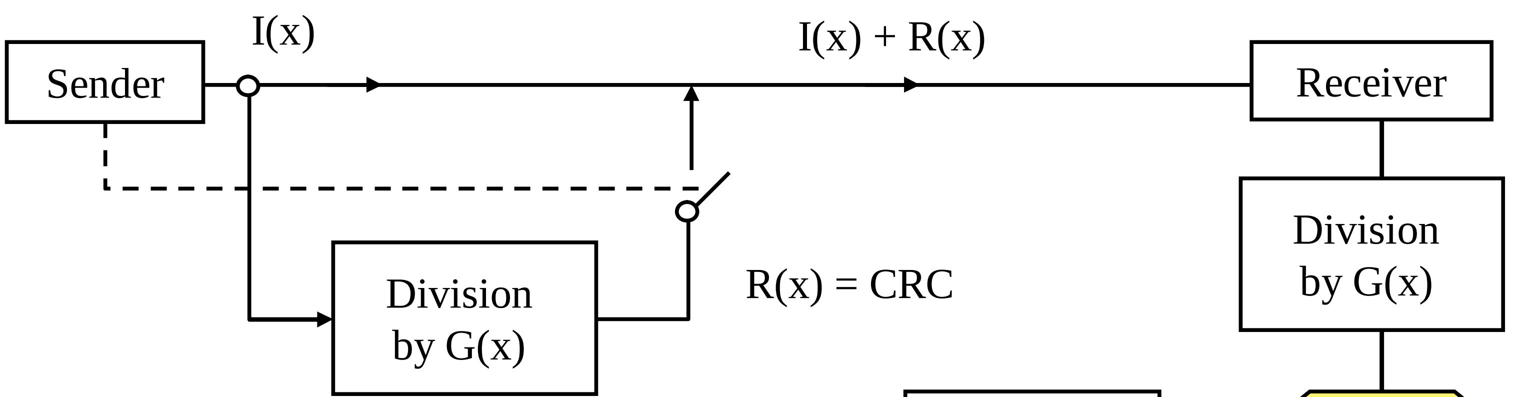
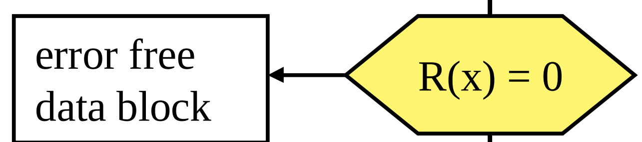
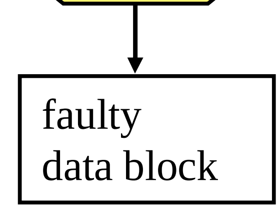
Error detection methods: Cyclic redundancy check

01111110					01111110
Flag	Address	Control	Data field	Check field	Flag







CRC 16: $G(x) = X^{16} + X^{15} + X^{2} + 1$

binary: 1 1000 0000 0000 0101

Reduction of the block failure rate by the factor > 10^{-5} against the bit failure rate!

(**CRC 32**: > 10^{-10})

Data integrity (line differential protection 7SD52/61)

Received data → Block failure rate

$P = 10^{-5}$

↓

Error detection
e.g. CRC = 32

↓

Residual data → Block failure rate

$R = 10^{-15}$

Residual error rate

Residual error rate: $$R = \frac{number\ of\ not\ detected\ faulty\ telegrams\ (data\ blocks)}{total\ number\ of\ sent\ telegrams\ (data\ blocks)}$$

Practical range of protection and control systems: $R < 10^{-10}$ to 10^{-15}

Time between 2 **not** detected errors: $$T = \frac{n}{v \cdot R}$$

n= length of telegram (data block)

v= transmission speed in bit/s

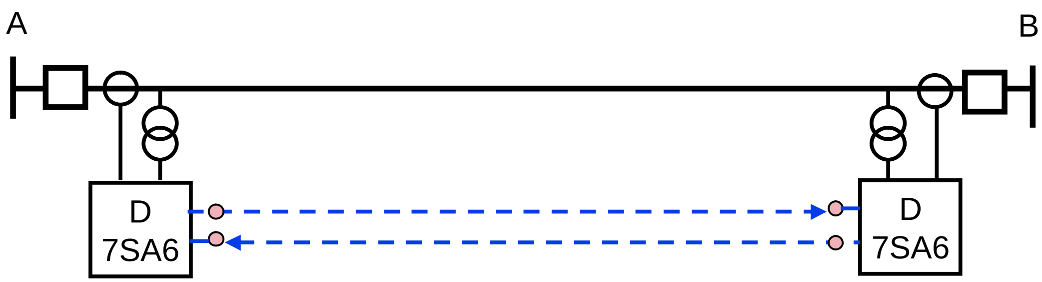
Example:

Telegrams of n =200 bit are continuously transmitted at 64 kbit/s.

R	T	typical application
10^{-7}	20 hours	cyclic transmission (metering)
10^{-10}	2.3 years	
10^{-15}	230000 years	remote control and **protection**

Protection of a short line lines

Differential relay using direct digital relay-to-relay communication



Communication via direct relay-relay connection

Fibre type	optical wave length	maximum attenuation	permissible distance
Multi-mode 62.5/125 µm	820 nm	16 dB	ca. 3.5 km
Monomode 9/ 125 µm	1300 nm	29 dB	ca. 60 km
9/ 125 µm	1500 nm	29 dB	ca. 100 km

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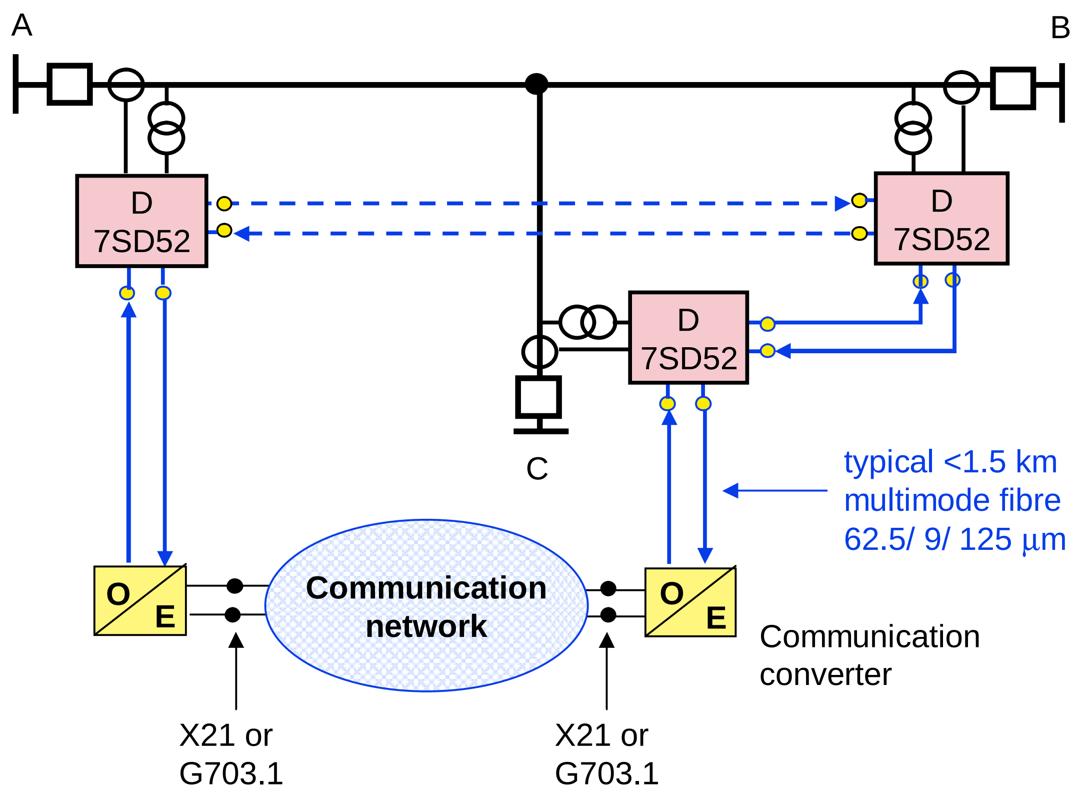
Line differential relaying using digital communication

Chain topology or

redundant ring topology



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Differential protection with communication through data net

Microsecond exact time keeping in the relays

- Each relay has its individual time keeping
- Sent and received telegrams get microsecond accurate time stamps

Special relay properties for network communication

- Measurement of propagation times and automatic correction 0 - 30 ms
- Detection of channel switching in the network
- Unique address for each relay (1 - 65525)
  to detect signal misdirection (channel cross-over of loop-back)
- Measurement of channel quality (availability, error rate)

Change of the network path -> Adaptive add-on stabilisation

Settable time difference to consider given data transmission asymmetry

Adaptive topology recognition

- Automatic recognition of connections and remote end devices
- Automatic re-routing from ring to chain topology if one data connection fails

In case of multi-terminal protection, remaining relay system continues operation
if one line end is switched off and the relay is logged out for maintenance

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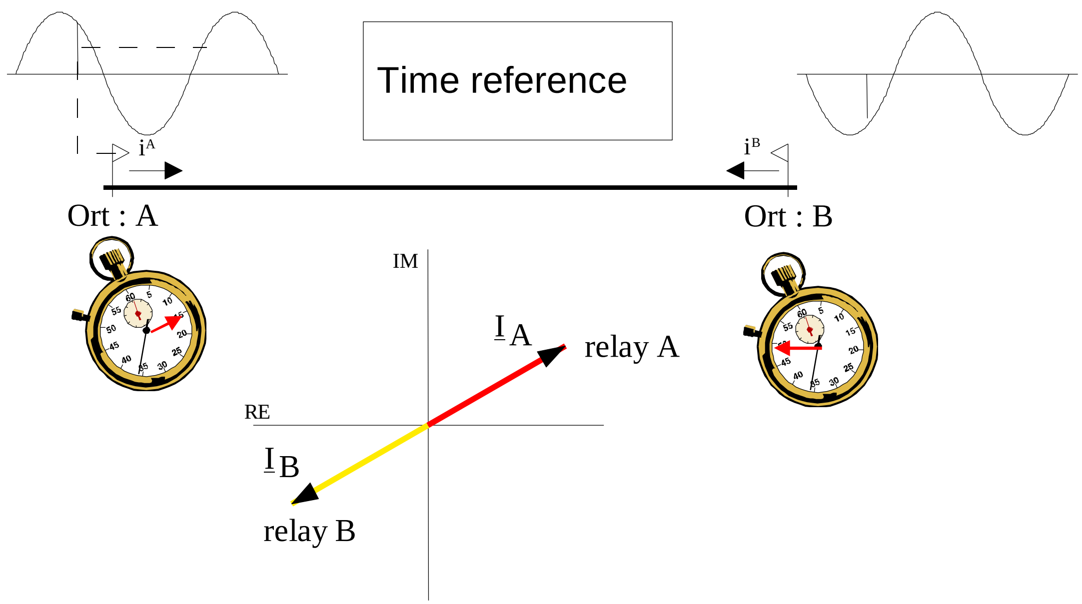
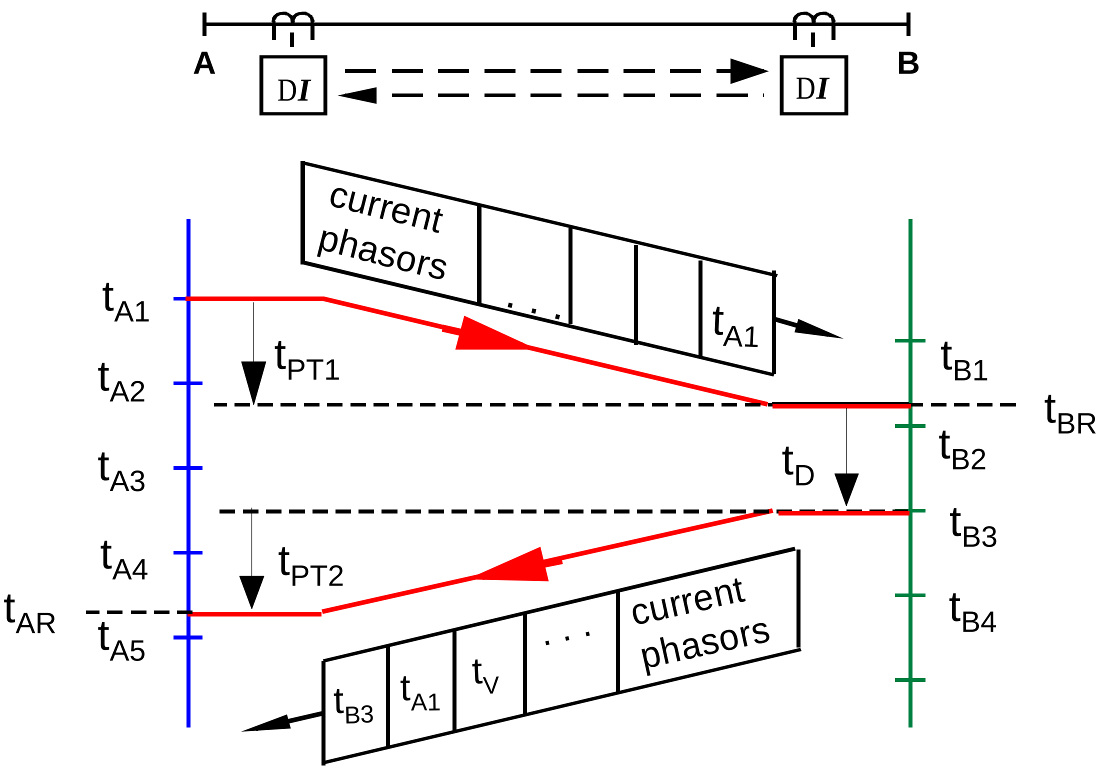
Individual time references by synchro-phasors

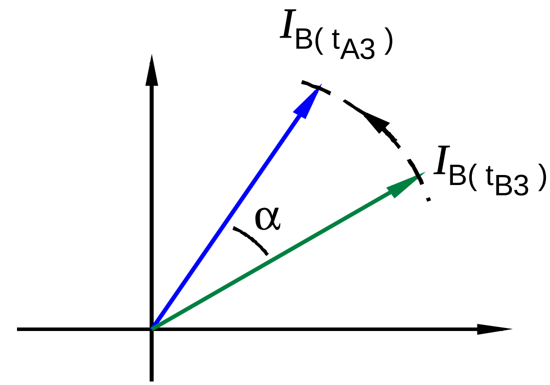
Definition of a synchro-phasor:

Synchro-phasors, are phasors, which are measured at different network locations by independent devices and referred to a common time basis



Phasor synchronisation between line ends





$$\alpha = \frac{t_{B3} - t_{A3}}{T_P} \cdot 360\,°$$

Signal transmission time: $t_{PT1} = t_{PT2} = \frac{1}{2}\left(t_{A1} - t_{AR} - t_D\right)$

Sampling instant: $t_{B3} = t_{AR} - t_{TP2}$

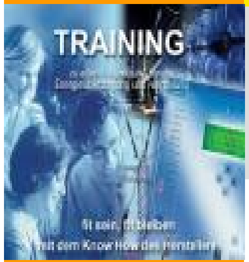
Specification of data channel for line differential protection

based on Cigre Report: Protection using Telecommunication *)

Data rate		64 kbit/s (min.)
Channel delay time:		< 5 ms
Channel delay time unsymmetry:		< 0.2 ms
Bit error rate	normal:	$< 10^{-6}$
	during power system fault	$< 10^{-5}$ *)
Availability:		> 99.99 %

*) Report of WG34/35.11, Brochure REF. 192, Cigre Central Office, Paris, 2001,

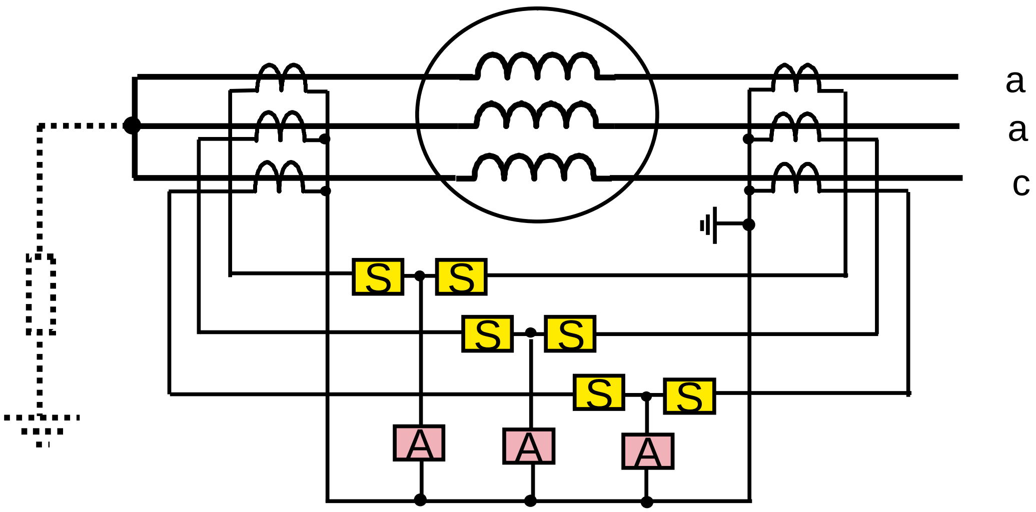
*) It is suggested that for a BER of less than 10^{-6} the dependability shall not suffer a noticeable deterioration . For a BER of 10^{-6} to 10^{-3} the teleprotection may still able to perform its function although a loss in dependability is to be expected.



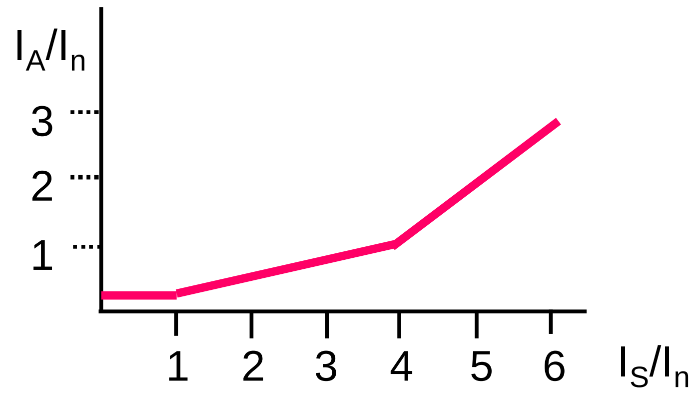
Digital Protection of Generators and Motors

Gerhard Ziegler

Generator differential protection

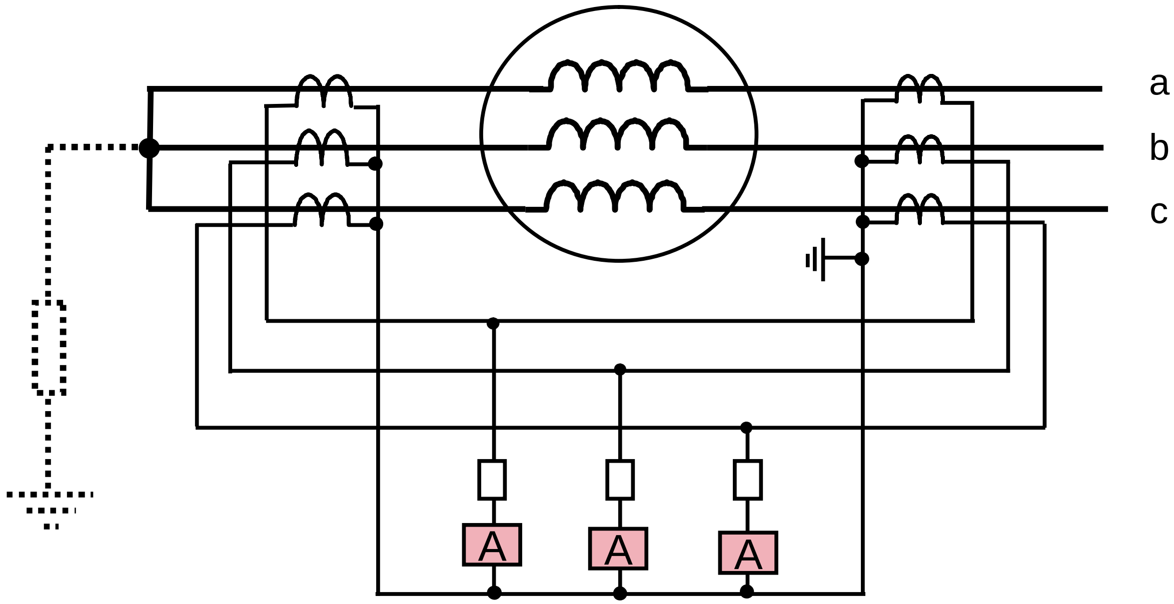


Connection circuit



Operating characteristic

Generator HI differential protection



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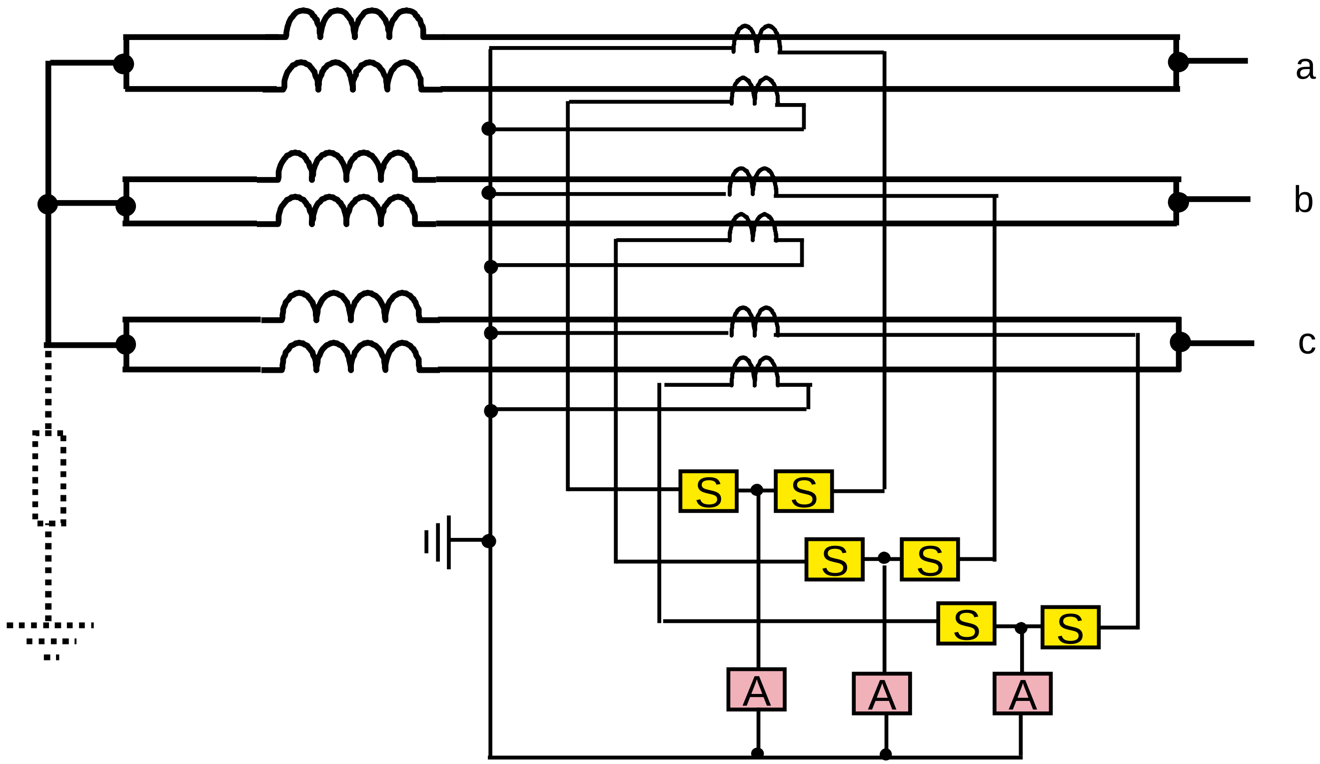
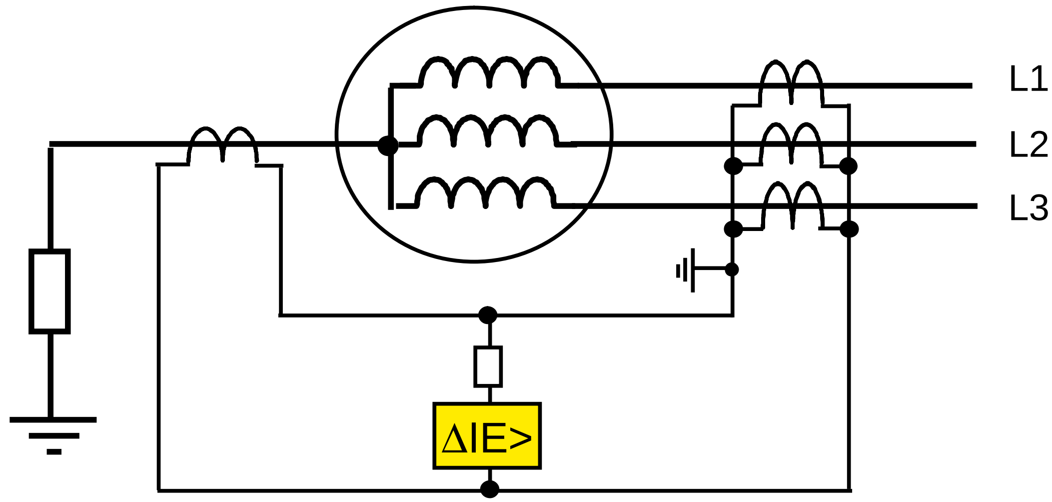
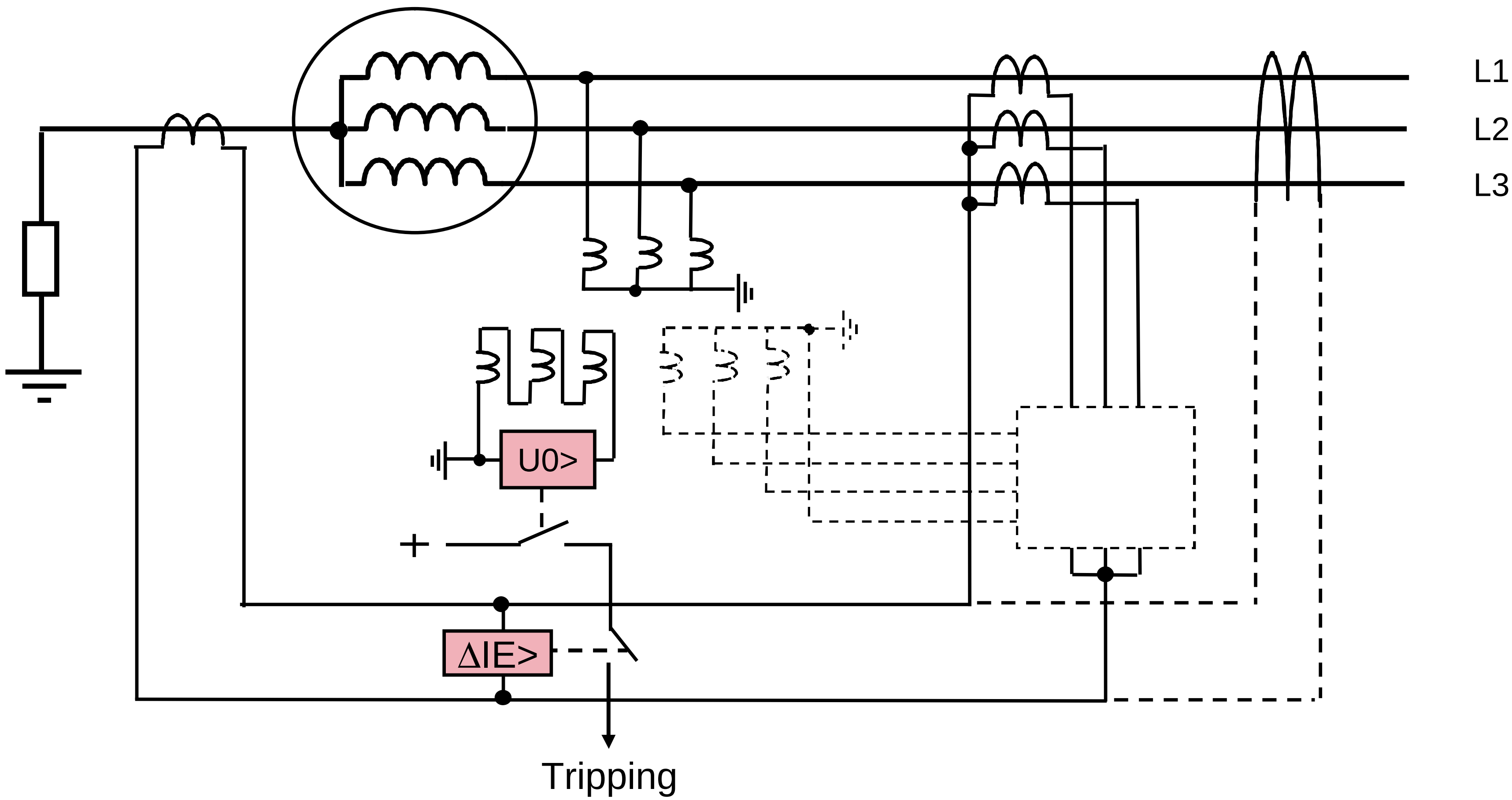
Transverse differential protection



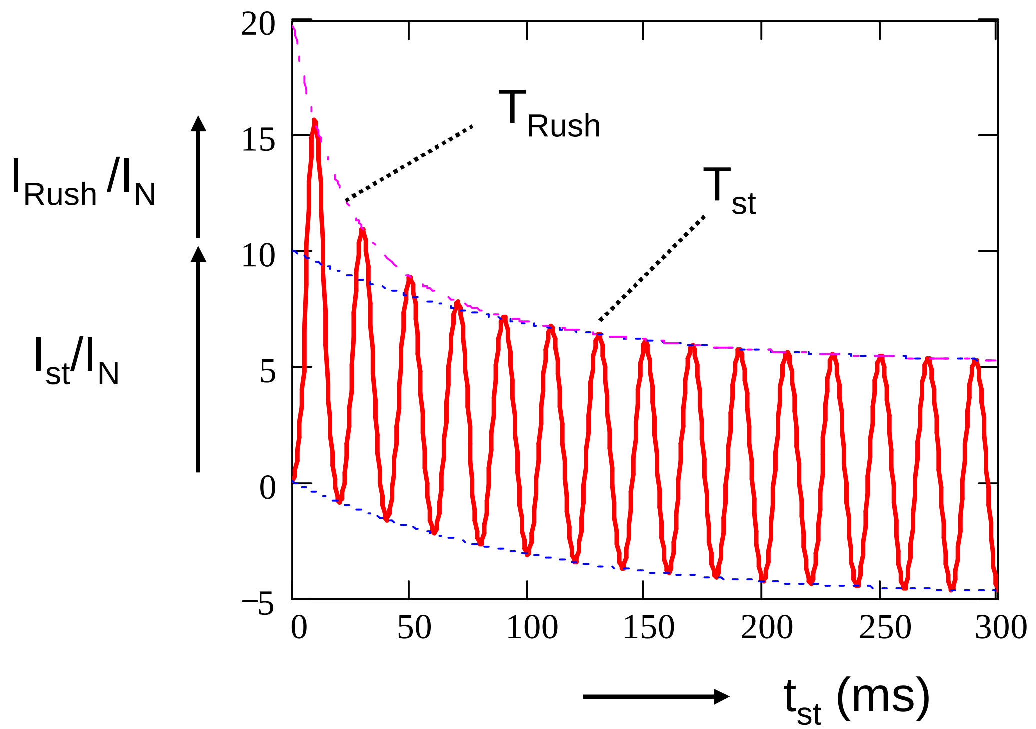
HI earth current differential protection



Earth current differential protection for generators



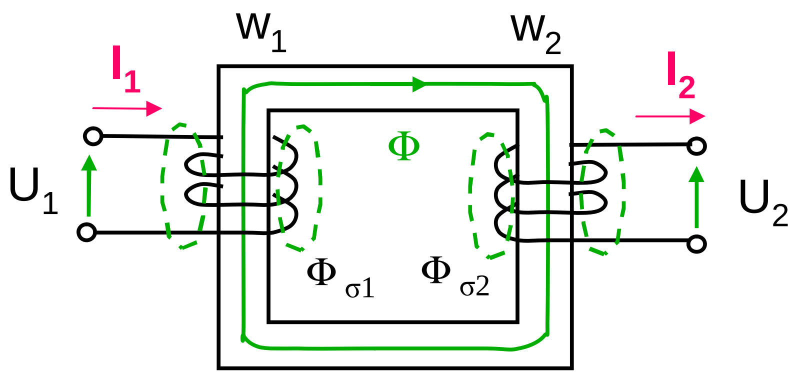
Motor starting current



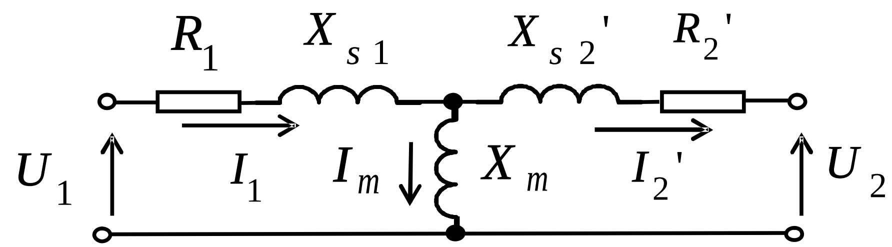
Transformer Differential Protection

Gerhard Ziegler

Transformer: Function principle and equivalent circuits



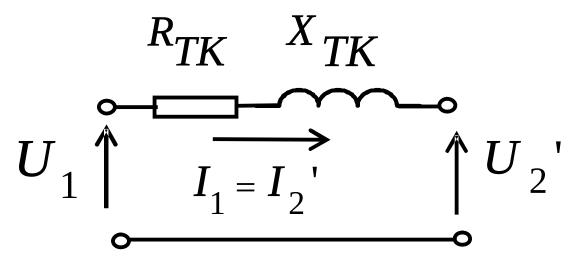
Equivalent electromagnetic circuit



Equivalent electric circuit

$$I_1 \cdot w_1 + I_2 \cdot w_2 = I_m \cdot w_1$$

At load and short-circuit: $I_m \ll I_{1,2}'$



$$I_1 \cdot w_1 = I_2 \cdot w_2$$

$$X_{TK} = X_{s\,1} + X_{s\,2}'$$

$$R_{TK} = R_1 + R_2'$$

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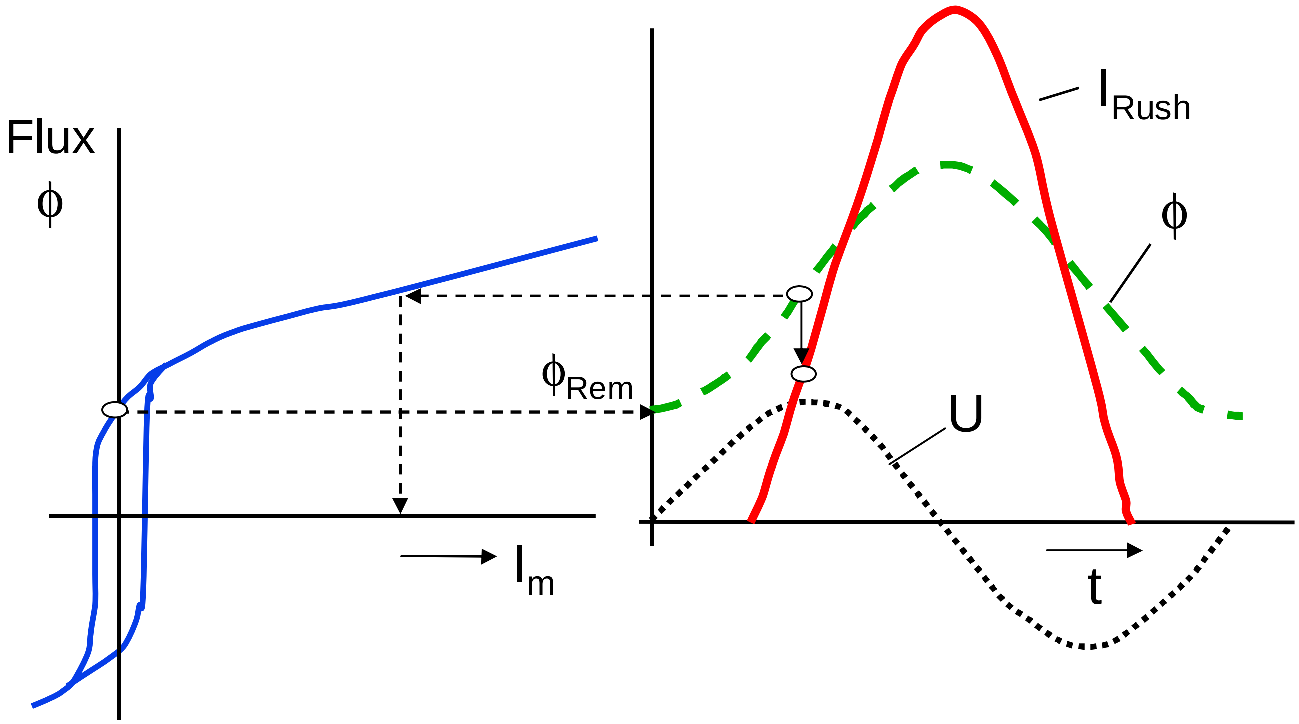
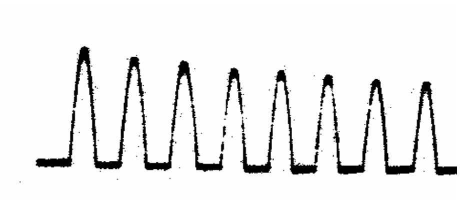
Typical Transformer data

Rated power MVA	Ratio kV/kV	Short-circuit voltage % UN	No-load magnetizing current % In
850	850/21	17	0.2
600	400/230	18.5	0.25
300	400/120	19	0.1
300	230/120	24	0.1
40	110/11	17	0.1
16	30/10.5	8.0	0.2
6.3	30/10.5	7.5	0.2
0.63	10/0.4	4.0	0.15

Transformer Inrush current





Inrush-current of a single phase transformer

Source: Sonnemann, et al.: Magnetizing Inrush phenomena in transformer banks, AIEE Trans., 77, P. III, 1958, pp. 884-892

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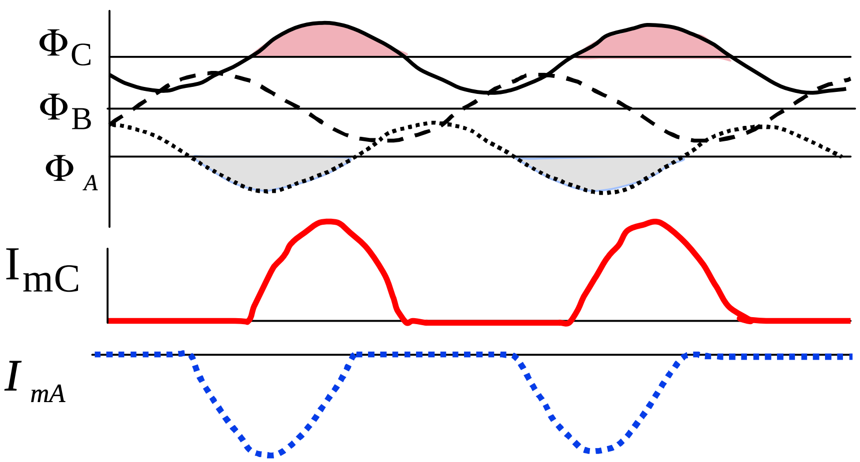
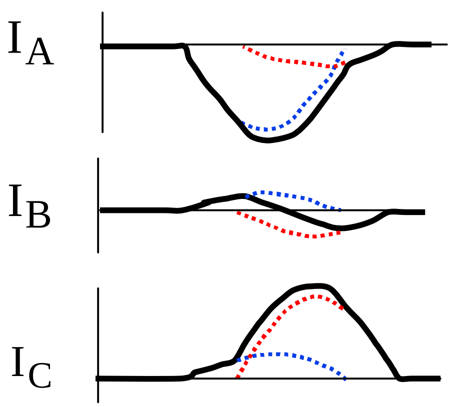
Inrush currents of a Y-Δ-transformer

Neutral of Y-winding earthed

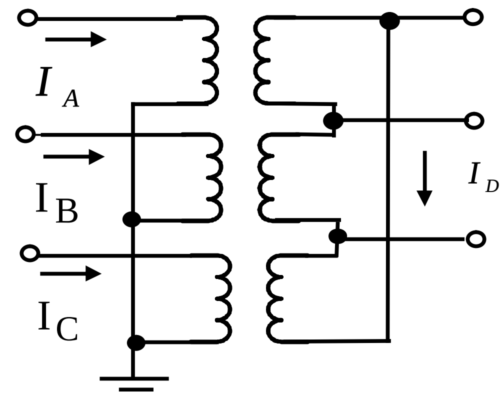




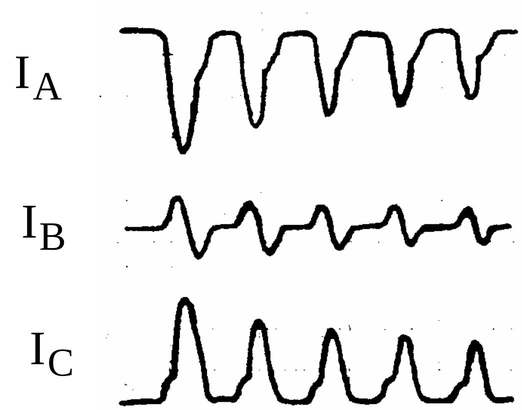
$$I_A = \frac{5}{6} \cdot I_{mA} - \frac{1}{6} \cdot I_{mC}$$

$$I_B = -\frac{1}{6} \cdot I_{mA} - \frac{1}{6} \cdot I_{mC}$$

$$I_C = \frac{5}{6} \cdot I_{mC} - \frac{1}{6} \cdot I_{mA}$$

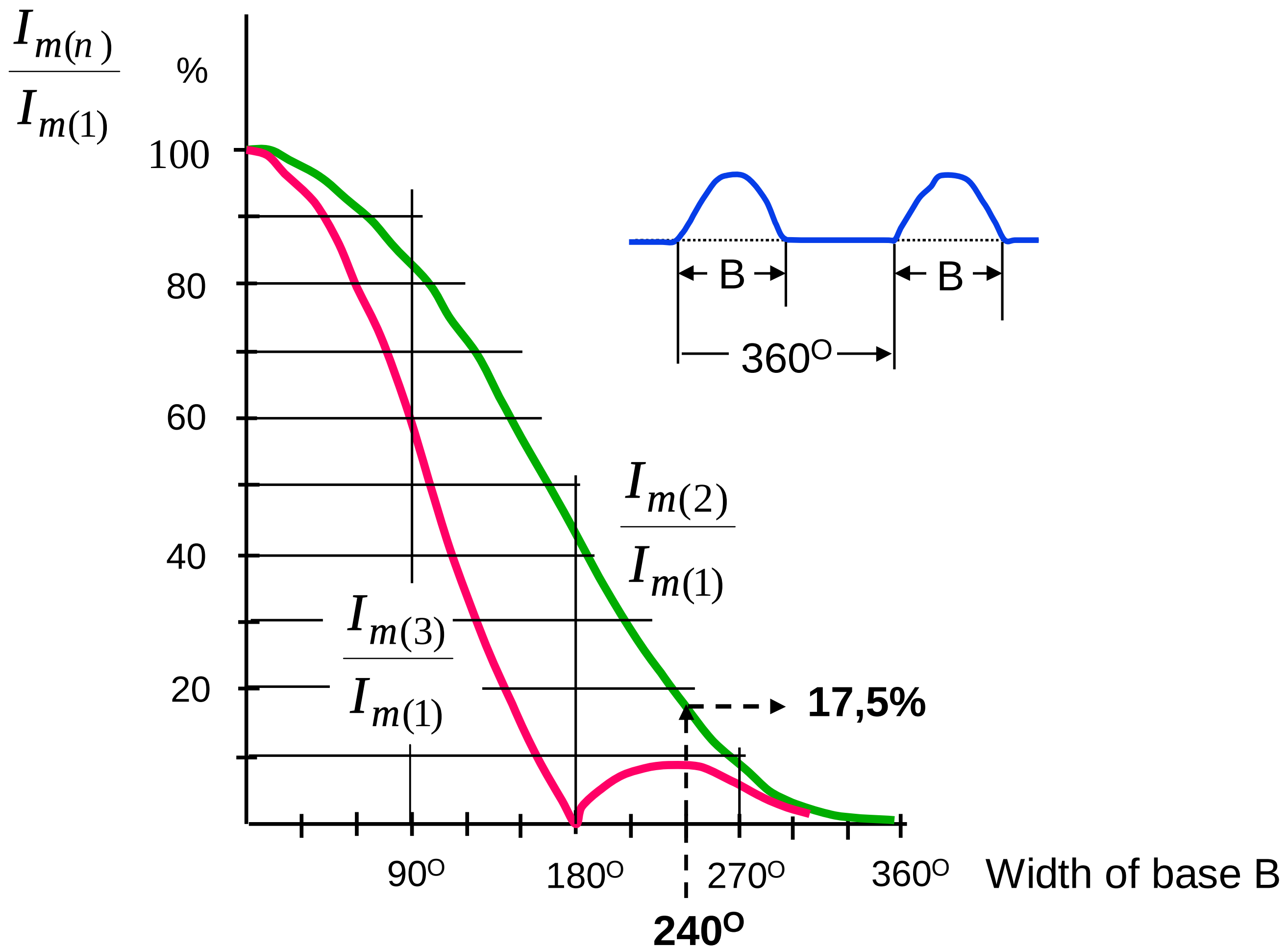


Oscillogram:



Source: Sonnemann et al. : Magnetizing Inrush phenomena in transformer banks, AIEE Trans., 77, P. III, 1958, pp. 884-892

Inrush current : Content of 2nd und 3rd harmonic



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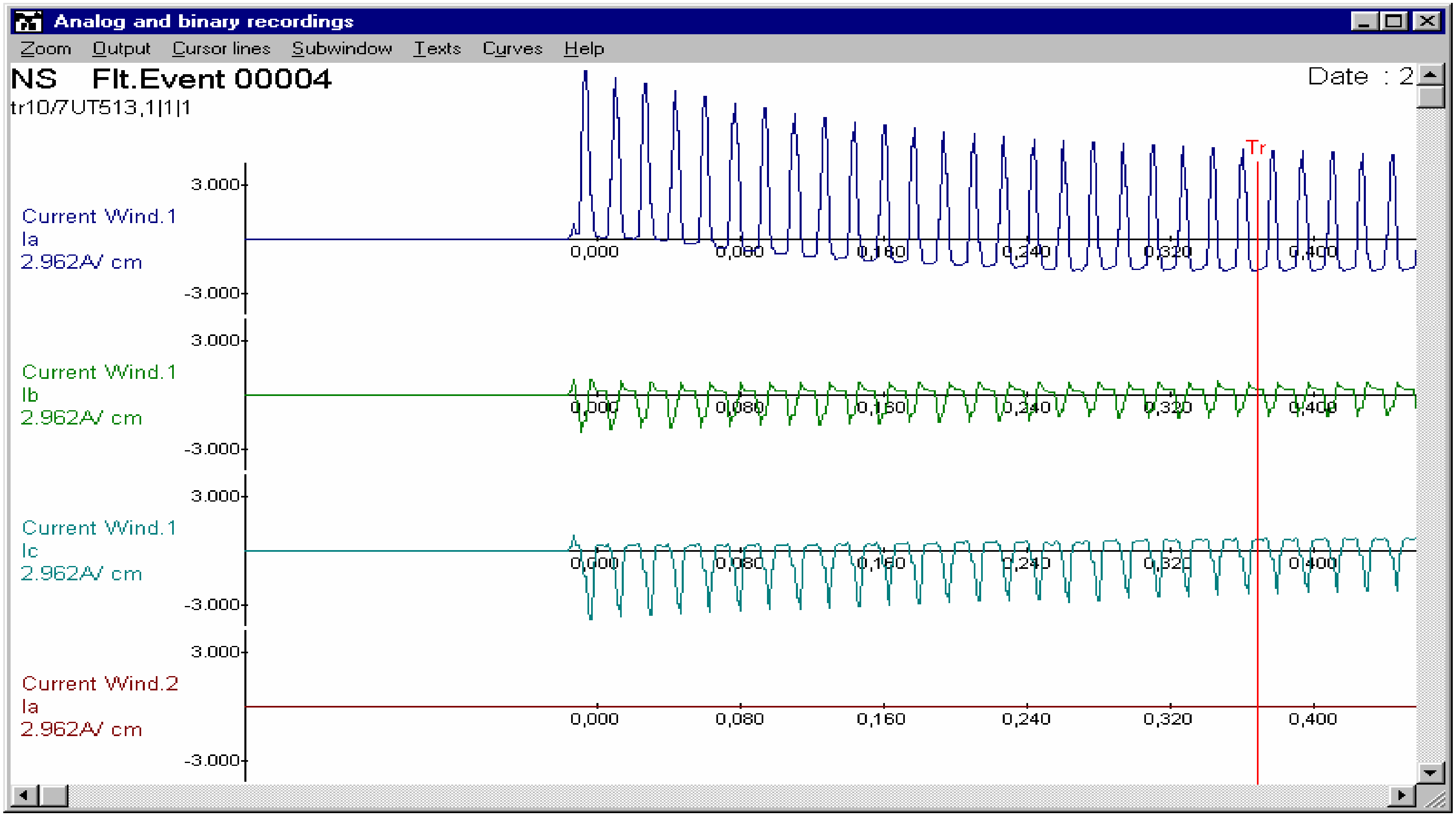
Inrush currents of a three-phase transformer
recorded with relay 7UT51



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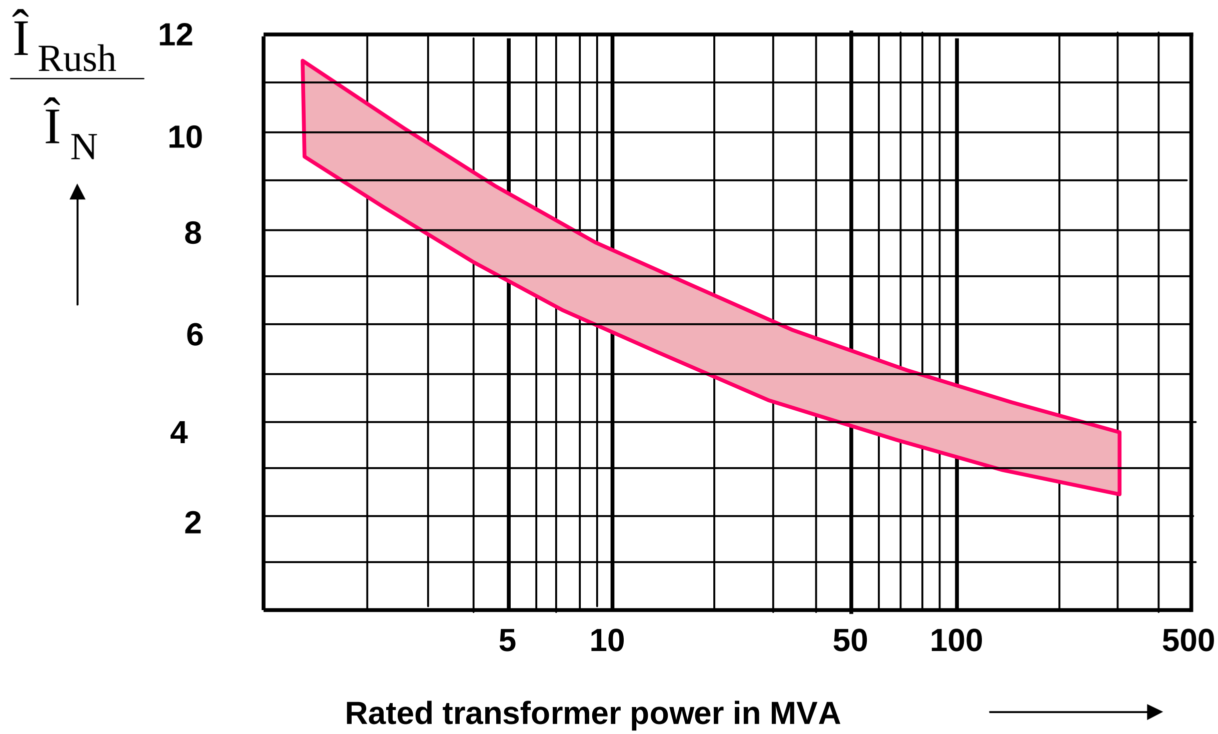
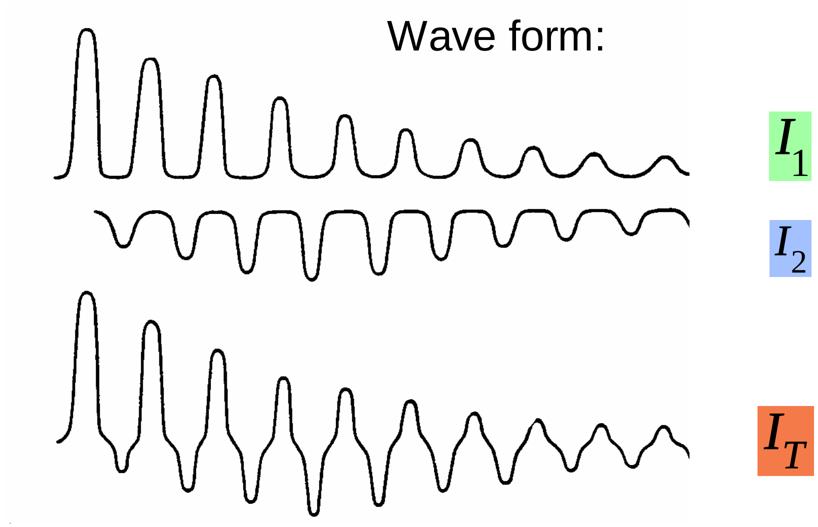
Transformer Inrush current:
Amplitude and time constant

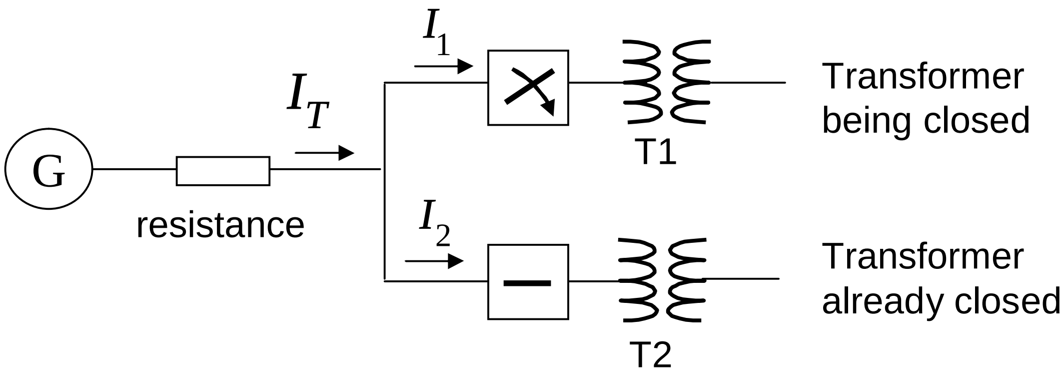


Rated power in MVA	time constant in seconds
0,5....1,0	0,16....0,2
1,0 10	0,2 1,2
>10	1,2 720

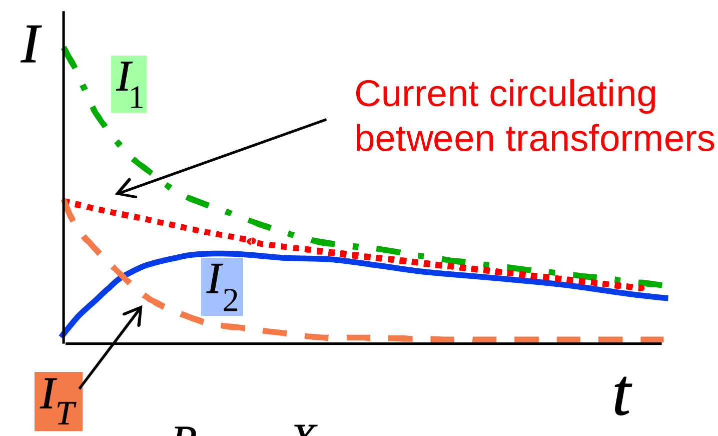
Sympathetic Inrush

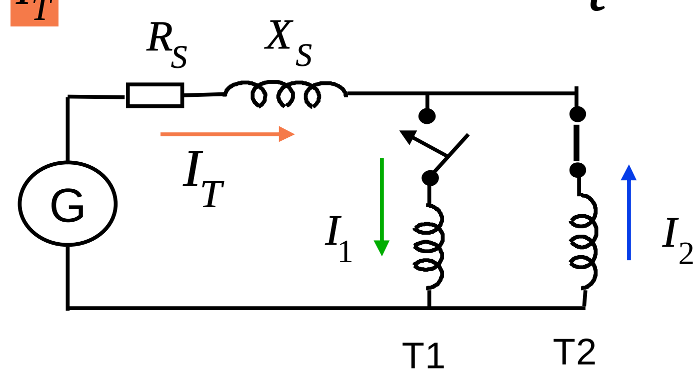
Wave form:





Transient currents:





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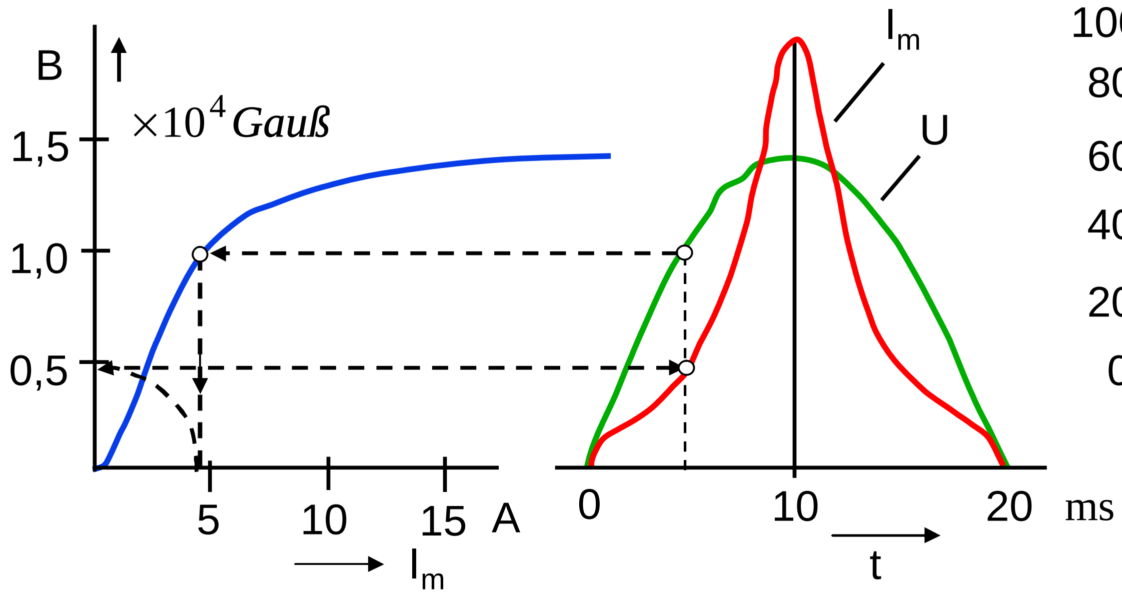
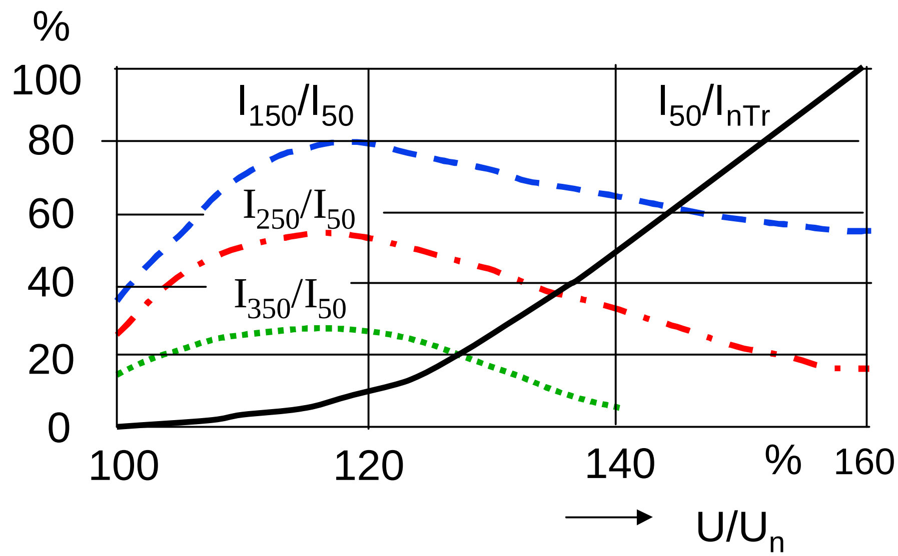
Transformer overfluxing

Deduction of wave form



Harmonic content



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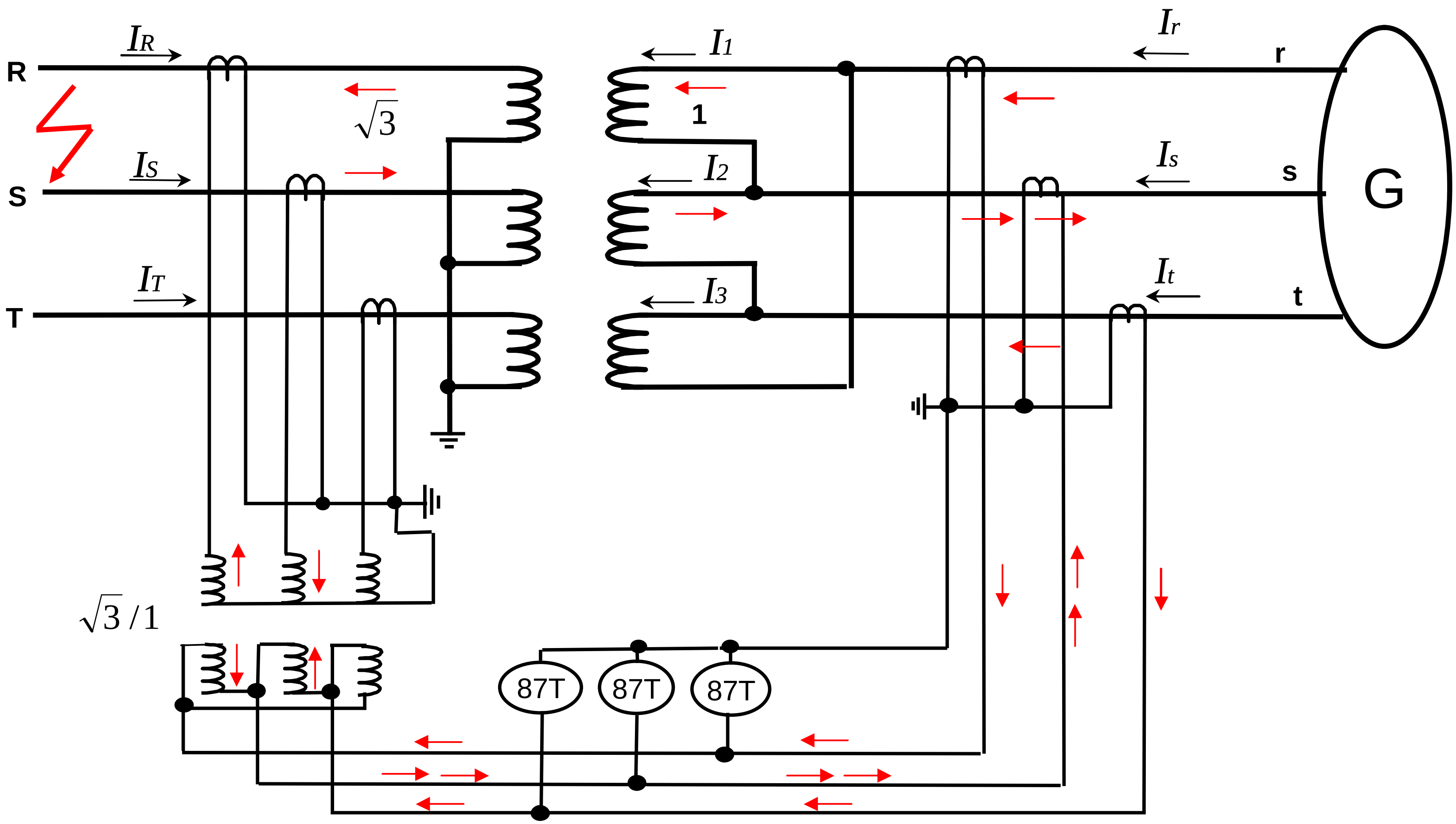
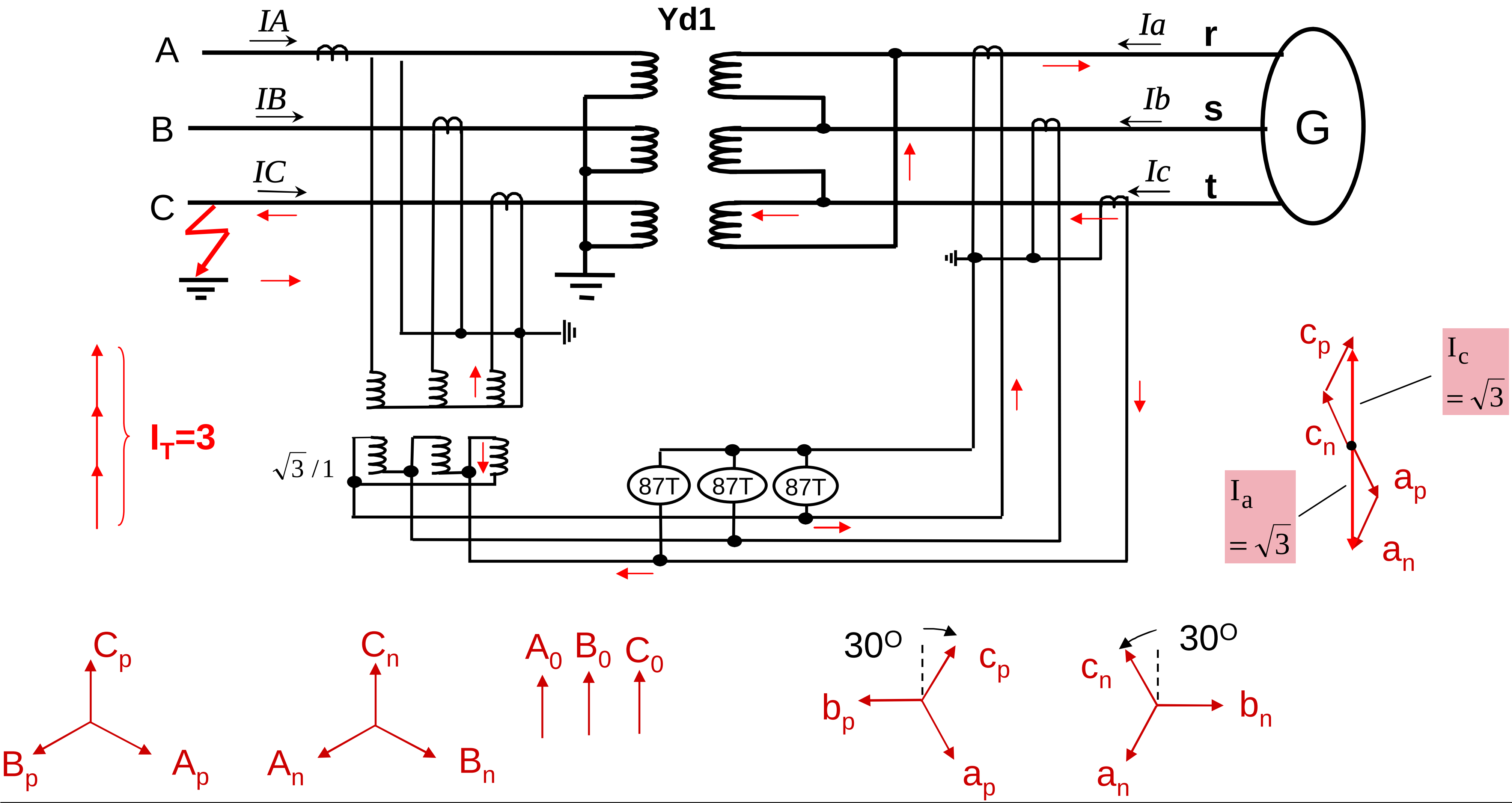
Vector group adaptation with matching CTs
Current distribution with external ph-ph fault



Vector group adaptation and I_0-elimination with matching CTs
Current distribution with external ph-E fault



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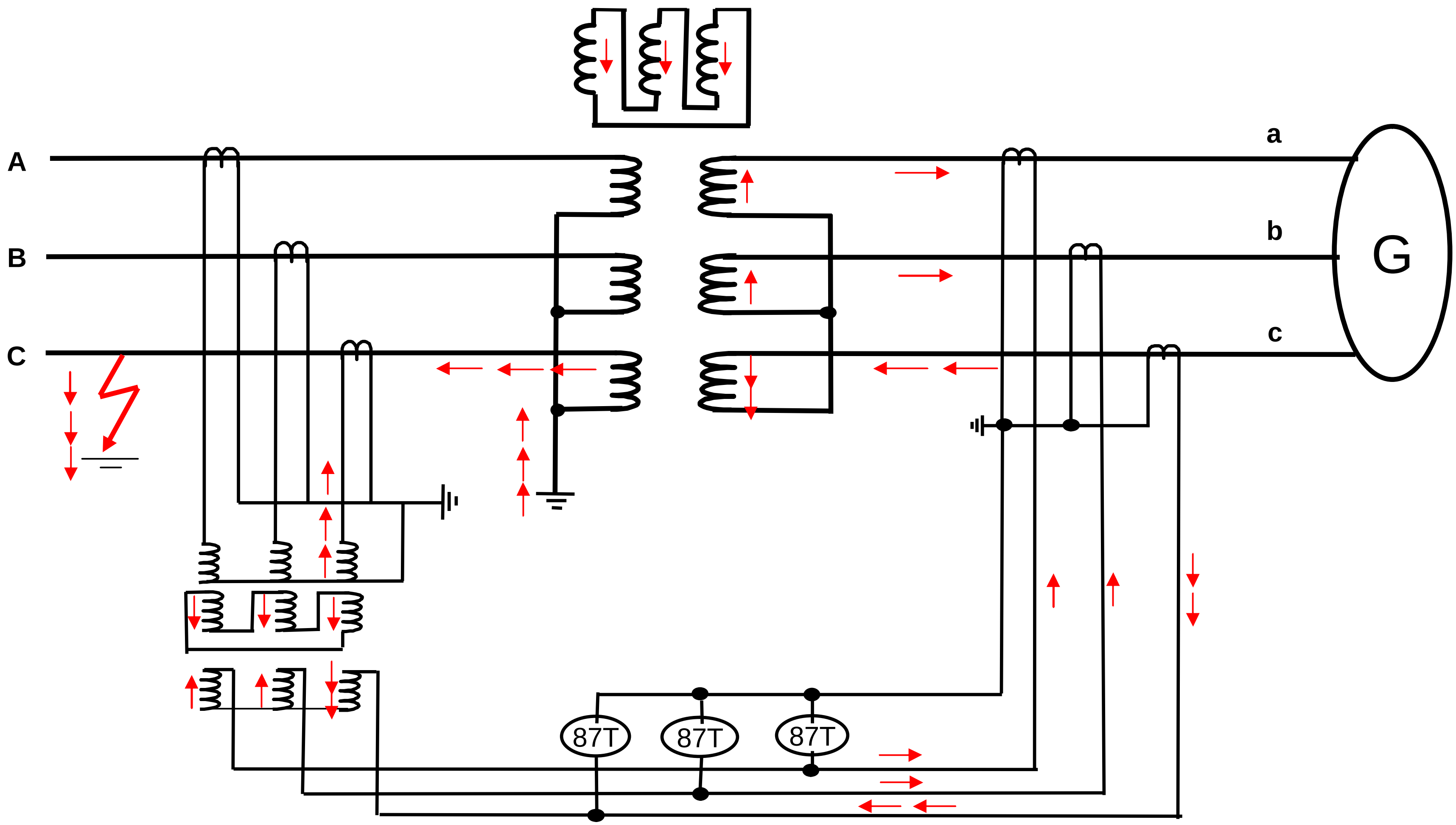
Traditional I_0-elimination with matching CTs
Current distribution in case of an external earth fault



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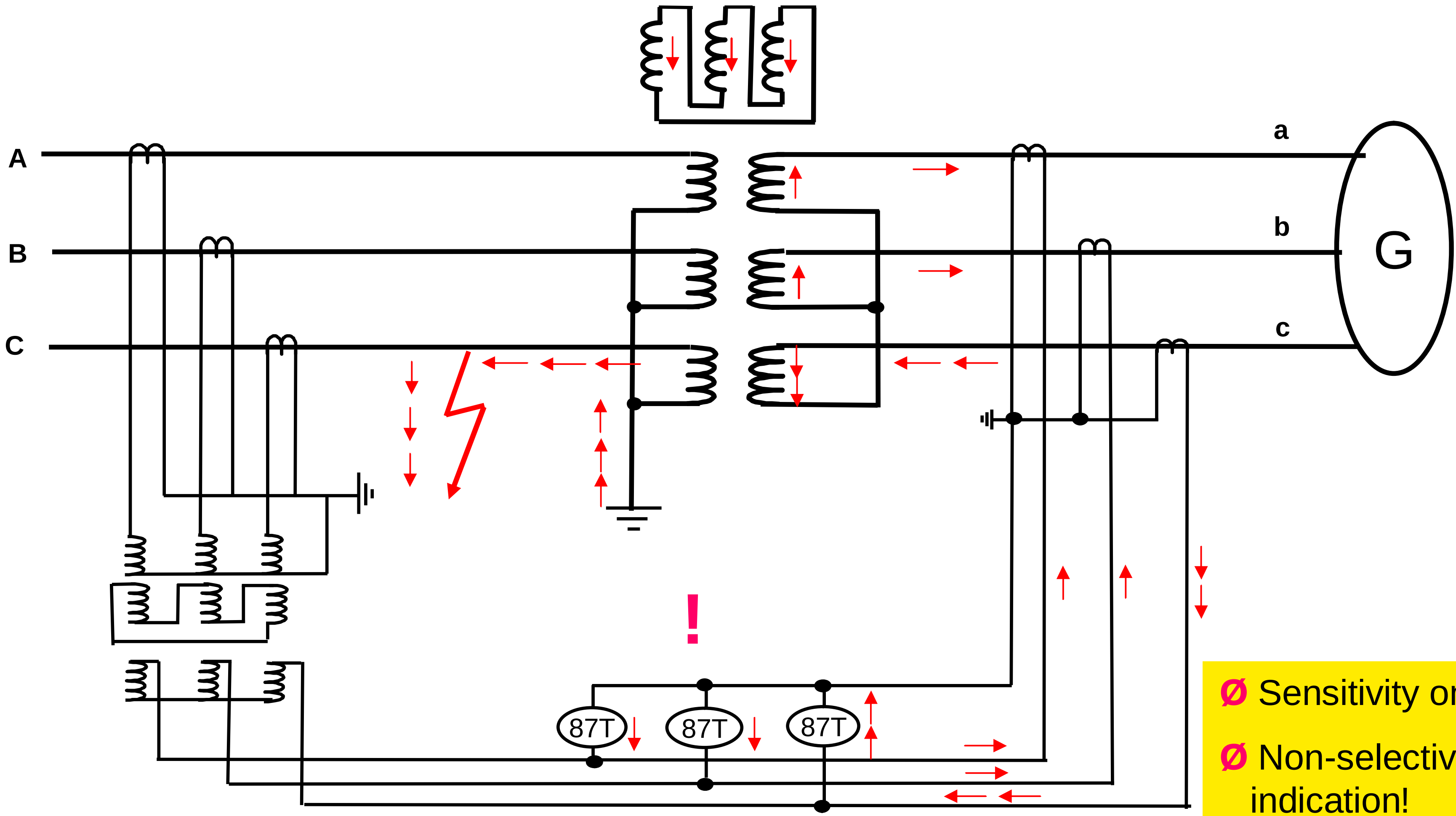
Traditional I_0-elimination with matching CTs
Current distribution in case of an internal earth fault



- Sensitivity only 2/3 I_F!
- Non-selective fault indication!

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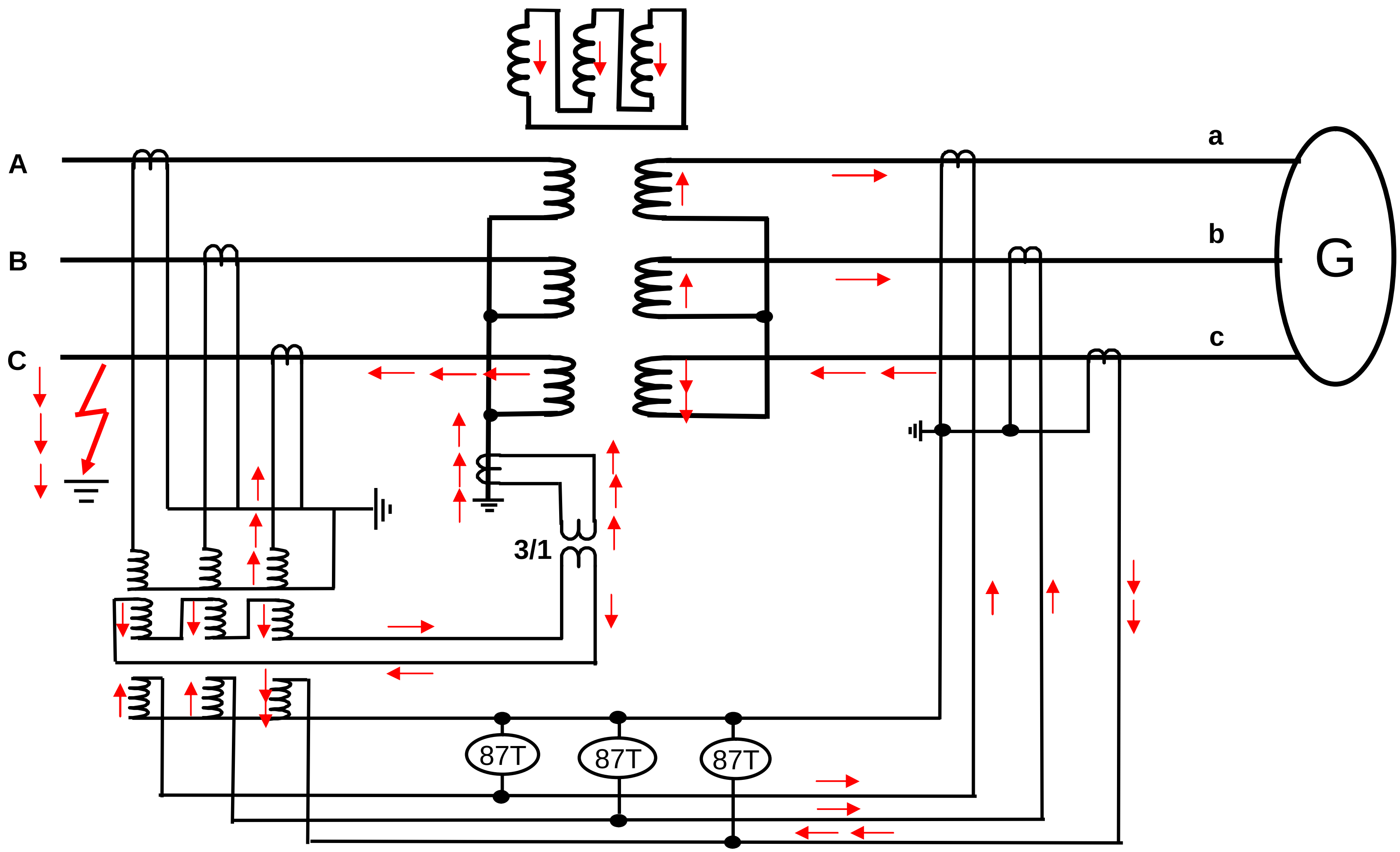
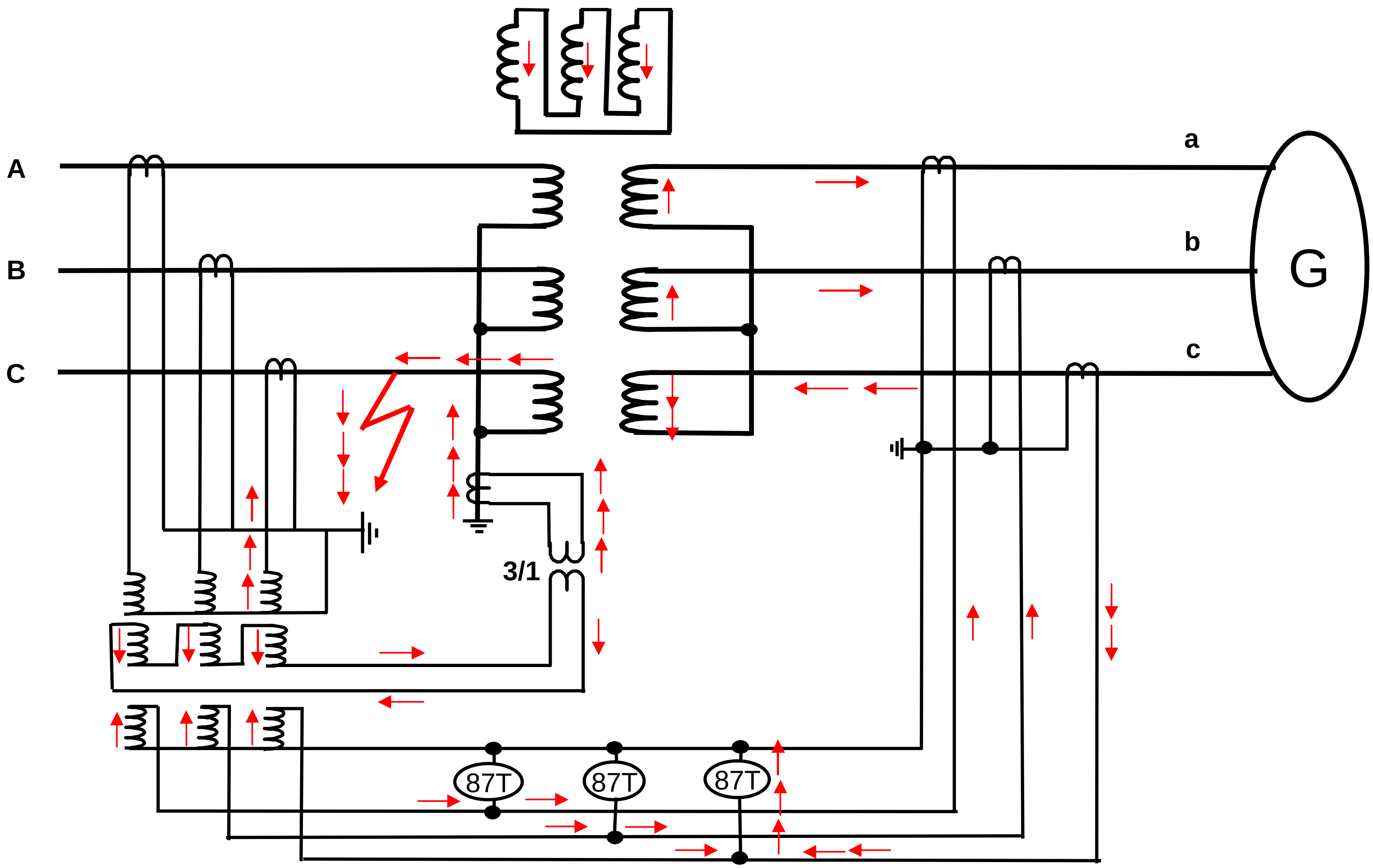
Traditional I_0-correction with matching CTs
Current distribution with external ph-E fault



Traditional I_0-correction with matching CTs
Current distribution with internal ph-E fault



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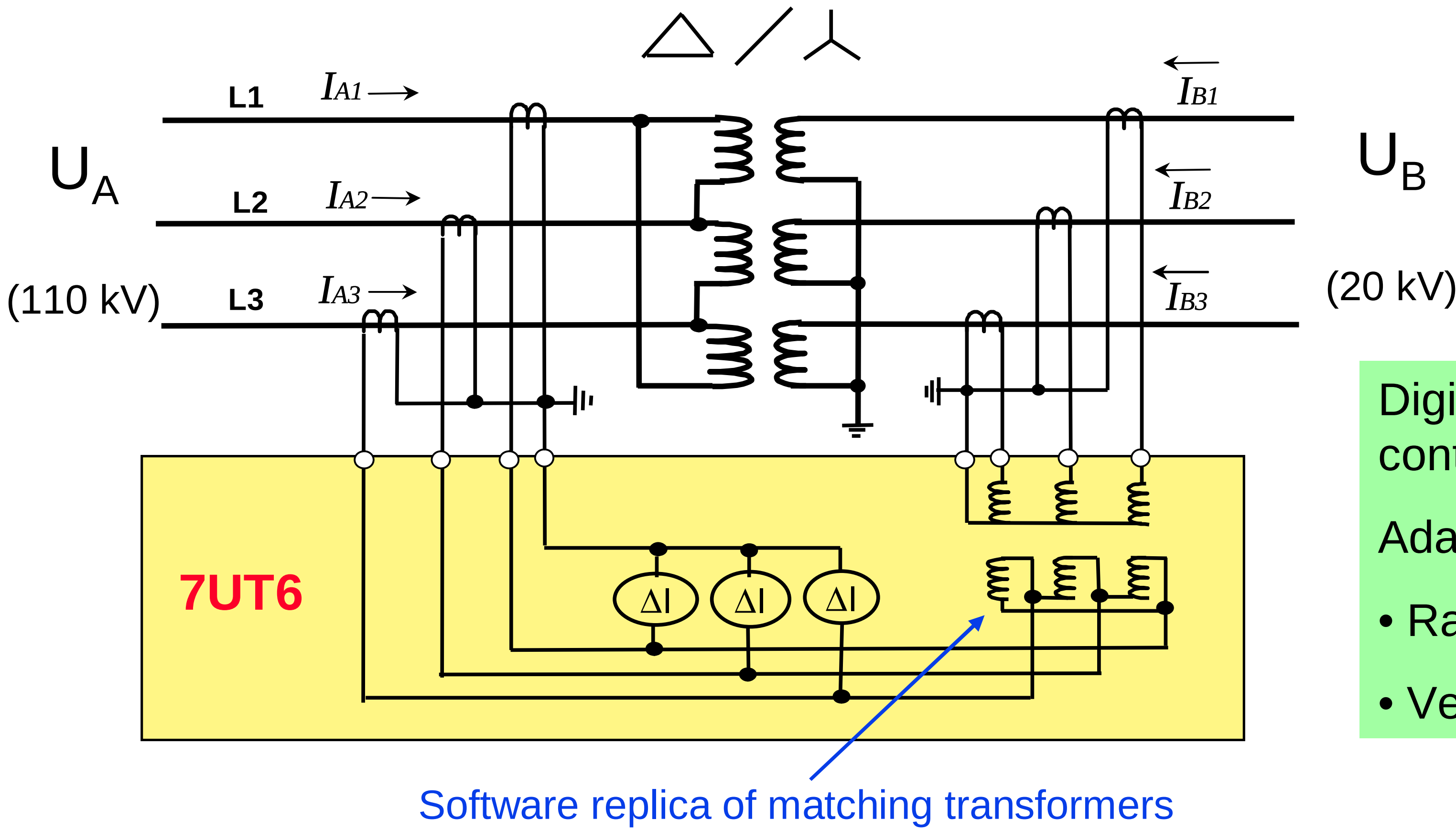
Transformer differential protection, connection



Digital protection contains:

Adaptation to

- Ratio U_A / U_B
- Vector group

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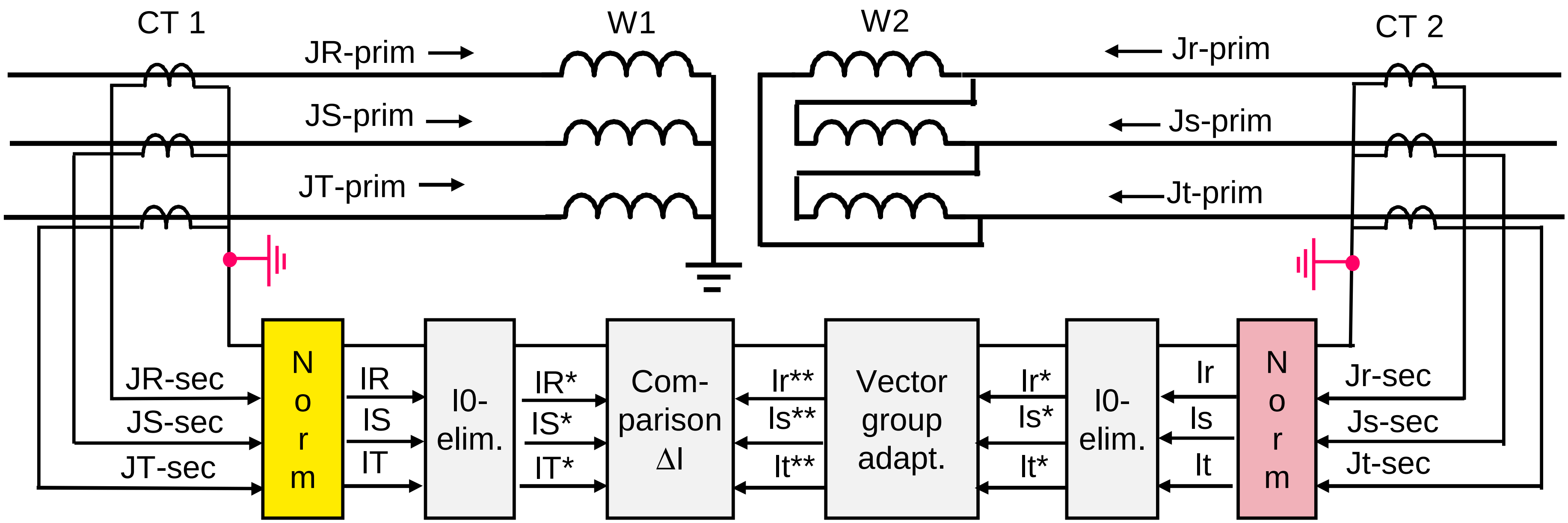
Digital transformer protection
Adaptation of currents for comparison (1)



$$I_{N-Transf-W1} = \frac{S_N}{\sqrt{3}\cdot U_{N-1}}$$

$$I_{N-Transf-W2} = \frac{S_N}{\sqrt{3}\cdot U_{N-2}}$$

$$\begin{vmatrix} I_R \\ I_S \\ I_T \end{vmatrix} = \frac{I_{N-Prim-CT1}}{I_{N-Transf-W1}} \cdot \begin{vmatrix} J_{R-sec} \\ J_{S-sec} \\ J_{T-sec} \end{vmatrix} = k_{CT-1} \cdot \begin{vmatrix} J_{R-sec} \\ J_{S-sec} \\ J_{T-sec} \end{vmatrix}$$

$$\begin{vmatrix} I_r \\ I_s \\ I_t \end{vmatrix} = \frac{I_{N-Prim-CT\ 2}}{I_{N-Transf\ -W2}} \cdot \begin{vmatrix} J_{r-sec} \\ J_{s-sec} \\ J_{t-sec} \end{vmatrix} = k_{CT-2} \cdot \begin{vmatrix} J_{r-sec} \\ J_{s-sec} \\ J_{t-sec} \end{vmatrix}$$

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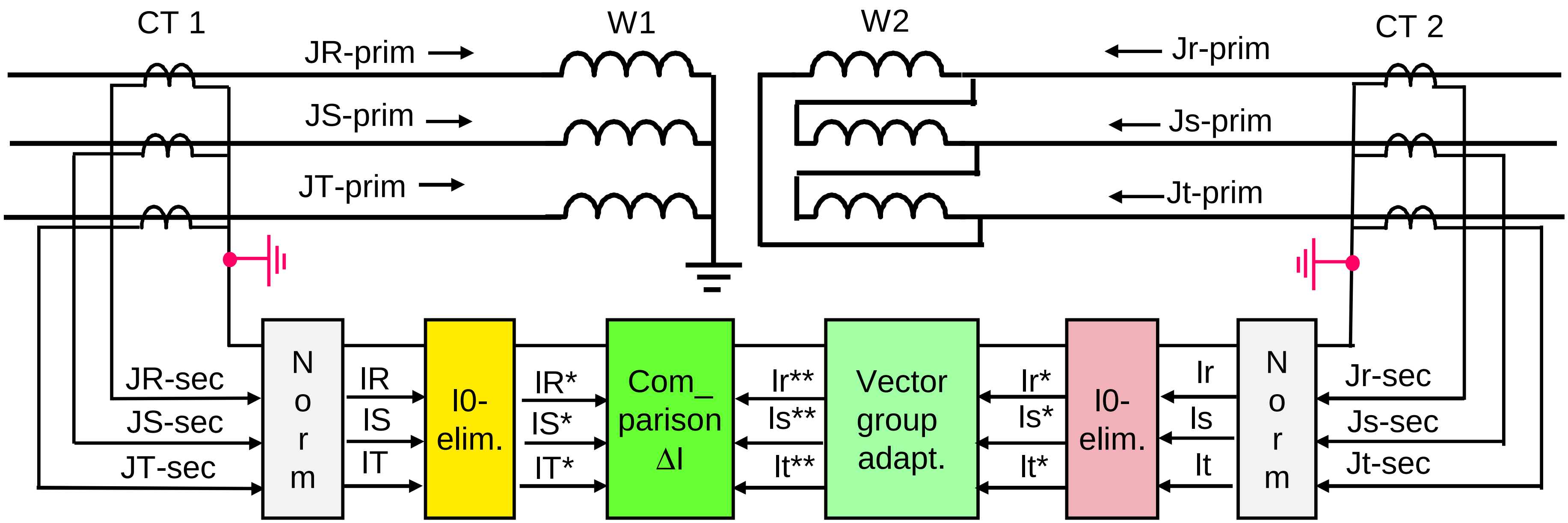
Digital transformer protection
Adaptation of currents for comparison (2)



$$I_0 = \frac{1}{3}\cdot(I_R + I_S + I_T)$$

$$I_R{}^* = I_R - I_0$$

$$I_S{}^* = I_S - I_0$$

$$I_T{}^* = I_T - I_0$$

$$\begin{vmatrix} I_{\Delta-R} \\ I_{\Delta-S} \\ I_{\Delta-T} \end{vmatrix} = \begin{vmatrix} I_R{}^* \\ I_S{}^* \\ I_T{}^* \end{vmatrix} + \begin{vmatrix} I_r{}^{**} \\ I_s{}^{**} \\ I_t{}^{**} \end{vmatrix}$$

Example Yd5:

$$\begin{vmatrix} I_r{}^{**} \\ I_s{}^{**} \\ I_t{}^{**} \end{vmatrix} = \frac{1}{\sqrt{3}} \begin{vmatrix} -1 & 0 & 1 \\ 1 & -1 & 0 \\ 0 & 1 & -1 \end{vmatrix} \cdot \begin{vmatrix} I_r{}^* \\ I_s{}^* \\ I_t{}^* \end{vmatrix}$$

$$I_0 = \frac{1}{3}\cdot(I_r + I_s + I_t)$$

$$I_r{}^* = I_r - I_0$$

$$I_s{}^* = I_s - I_0$$

$$I_t{}^* = I_t - I_0$$

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Adaptation of currents for comparison

Relay input data

Input data:

•n times 30^{O}	vector group number (only for 2nd and 3rd winding, 1st winding is reference)
•UN (kV)	Rated winding voltage
•SN (MVA)	rated winding power
•INW (A)	Primary rated CT current
•Line or BB	direction of CT neutral
•Elimination / Correction / without	I_0-treatment
•Side XX	Assignment input for REF
•INW S (A)	Primary rated current of neutral CT
•Neutral CT	Earth side connection to relay: Q7 or Q8?

Winding 1 (reference) is normally:

•High voltage side

At windings with tap changer:

$$U_N = 2 \cdot \frac{U_{max} \cdot U_{min}}{U_{max} + U_{min}}$$

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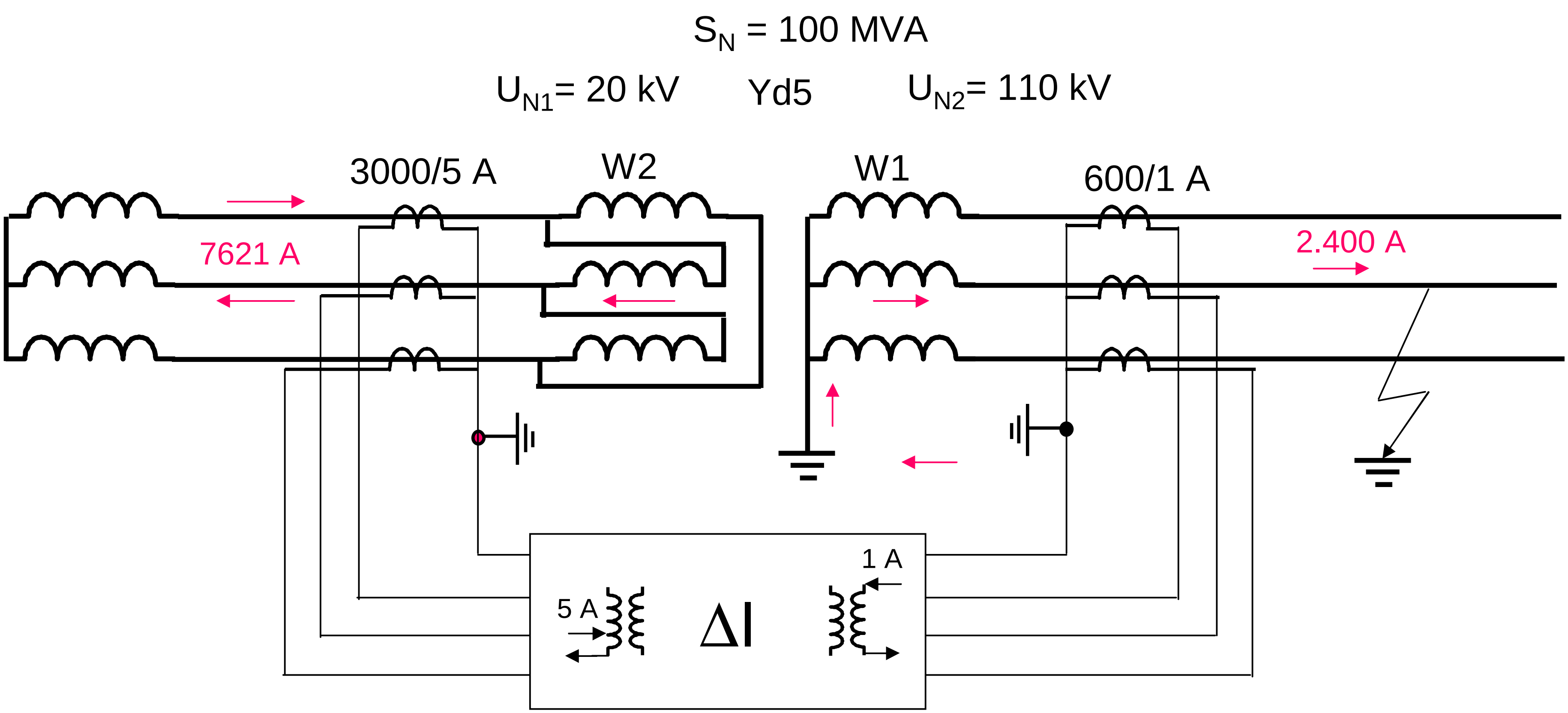
Digital transformer protection
Current adaptation, Example (1)



Digital transformer protection
Current adaptation, Example (2)

20-kV-side

$$I_{N-Trafo-W2} = \frac{100MVA}{\sqrt{3}\cdot 20kV} = 2887A$$

$$J_{r,s,t\text{-sek}} = \frac{1}{3000}\cdot 13200/\sqrt{3} = 4{,}4/\sqrt{3}\ A$$

$$I_{Norm} = \frac{3000}{2887}\cdot 4{,}4/\sqrt{3} = 4{,}57/\sqrt{3}\ A$$

I0-elimination:

$$\begin{vmatrix} I_r ** \\ I_s ** \\ I_t ** \end{vmatrix} = \frac{1}{\sqrt{3}} \begin{vmatrix} -1 & 0 & 1 \\ 1 & -1 & 0 \\ 0 & 1 & -1 \end{vmatrix} \cdot \begin{vmatrix} 4{,}57/\sqrt{3} \\ -4{,}57/\sqrt{3} \\ 0 \end{vmatrix} = \begin{vmatrix} -4{,}57/3 \\ 2\cdot 4{,}57/3 \\ -4{,}57/3 \end{vmatrix}$$

110-kV-side

$$I_{N-Trafo-W1} = \frac{100MVA}{\sqrt{3}\cdot 110kV} = 525A$$

$$J_{R,S,T\text{-sek}} = \frac{1}{600}\cdot 2400 = 4{,}0\ A$$

$$I_{Norm} = \frac{600}{525}\cdot 4 = 4{,}57A$$

Vector group adaptation: Yd5

$$\begin{vmatrix} I_r * \\ I_s * \\ I_t * \end{vmatrix} = \frac{1}{3}\cdot \begin{vmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{vmatrix} \cdot \begin{vmatrix} 0 \\ -4{,}57 \\ 0 \end{vmatrix} = \begin{vmatrix} 4{,}57/3 \\ -2\cdot 4{,}57/3 \\ 4{,}57/3 \end{vmatrix}$$

$$I_{A-R} = I_R * + I_r ** = 4{,}57/\sqrt{3} - 4{,}57/\sqrt{3} = 0$$

$$I_{A-S} = I_S * + I_s ** = -2\cdot 4{,}57/\sqrt{3} + 2\cdot 4{,}57/\sqrt{3} = 0$$

$$I_{A-T} = I_T * + I_t ** = 4{,}57/\sqrt{3} - 4{,}57/\sqrt{3} = 0$$

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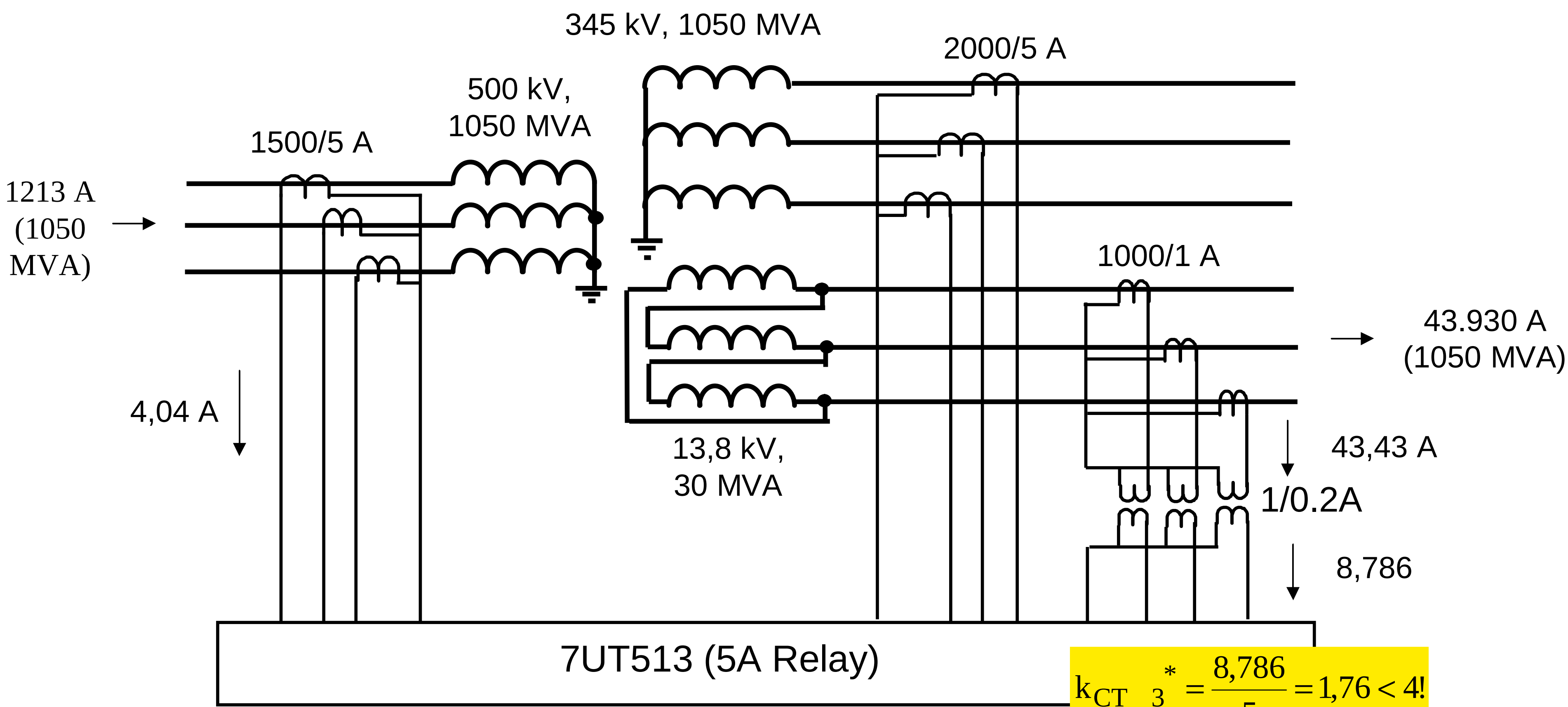
Current adaptation (1)

Practical example for the need of matching CTs

Matching CTs recommended, if
k_Wan_n > 4 or k_Wan_n < 1/4: *)

*) To keep the specified measuring accuracy of 7UT51. For protection only necessary if 8 <k_Wan_n <1/8



$$k_{CT\_3}^{*} = \frac{8{,}786}{5} = 1{,}76 < 4!$$

Current adaptation (2)

Practical example for the need of matching CTs

$$I_{n-Tr-W1} = \frac{1050 \cdot 10^3}{\sqrt{3} \cdot 500} = 1213A$$

$$I_{n-Tr-W1-sec} = \frac{1213A}{1500/5} = 4{,}04A$$

$$k_{CT-1} = \frac{4.04}{5} = 0{,}809$$

$$I_{n-Tr-W2} = \frac{1050 \cdot 10^3}{\sqrt{3} \cdot 345} = 1757A$$

$$I_{n-Tr-W2-sek} = \frac{1757A}{2000/5} = 4{,}39A$$

$$k_{CT-2} = \frac{4{,}39}{5} = 0{,}878$$

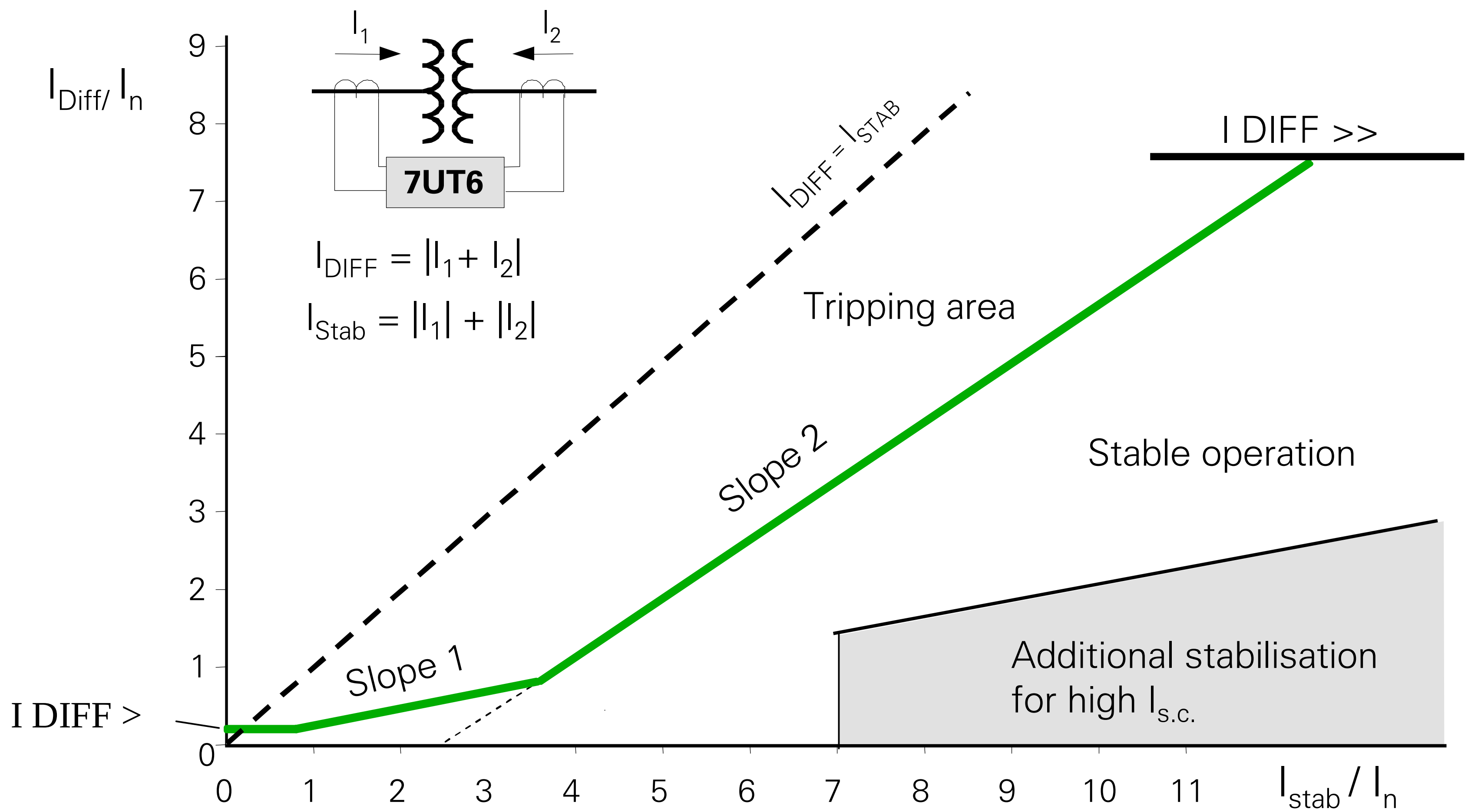
$$I_{n-Tr-W3} = \frac{1050 \cdot 10^3}{\sqrt{3} \cdot 13{,}8} = 43.930A$$

$$I_{n-Tr-W3\_sek} = \frac{43.930A}{1000/1} = 43{,}93A$$

$$k_{CT-3} = \frac{43{,}93}{5} = 8{,}786 > 4!$$

Relay	Transformer winding 1	Transformer winding 3
40·In= 15 Bit +sign = 2^{15} = 32.768		
32.768 — 15 — 40·In	32.36	351,44
1 — 0,122%In	0,099%	1,072%

7UT6
Operating characteristic



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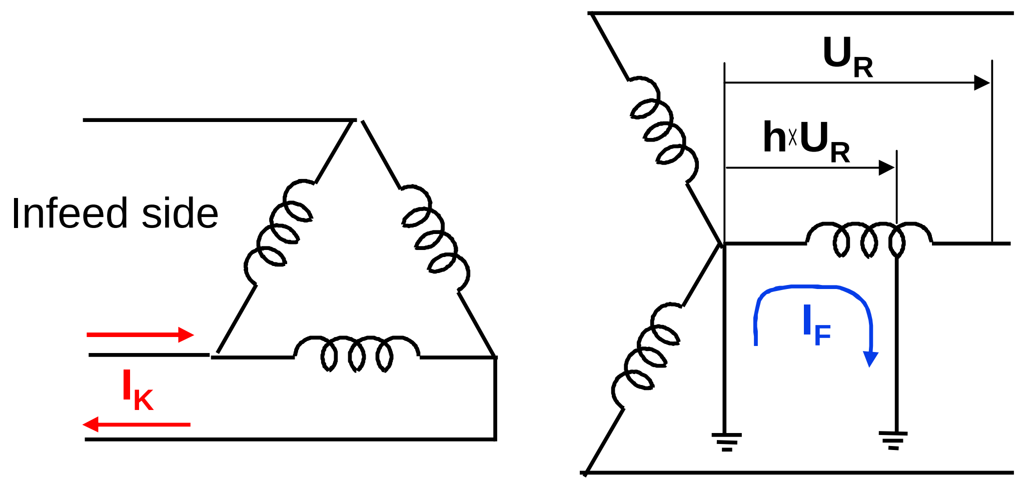
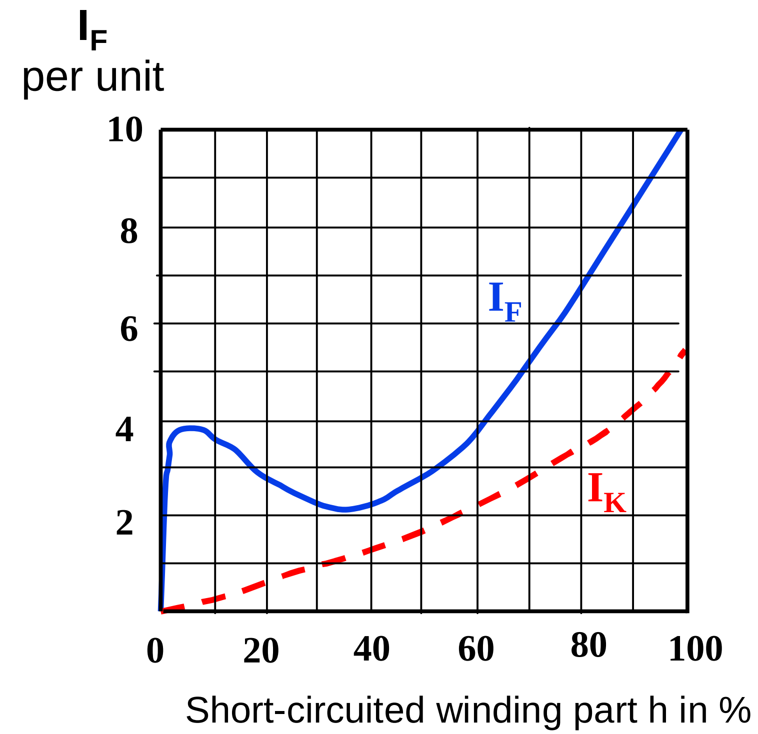
I_0-elimination / correction: Summary

- **I_0- elimination** necessary at all windings with earthed neutral or with grounding transformer in the protection range
  Earth fault sensitivity reduced to 2/3 !
  Incorrect fault type indication!
- **I_0- correction** provides full earth current sensitivity and correct phase selective fault type indication, however requires CT in the neutral-to-earth connection of the transformer.
- As an alternative, earth differential protection can be used to enhance earth fault sensitivity.

Transformer winding to earth fault

Solid earthed neutral

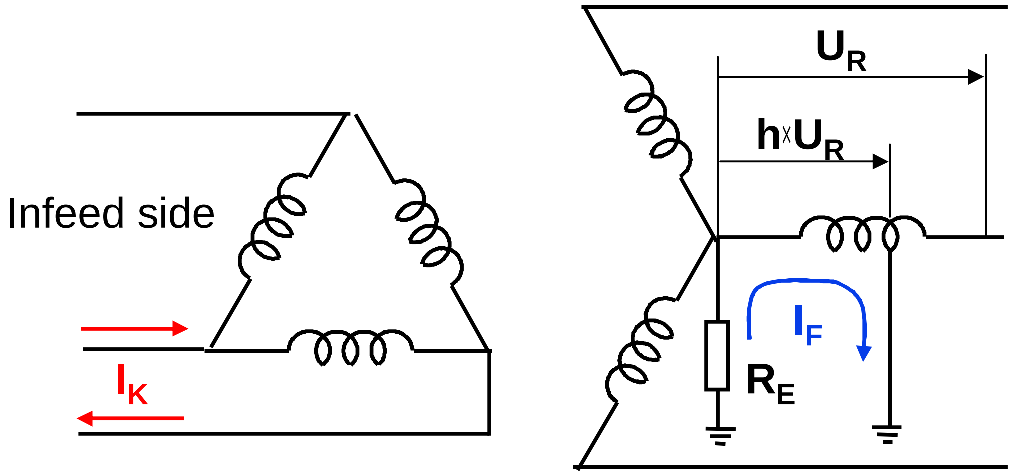


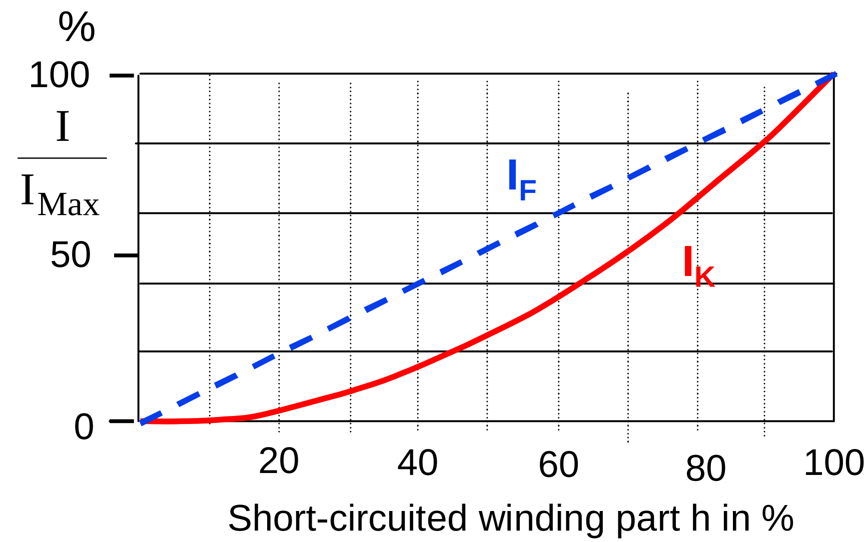


Source: P.M. Anderson: Power System Protection, McGraw-Hill and IEEE Press (Book)

Transformer winding to earth fault

Resistance or reactance earthed neutral





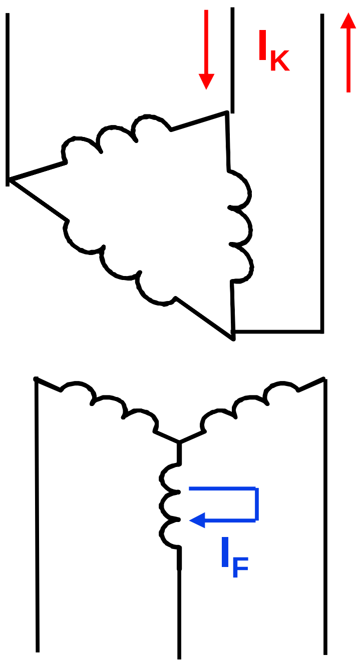
$$I_F = \frac{h \cdot U_R}{R_E}$$

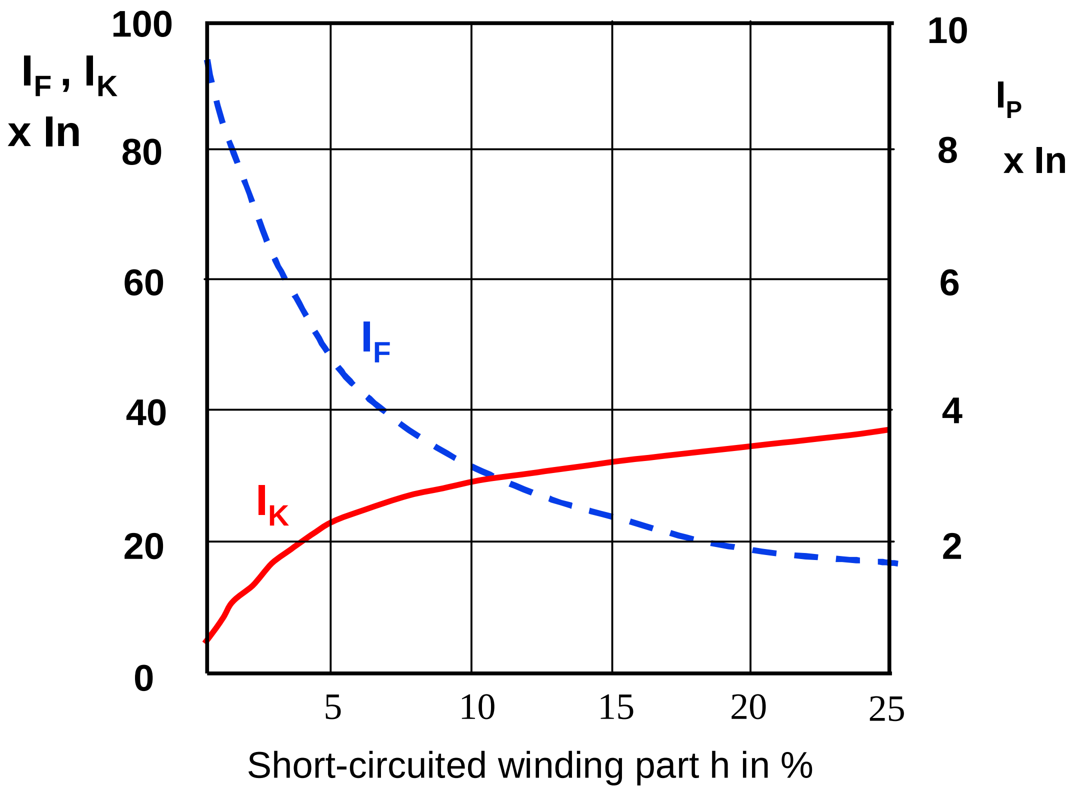
$$I_K = \frac{h \cdot w_2}{w_1} \cdot I_F = h \cdot \frac{U_{2n}}{U_{1n} \cdot \sqrt{3}} \cdot I_F$$

$$I_K = h^2 \cdot \frac{1}{\sqrt{3}} \cdot \frac{U_{2n}}{U_{1n}} \cdot \frac{U_R}{R_E}$$

Source: P.M. Anderson: Power System Protection, McGraw-Hill and IEEE Press (Book)

Transformer winding short-circuit





Source: Protective Relays, Application Guide, GEC Alstom T&D, 1995

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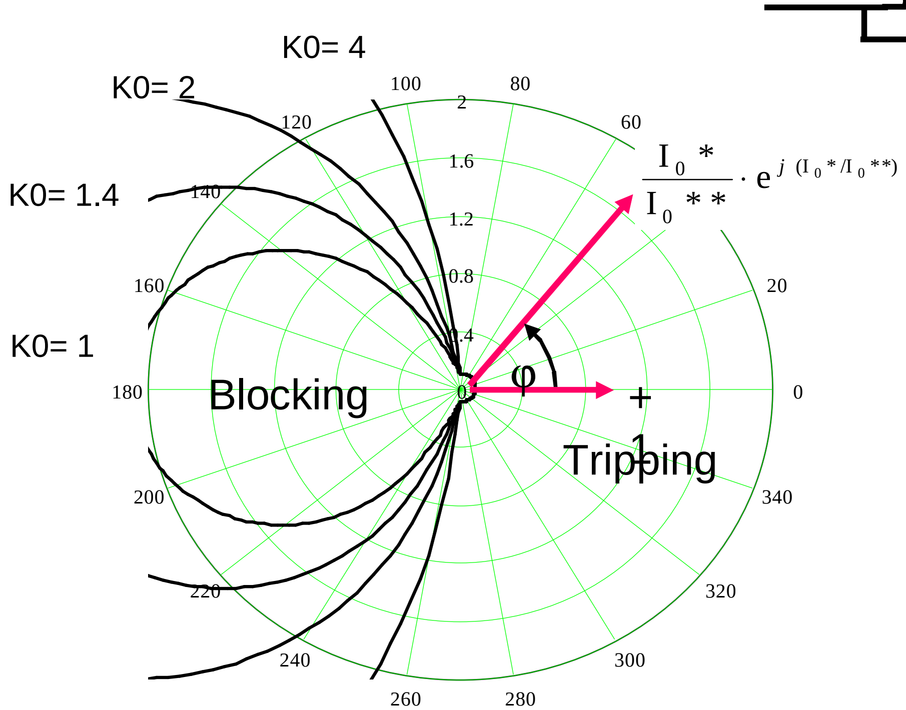
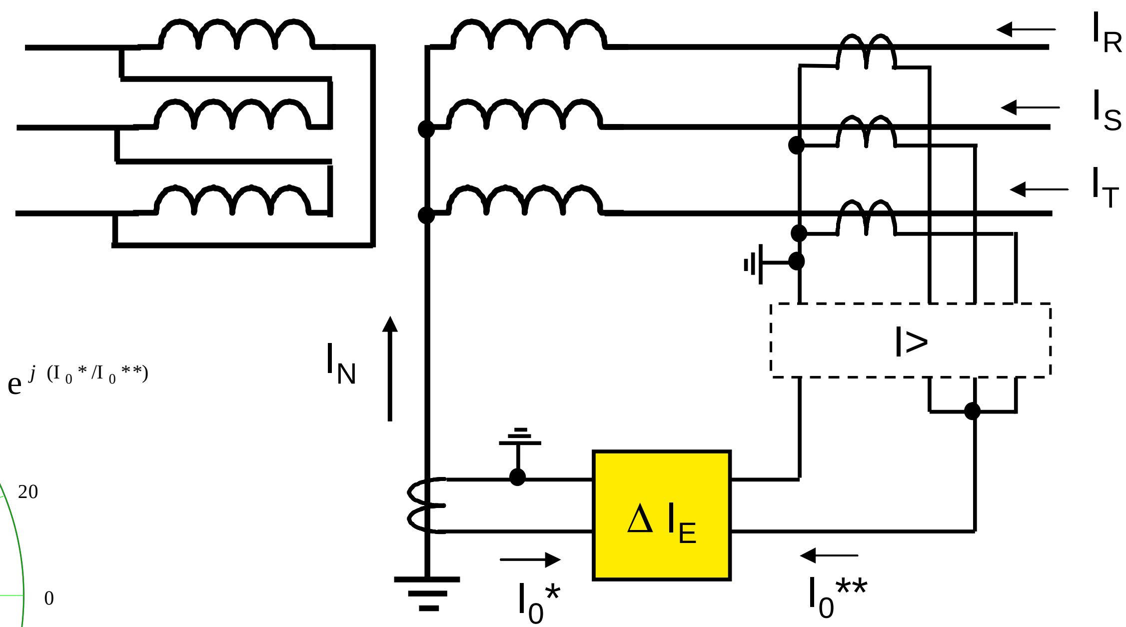
Restricted earth fault protection of relay 7UT6





Polarised earth current differential protection

SIEMENS

Restricted earth fault protection 87N (7UT6) Application aspects

- Increased sensitivity with earth faults near winding neutral
  Preferably used in case of resistance or reactance neutral earthing
- Sensitive to turns short-circuit
- I0 / IN amplitude and angle comparison
- 2nd harmonic stabilised
- Can protect a separate shunt reactor or neutral earthing transformer in addition to the two winding transformer differential protection
- Not applicable with autotransformers! (as only one stabilising input at transformer terminal side, -- high impedance principle to be used in this case.

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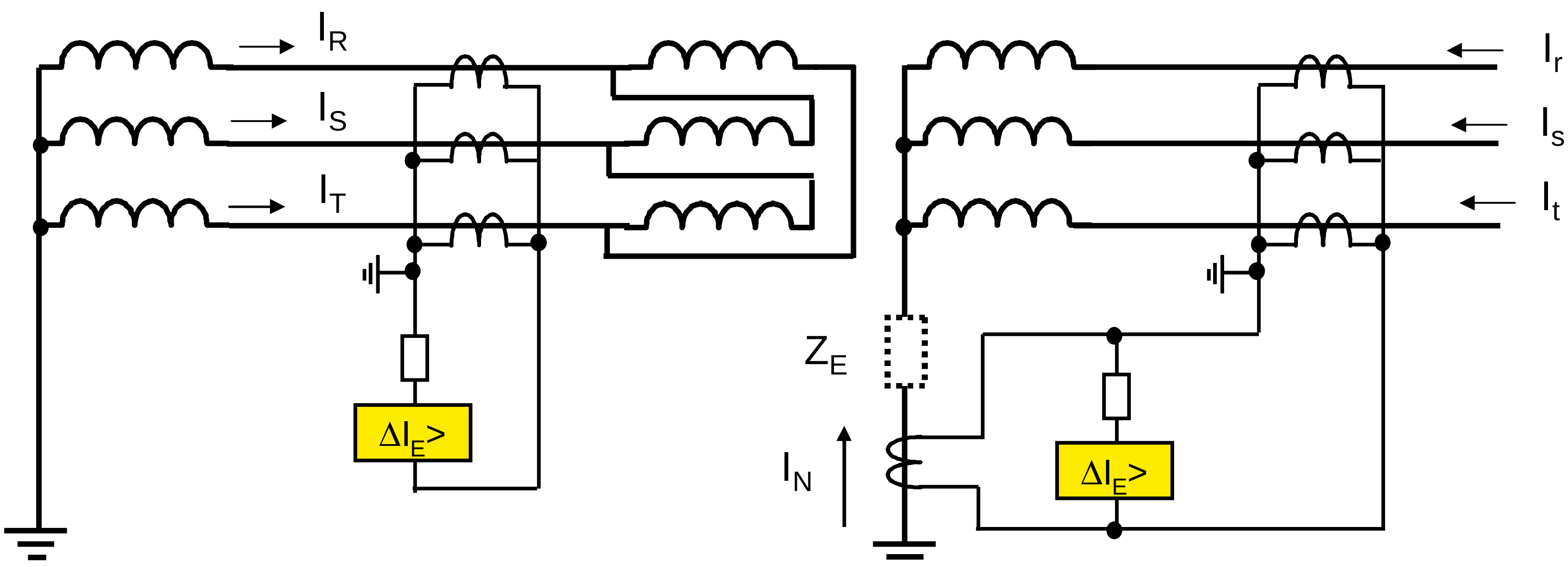
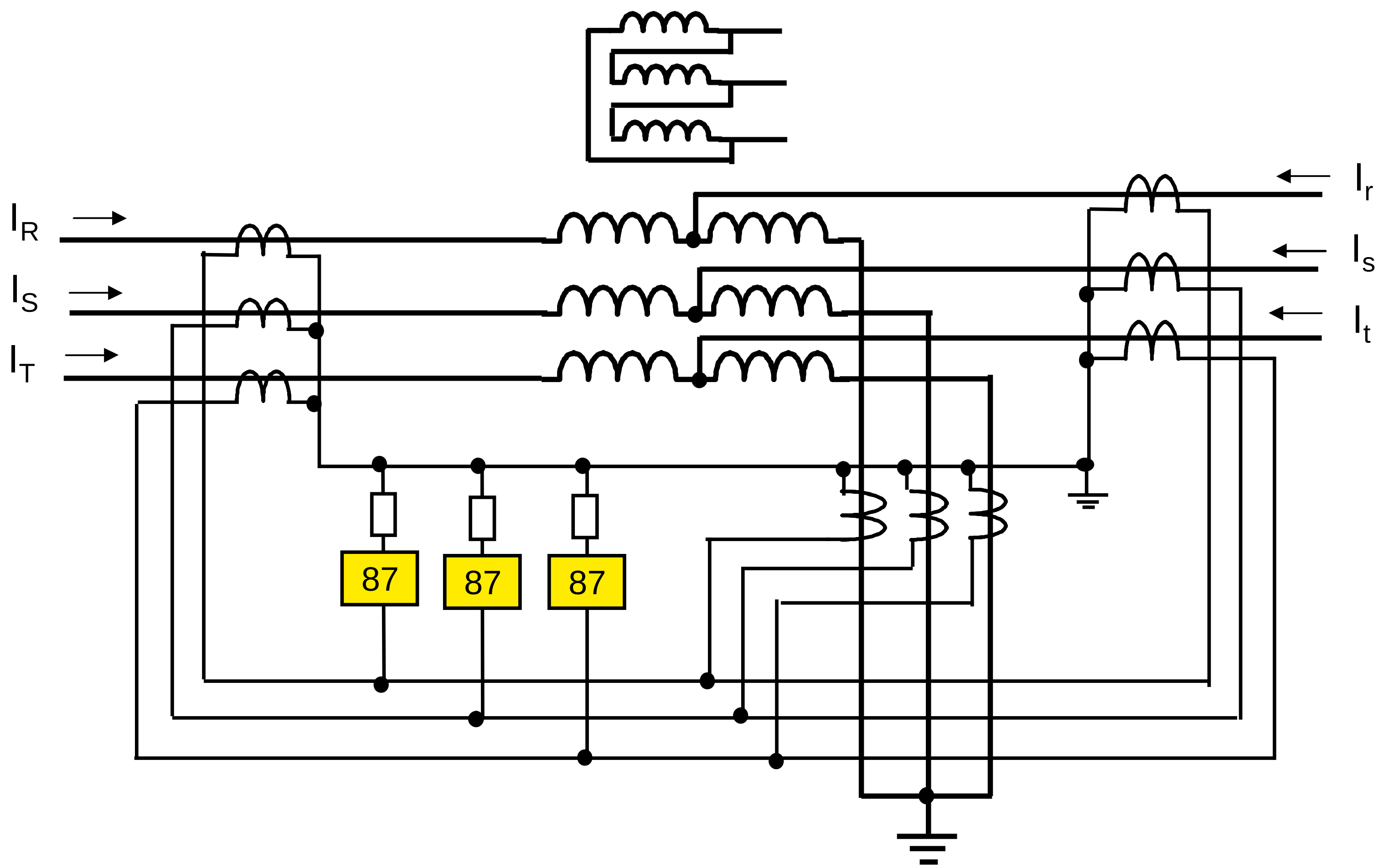
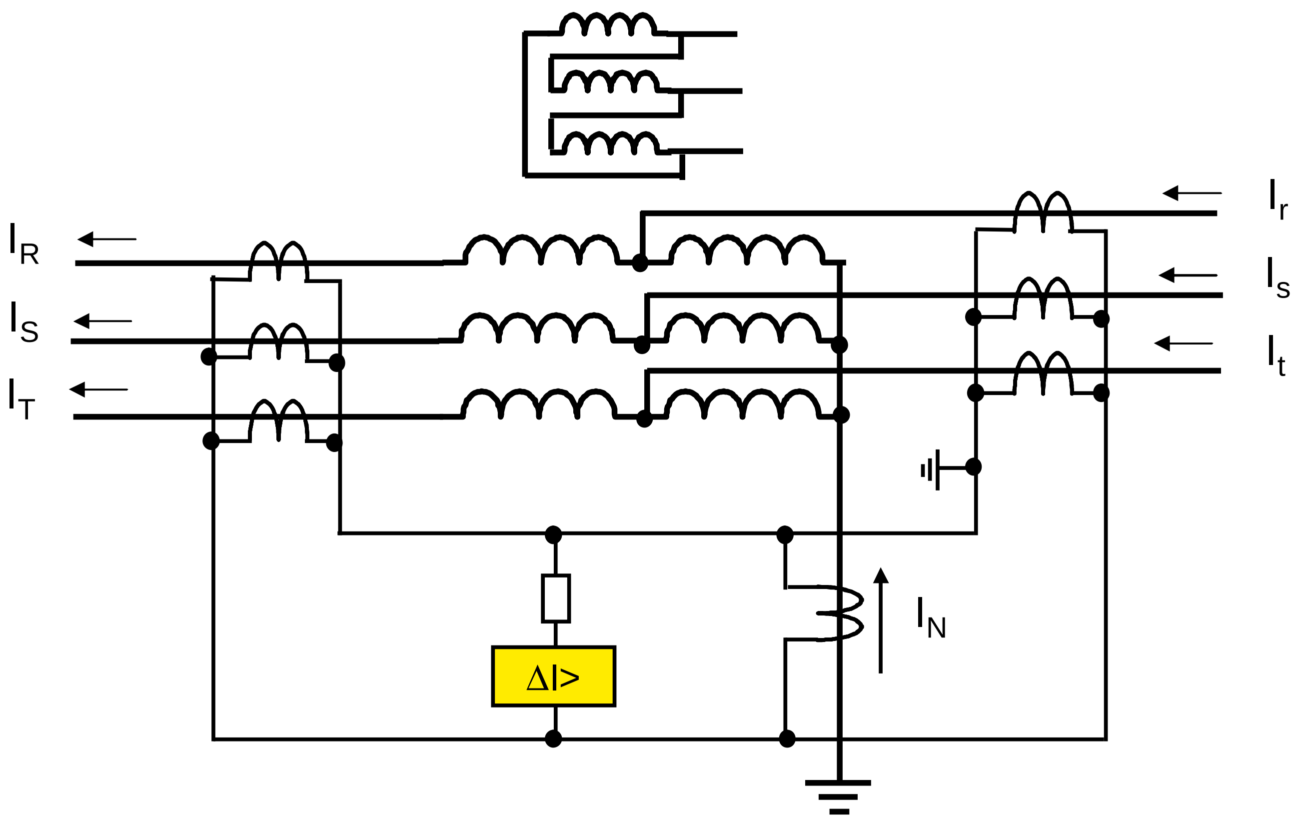
Transformer HI-earth fault protection



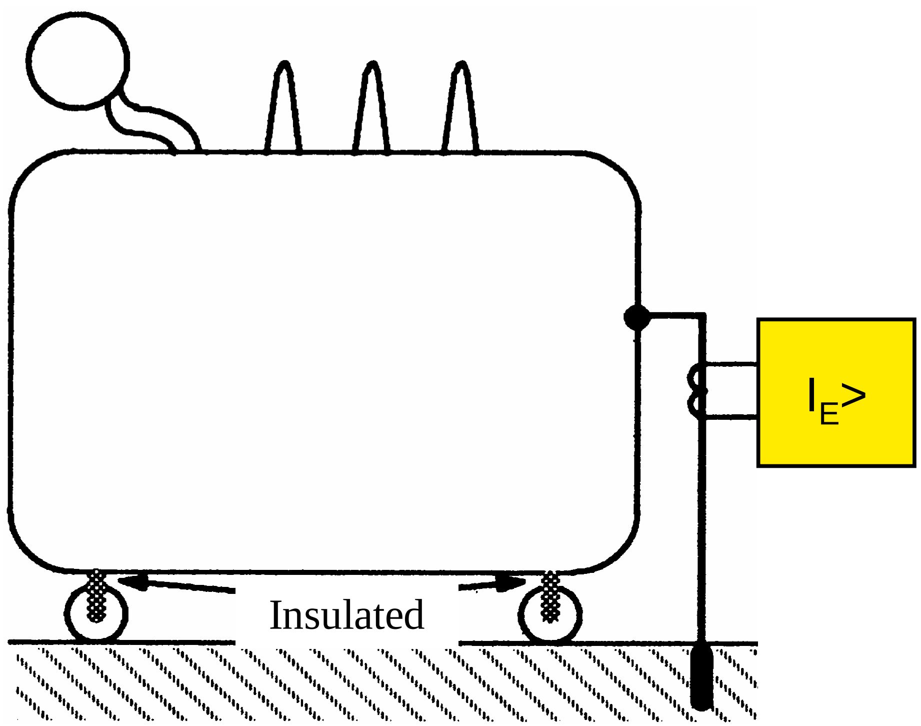
HI differential protection of an autotransformer



HI earth fault protection of an autotransformer



Transformer tank protection 64T: Principle



Transformer protection, Relay design

Fig. 1 SIPROTEC 4
7UT6 differential protection relay for transformers, generators, motors and busbars

7UT6 differential protection for

- Transformers
- Generators
- Motors
- Busbars

7UT612: for protection objects with 2 ends (1/3 x 19" case 7XP20)
7UT613: for protection objects with 3 ends (1/2 x 19" case 7XP20)
7UT633: for protection objects with 3 ends (1/1 x 19" case 7XP20)
7UT635: for protection objects with 5 ends (1/1 x 19" case 7XP20)

SIEMENS

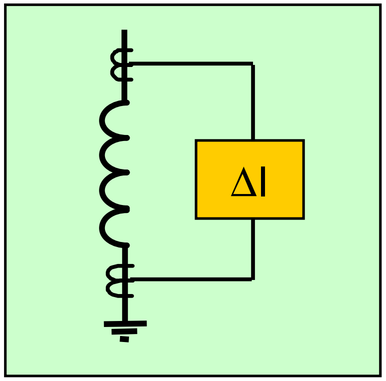
7UT6
Integrated protection functions

Function	ANSI No.
Differential	87T
Earth differential	87 N
Phase overcurrent,	50/51
Neutral overcurrent I_N>, t	50N/51N
Ground overcurrent (I_E, t)	50G/51G
Unbalanced current I_2>, t	46
Thermal overload IEC 60255-8	49
Therm. OL IEC 60354 (hot spot)	49

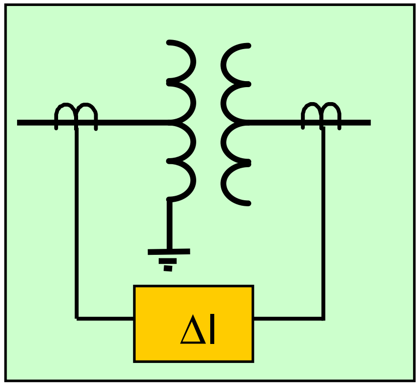
Function	ANSI No.
Overfluxing V/Hz	24
Breaker failure	50BF
Temperature monitoring	38
Hand reset trip	86
Trip circuit supervision	74TC
Binary inputs for tripping commands	

SIEMENS

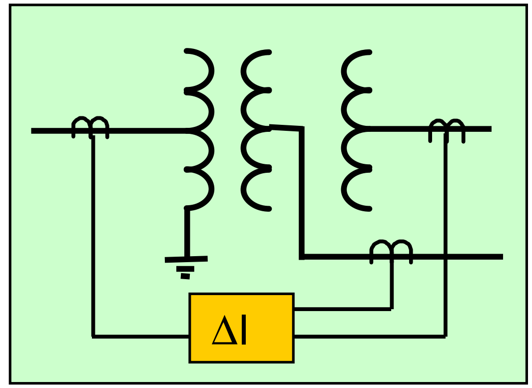
Application range (7UT6)



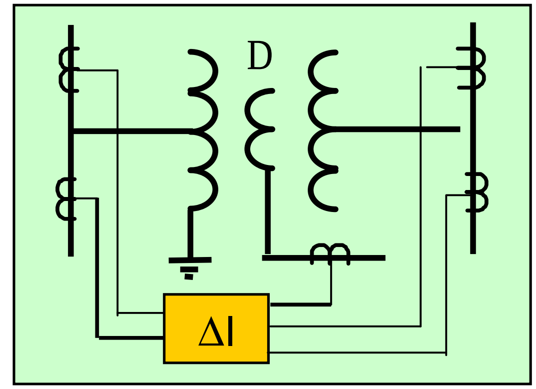
Shunt Reactor



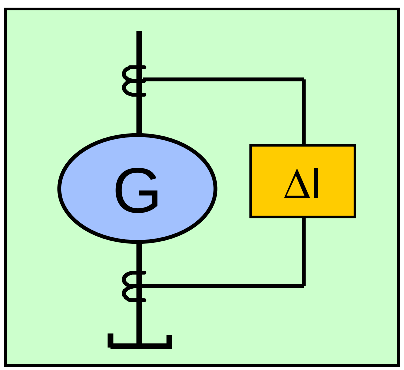
Two winding transformer



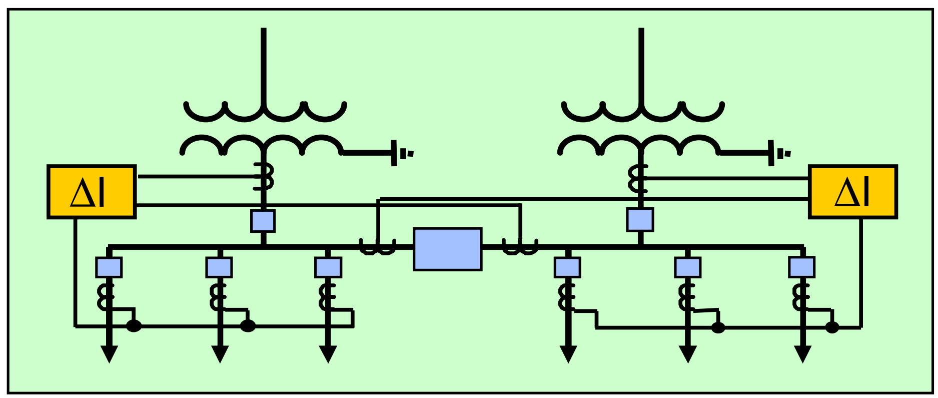
Three winding transformer



Transformer bank (1-1/2-LS)

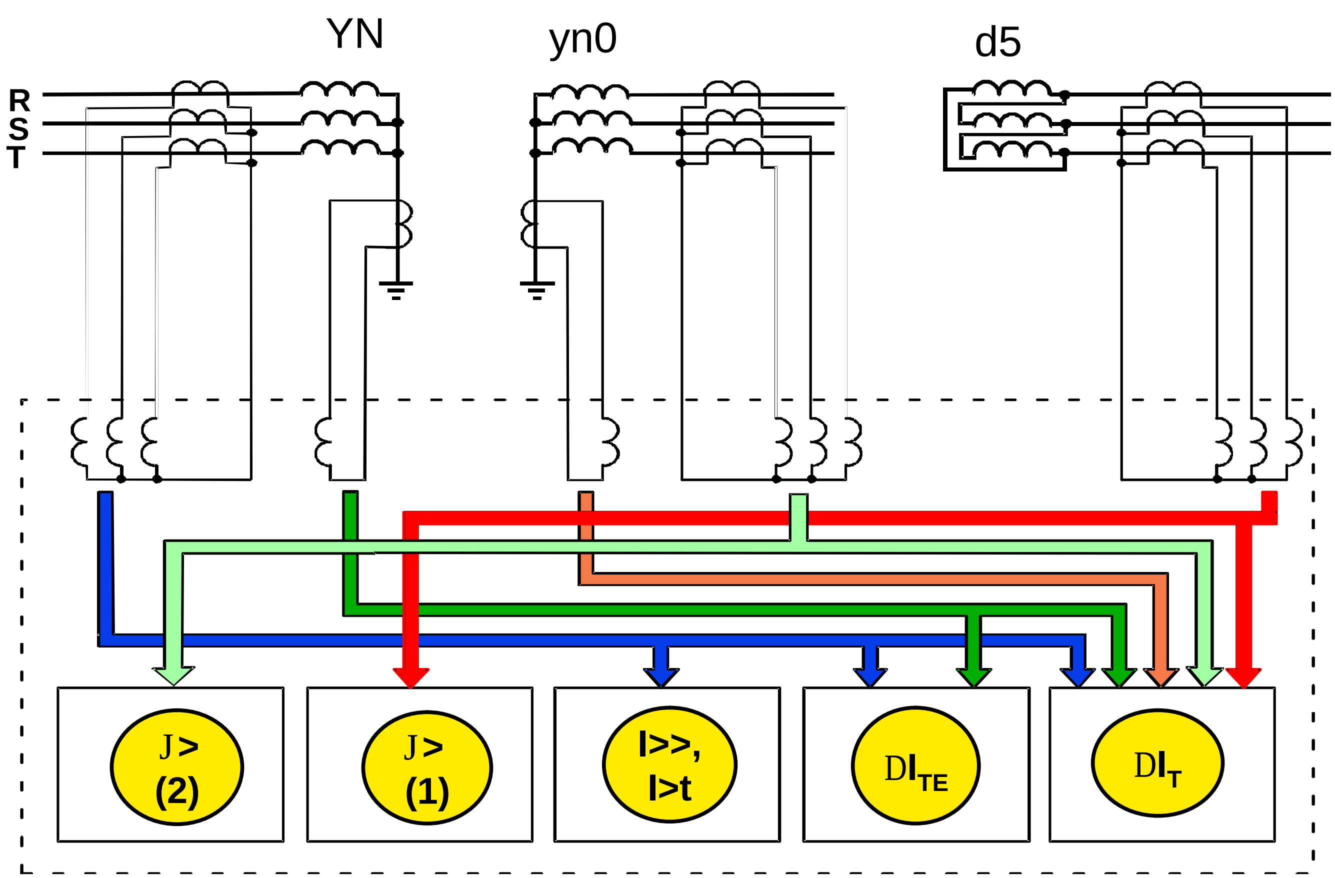


Generator / Motor



Busbars

Digital transformer protection relay 7UT613: Current inputs and integrated protective functions



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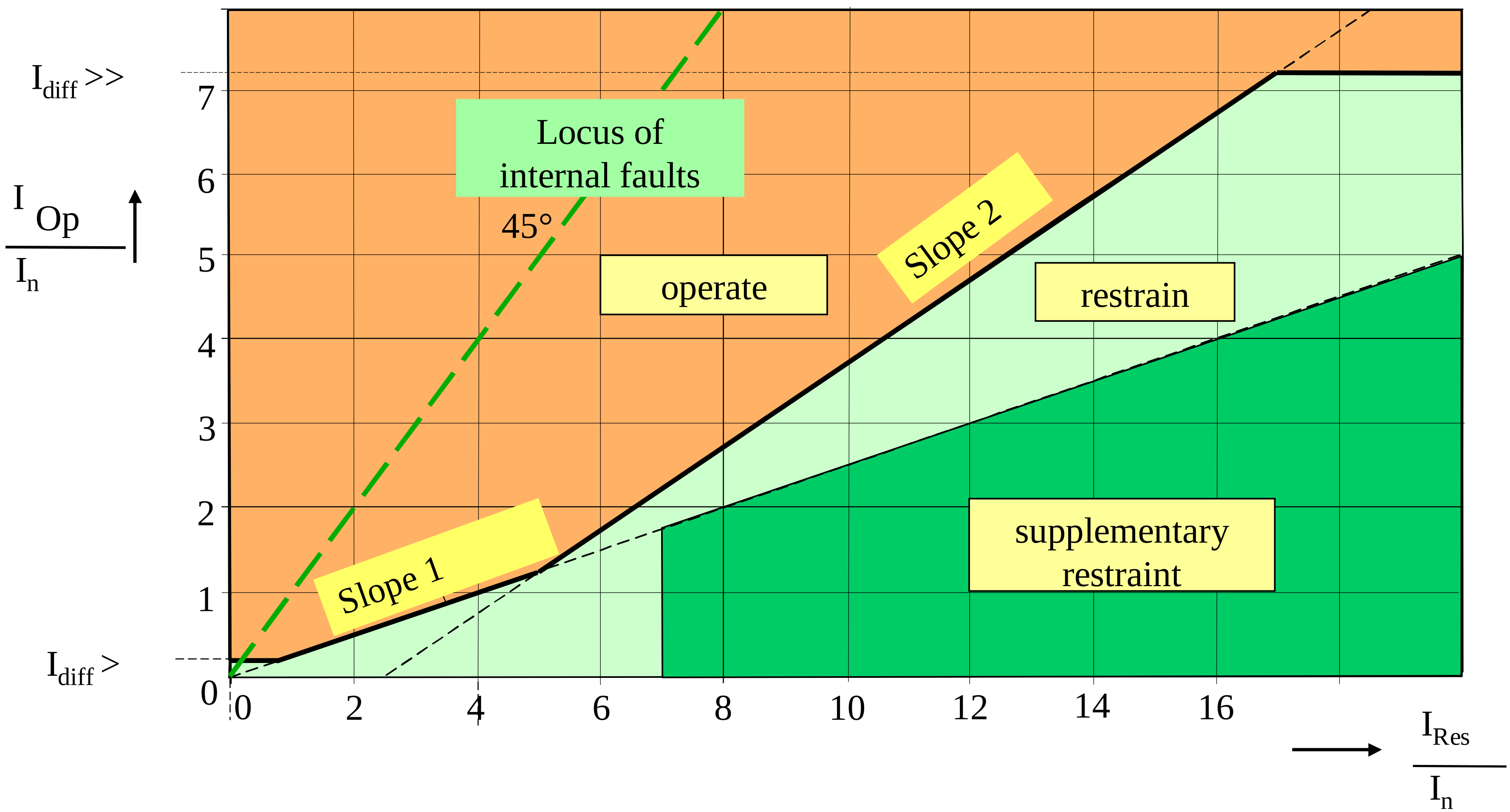
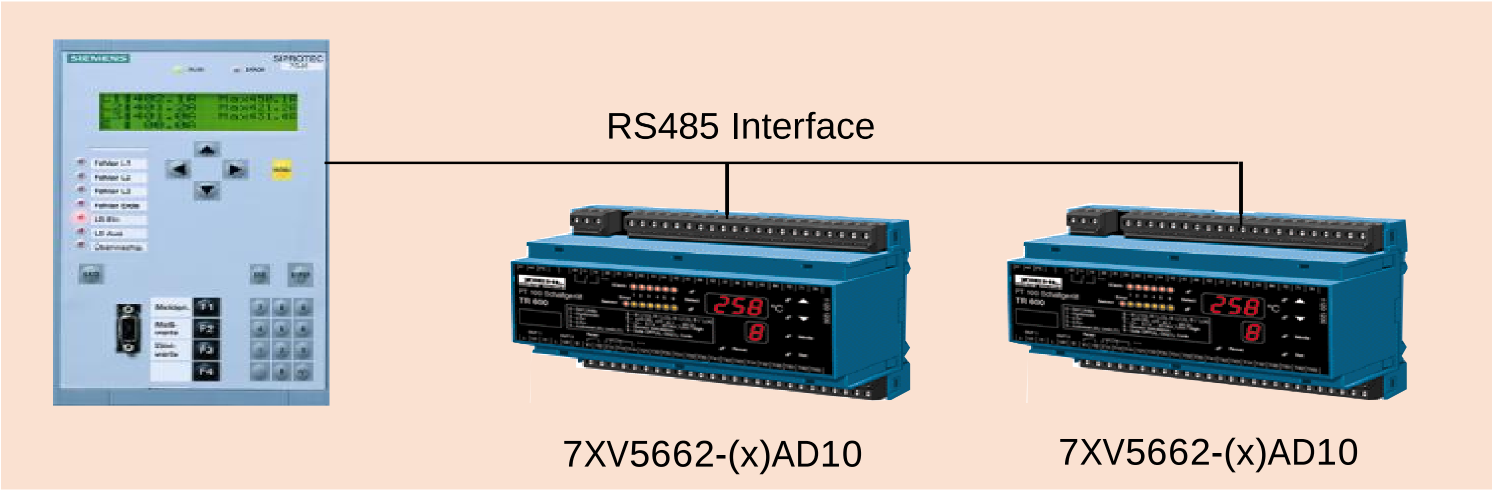
Operating characteristic (7UT6)



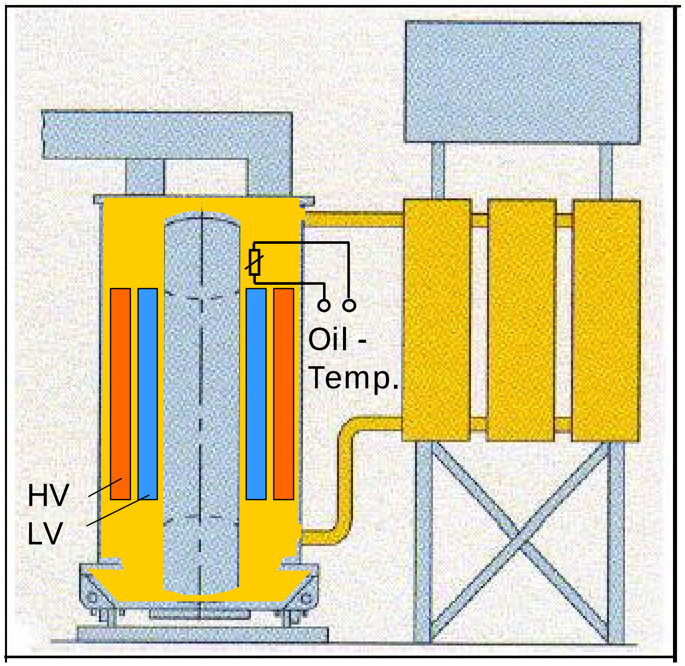
7SA6: Temperature monitoring



- Two thermo-devices can be connected to the serial service interface (RS485)
- Monitoring of up to 12 measuring points (6 per thermo-device)
  - each with two pick-up levels
- Display of the measured temperatures
  - directly at the thermo-device (which can also be used stand alone)
  - at the relay
- One input is reserved for hot spot monitoring (measurement of oil temperature)
- Thermistors: Pt100, Ni100 or Ni120

7UT6: Temperature monitoring with hot spot calculation (1)

Example: Natural cooling



$$\Theta_h = \Theta_O + H_{gr} \cdot k^Y$$

Θ_h= hot spot temperature

Θ_O= oil temperature

H_{gr}=hot-spot-to-oil temperature gradient

k= load factor I/In

Y= winding exponent

Aging rate:

$$V = \frac{\text{Aging at } \Theta_h}{\text{Aging at } 98°C} = 2^{(\Theta_h - 98)/6}$$

98^O is reference for the aging of Cellulose insulation

Mean value of aging during a fixed time interval:

$$L = \frac{1}{T_2 - T_1} \cdot \int_{T_1}^{T_2} V \cdot dt$$

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7UT6: Temperature monitoring with hot spot calculation (2)

Thermal Meter - 22.09.2003 - Differential 7UT61 / 7UT612 / 7UT...

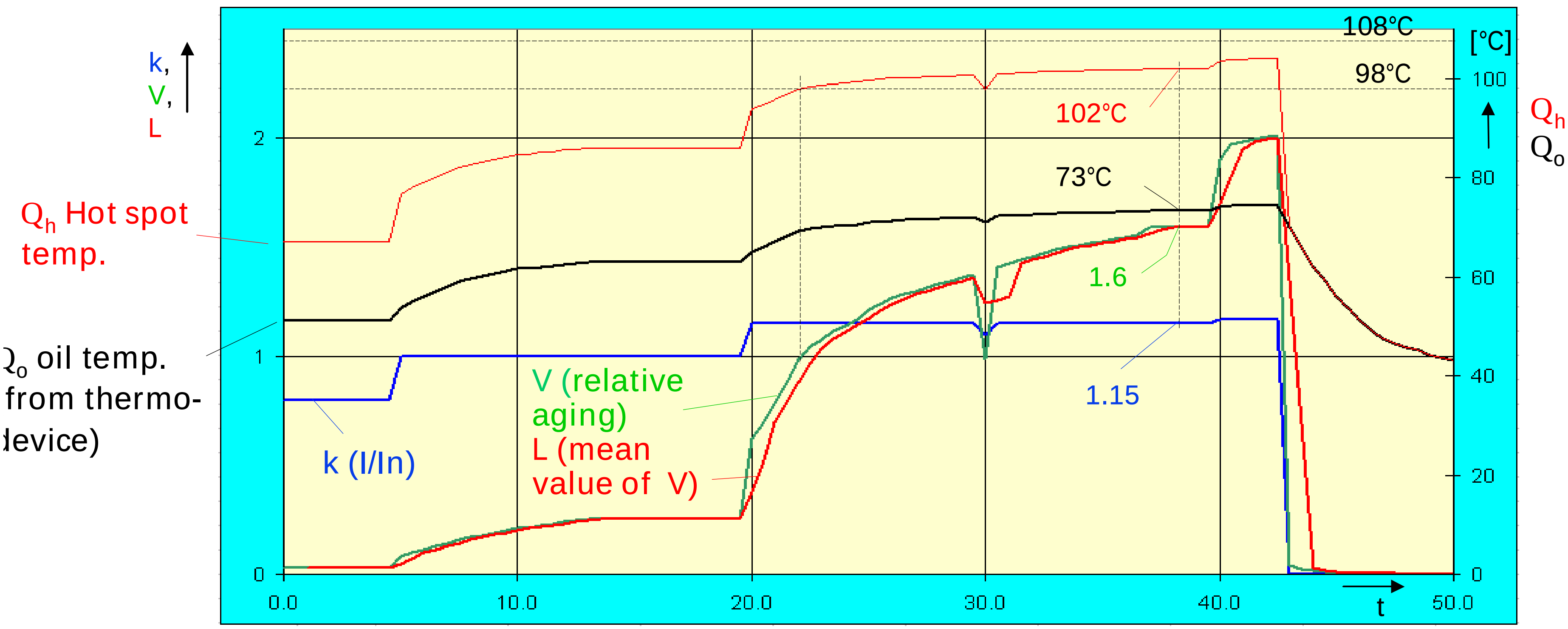
Number	Measured value	Value
01060	Hot spot temperature of leg 1	102 °C
01061	Hot spot temperature of leg 2	102 °C
01062	Hot spot temperature of leg 3	102 °C
01063	Aging Rate (L)	1.6
01066	Load Reserve to warning level	-10 %
01067	Load Reserve to alarm level	5 %

RTD-Box Measuring Values - 22.09.2003 - Differential 7UT61 / 7UT...

Number	Measured value	Value
01068	Temperature of RTD 1	73 °C

$$\Theta_h = \Theta_o + H_{gr} \cdot k^Y \approx 73 + 23 \cdot 1.15^{1.6} = 102°C$$

$$V = 2^{(\Theta_h - 98)/6} = 2^{(102-98)/6} \approx 1.6$$



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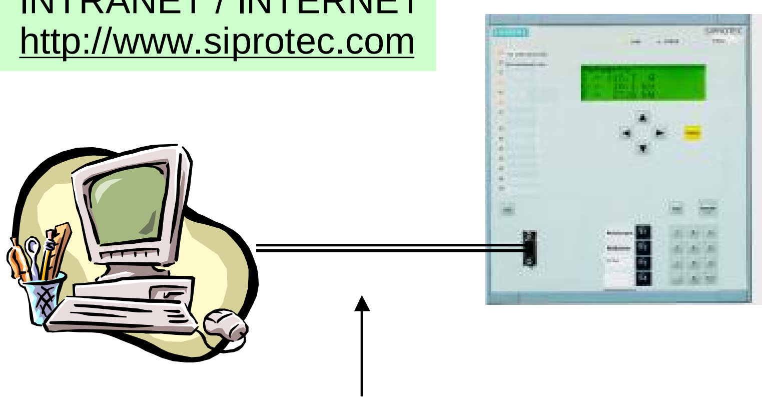
7UT6: Commissioning und service tool (1)

WEB-Technology

IBS-Tool

Help system in the
INTRANET / INTERNET
http://www.siprotec.com

Access to WEB Browser



Relay homepage address of :
http://141.141.255.160
IP-address can be set with program DIGSI 4 at the front or service interface of the relay

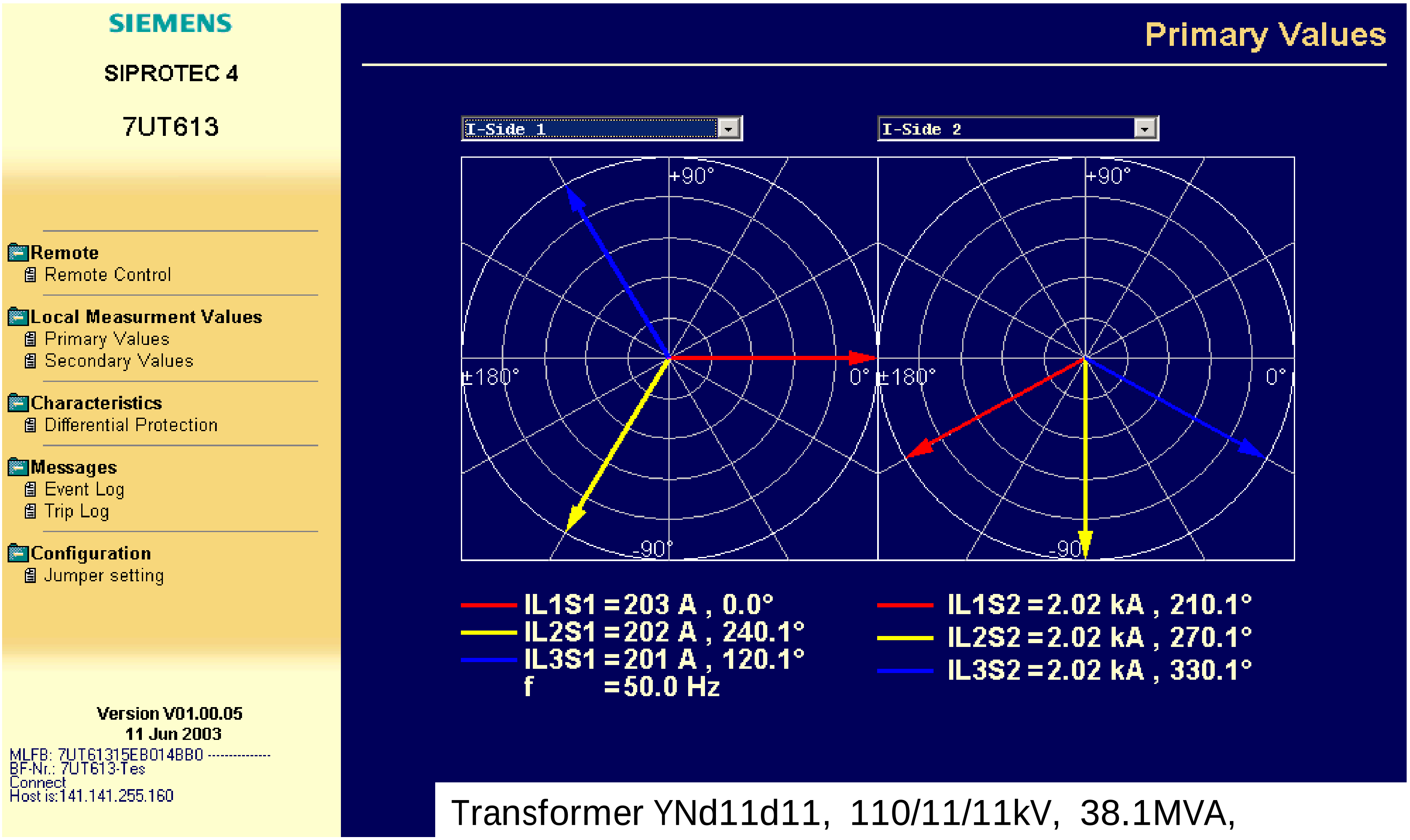
WEB server
in relay firmware

Server sends HTML pages and JAVA code to WEB Browser via DIAL-UP connection

1. Serial connection
Directy or with modem to standard DIAL-UP network

2. HTM L page view
at IP-address of the relay
http://141.141.255.160

7UT6: Commissioning and service tool (2)
Display of current phasors of all terminals



Transformer YNd11d11, 110/11/11kV, 38.1MVA,
IL2S2 à wrong polarity

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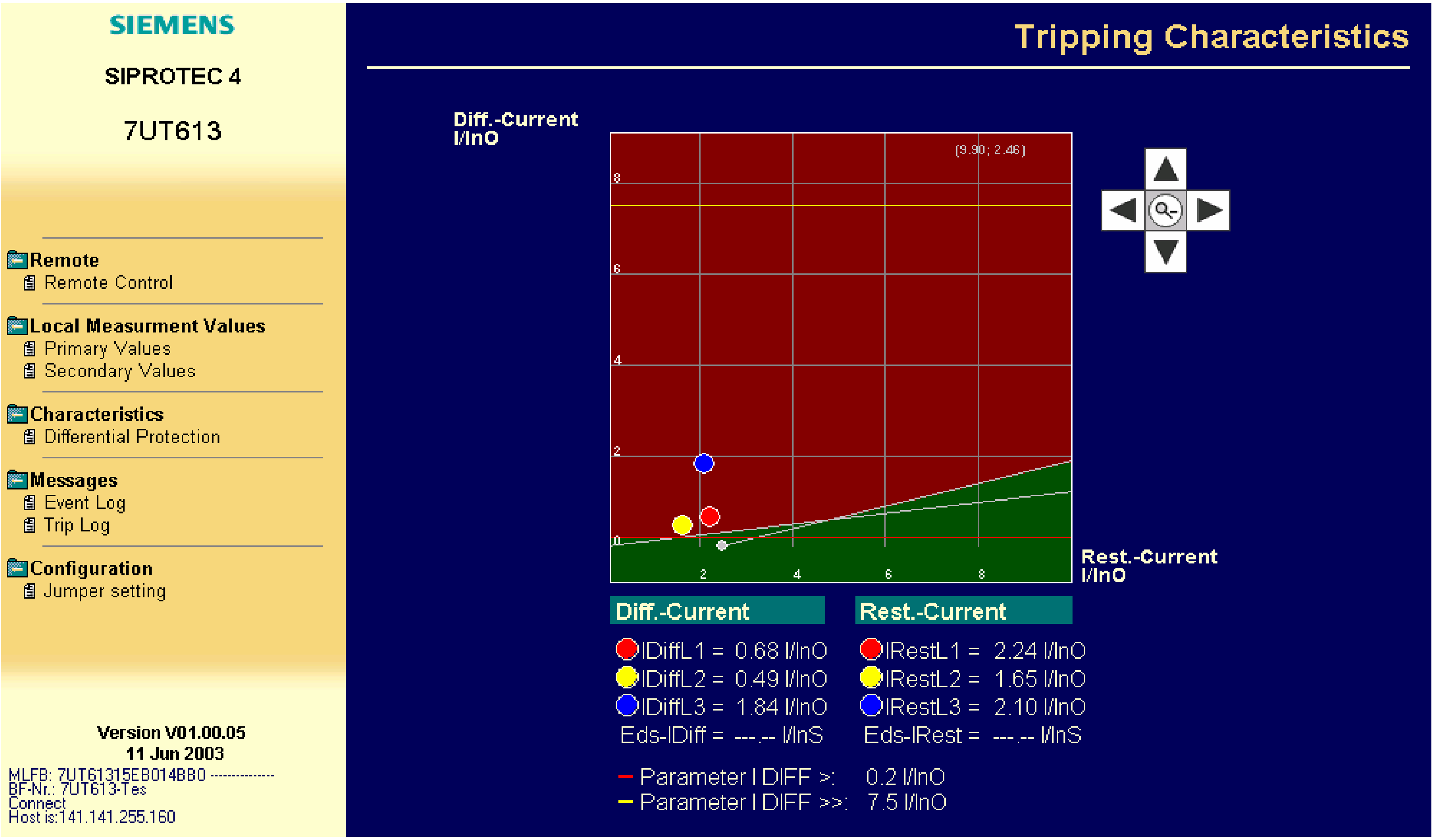
7UT6: Commissioning and service tool (3)
Display of operating/restraint state



Transformer YNd11d11, 110/11/11kV, 38.1MVA, IL2S2 à wrong polarity

Application examples

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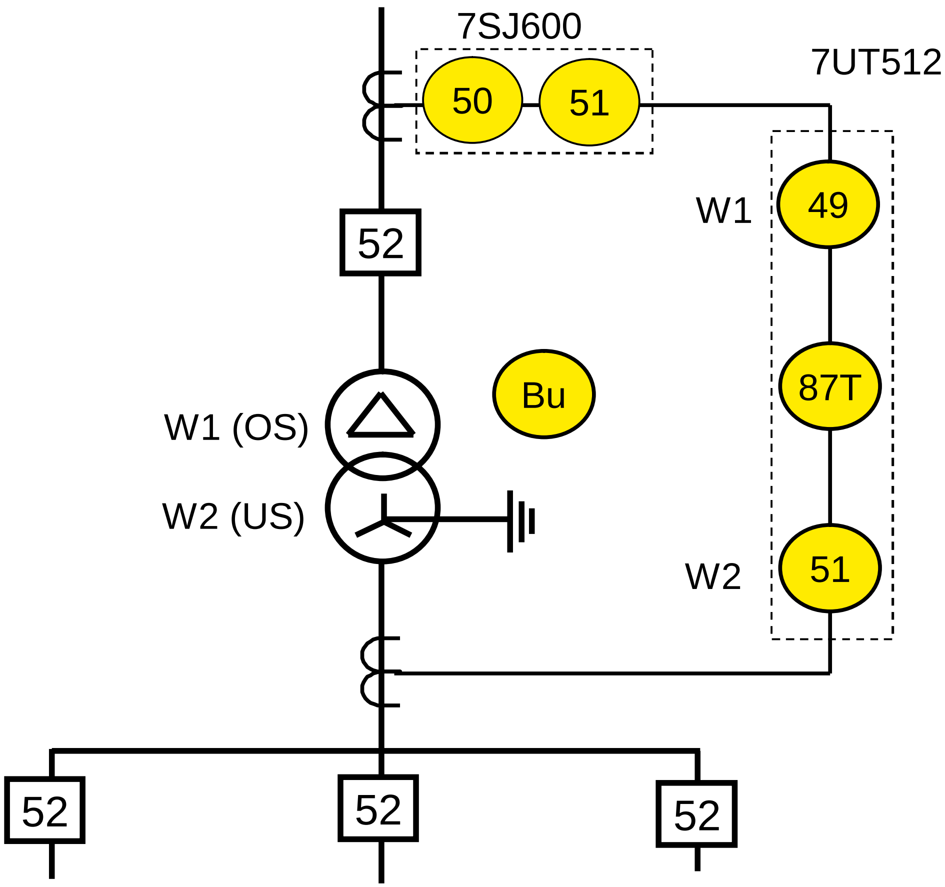
Protection of a two winding transformer



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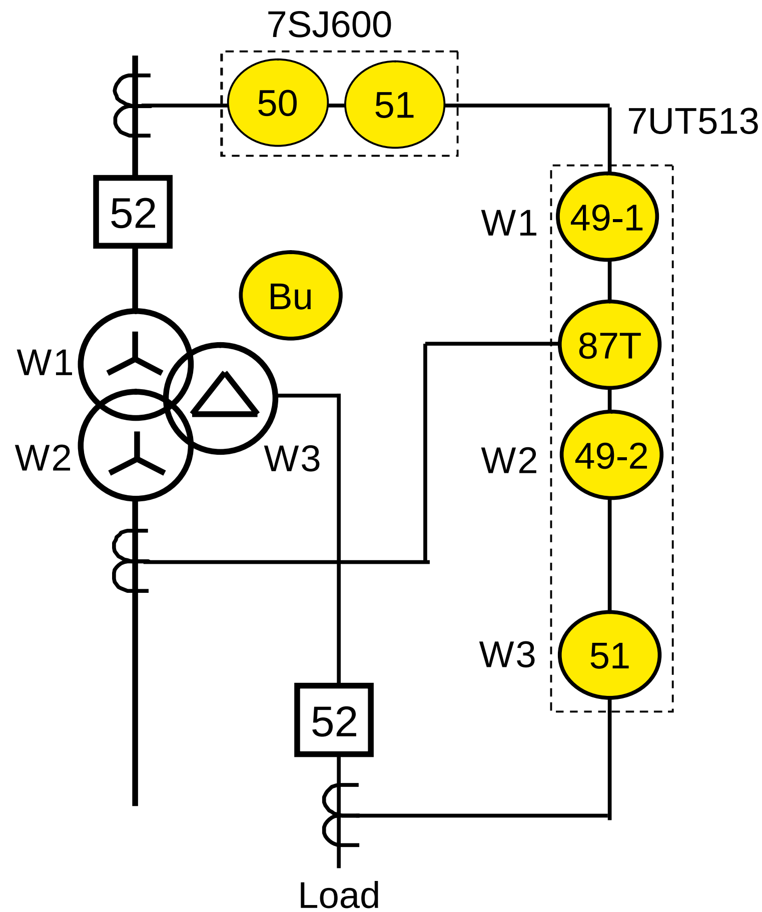
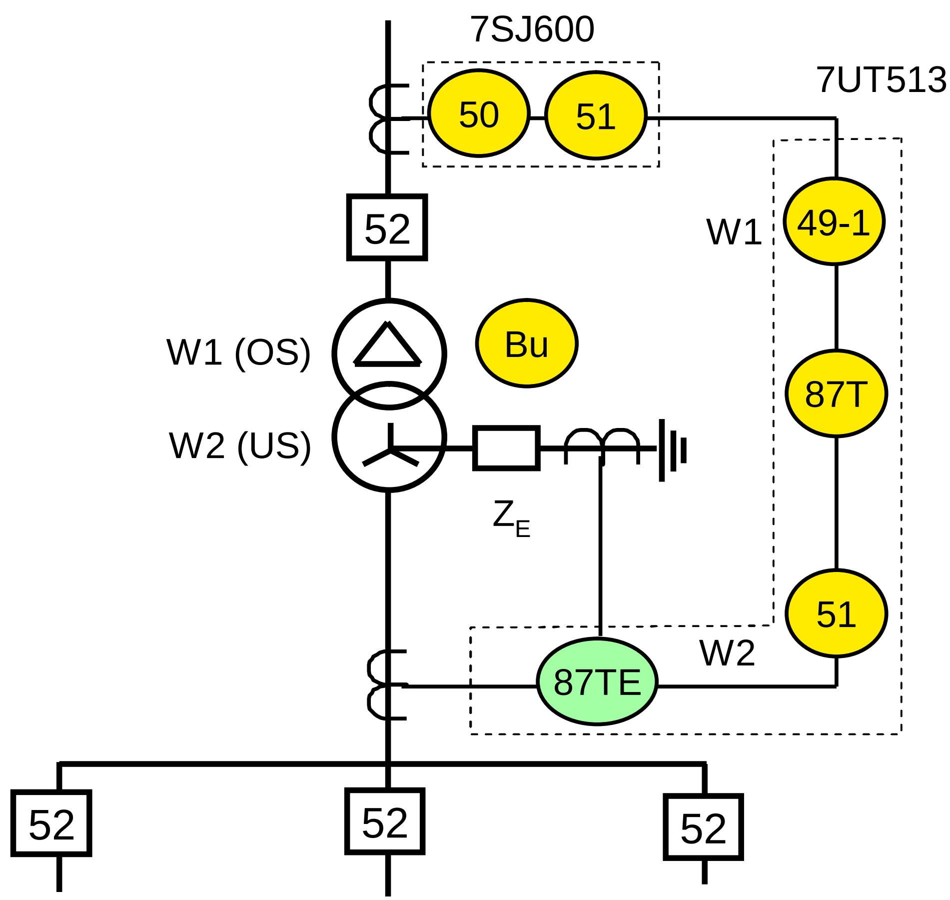
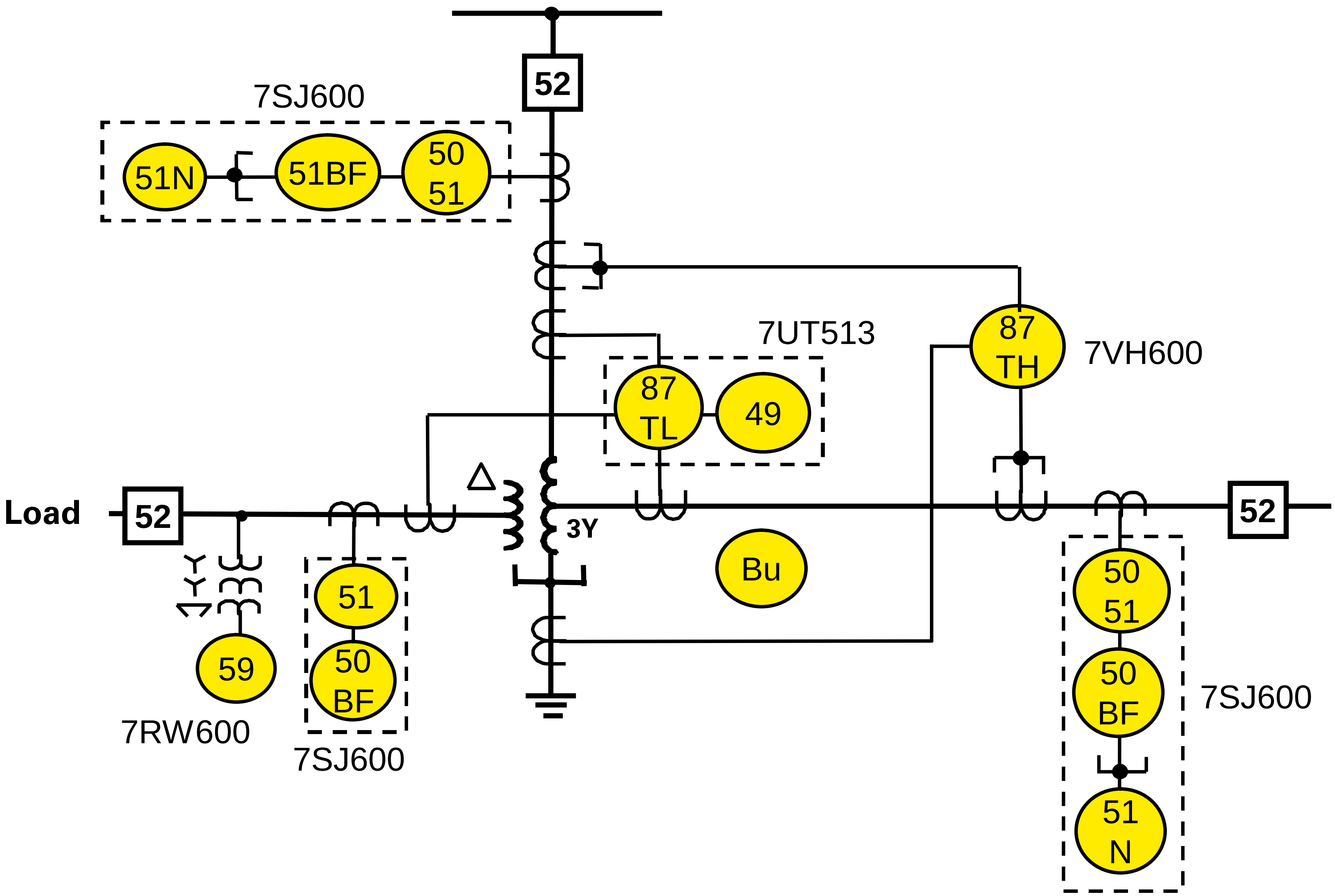
Protection of a three winding transformer



Restricted earth fault protection for a two winding transformer



Protection of an autotransformer



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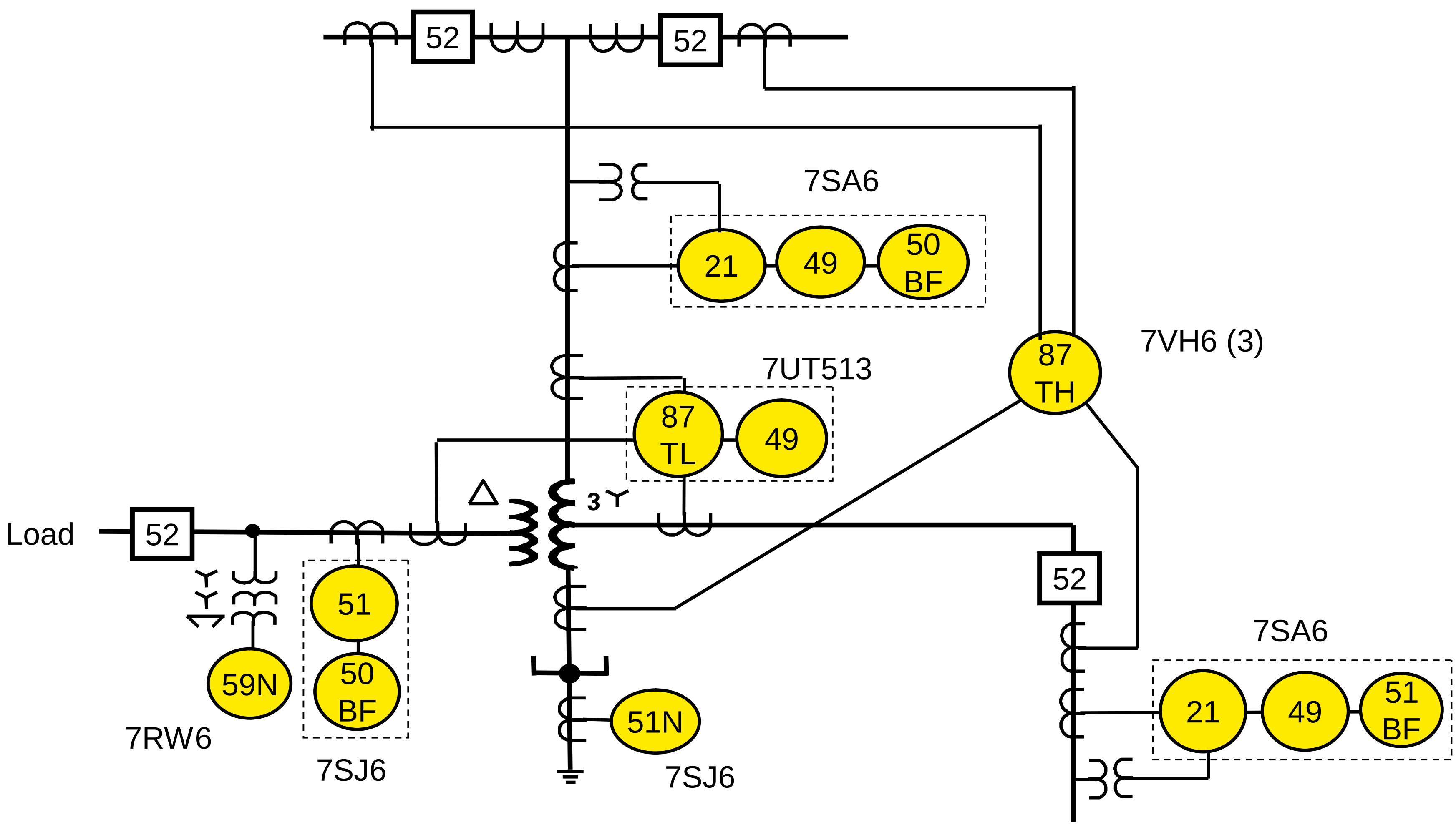
Protection of a large transformer bank



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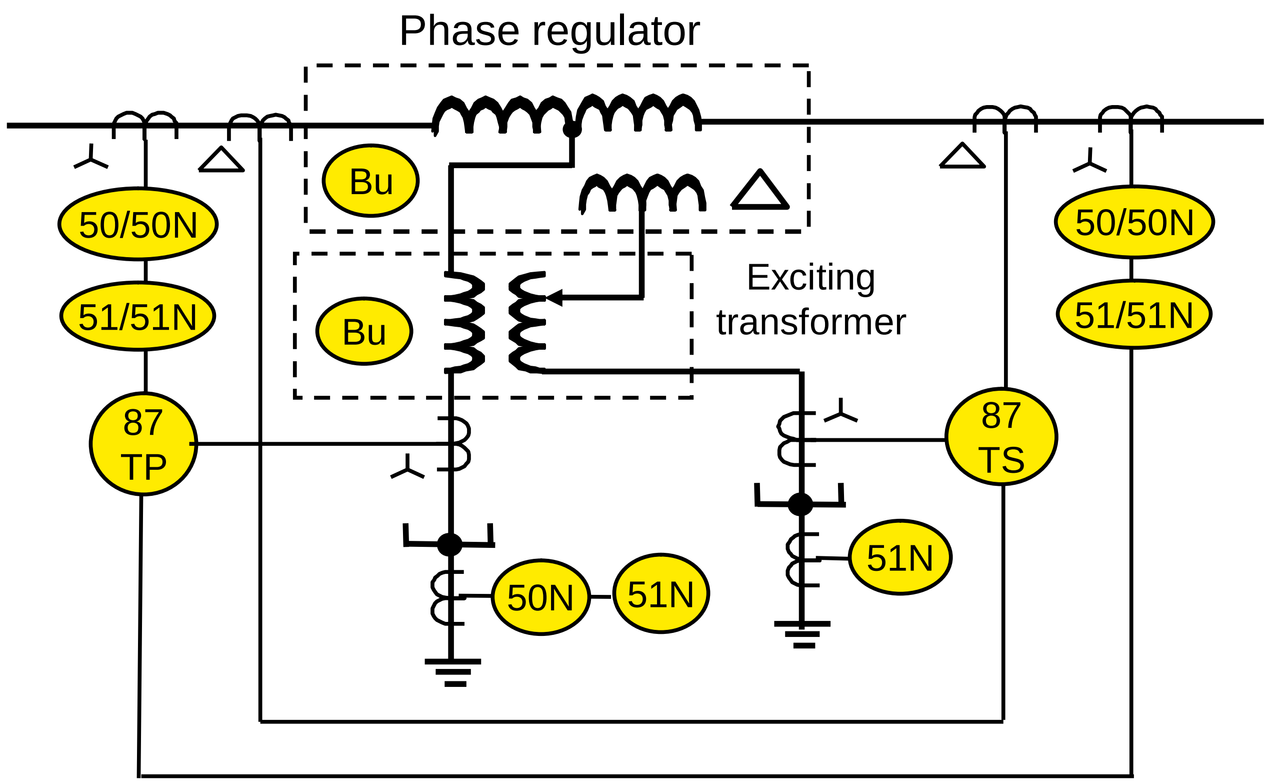
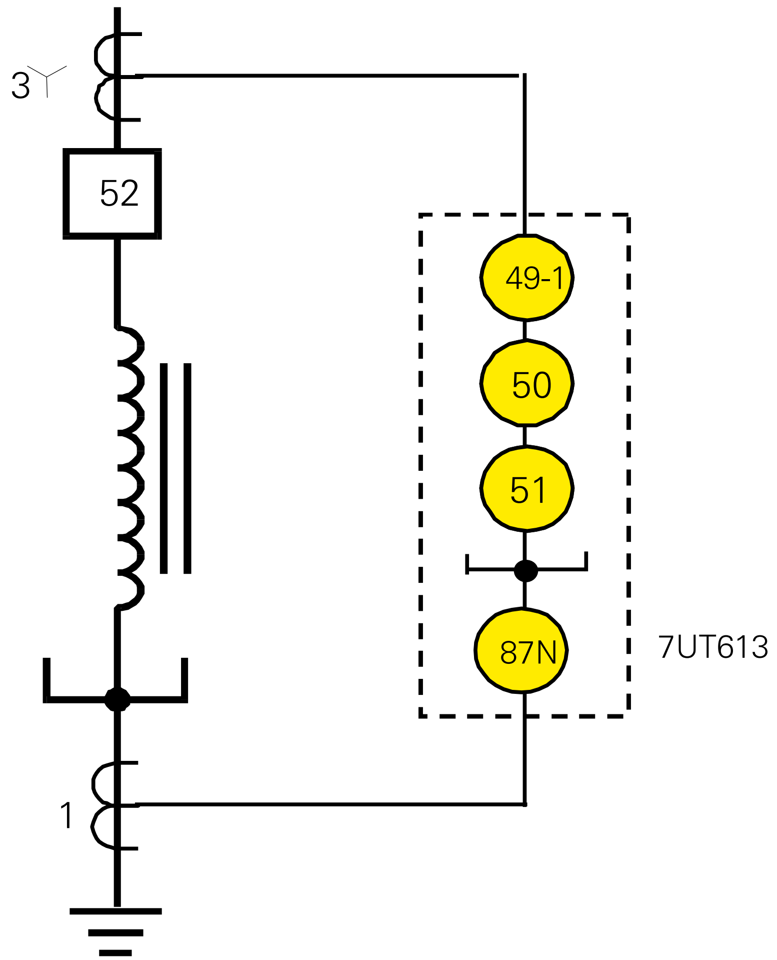
Protection of a phase regulating transformers



Protection of a compensation reactor
No phase CTs at neutral side



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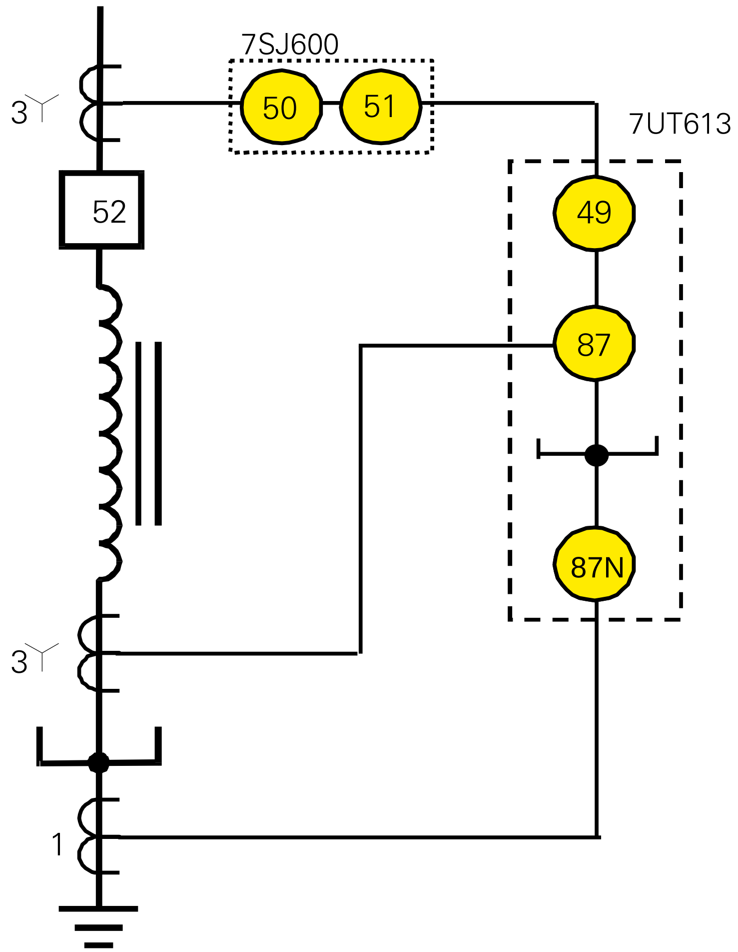
Protection of a compensation reactor
with phase CTs at neutral side



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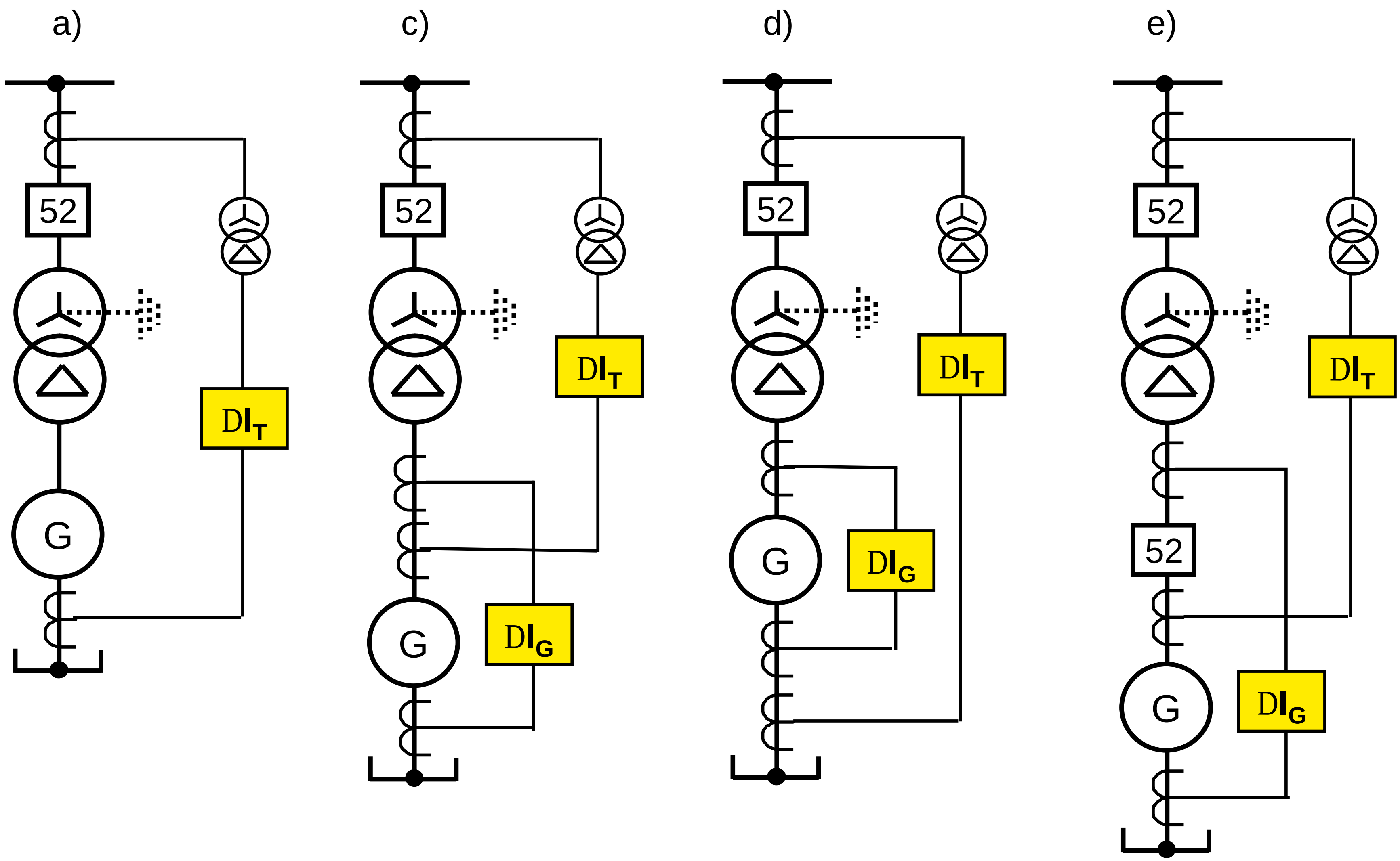
Differential protection of generation units (1)



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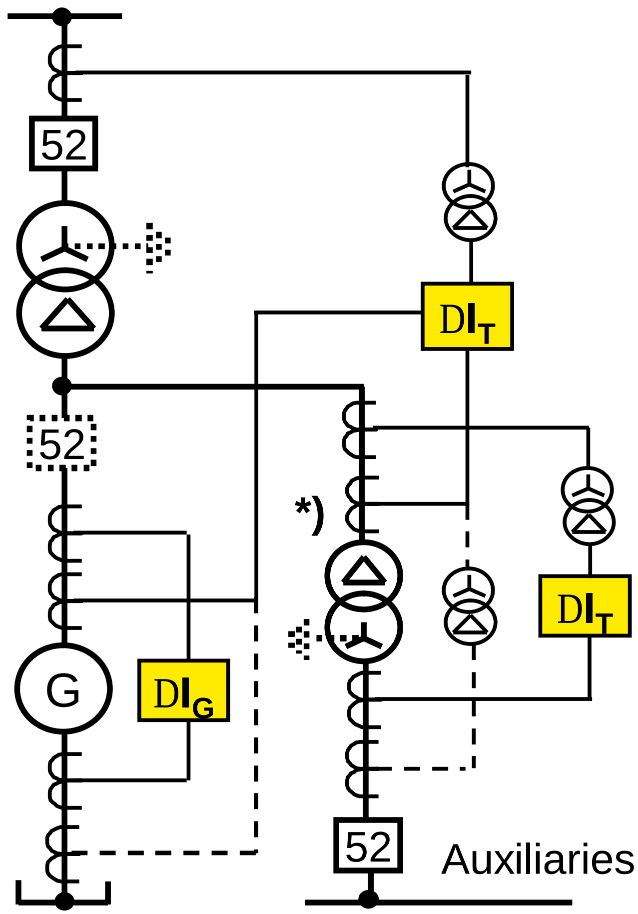
Differential protection of generation units (2)



*) same ratio as generator CTs

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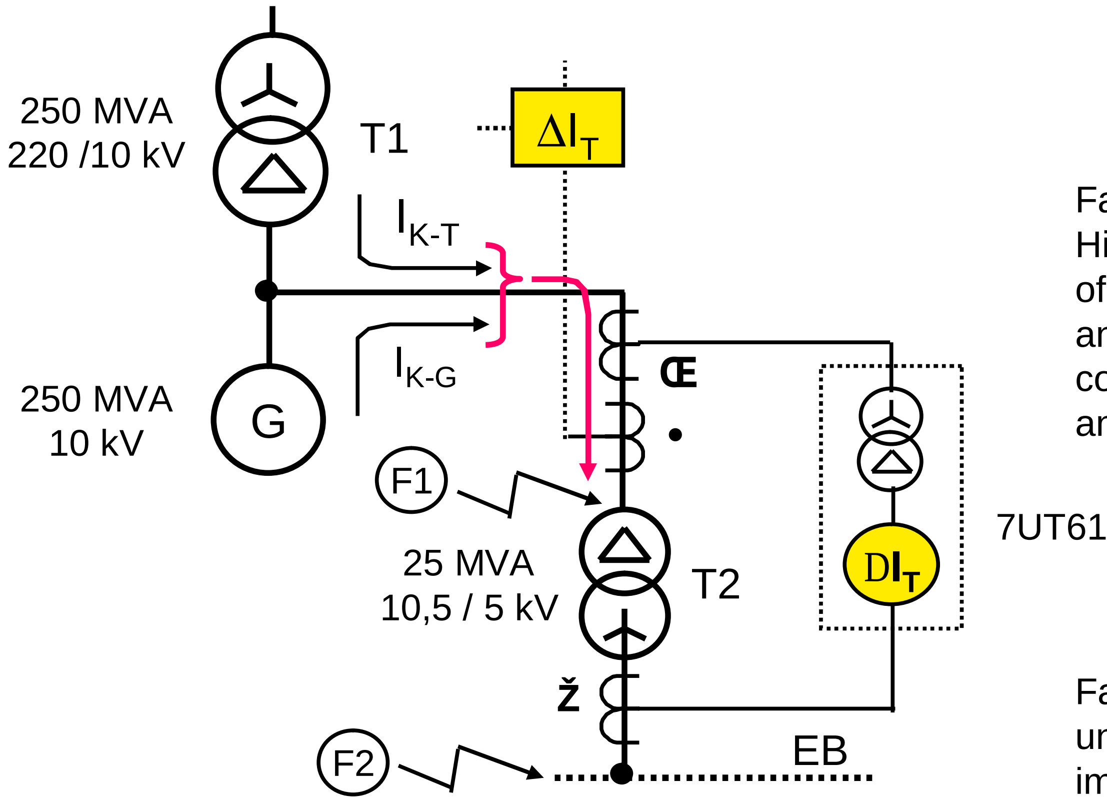
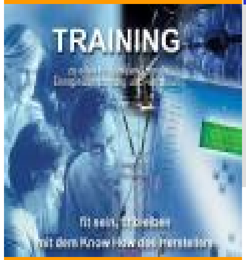
Dimensioning of CTs at the station service transformer



Fault F1:
High fault currents in relation to the rated current of the station-service transformer T2 (>100xI_N) and long DC time constants (>100 ms) require considerable over-dimensioning of CT cores **Œ** and • .

Fault F2:
uncritical as current is limited by short-circuit impedance of station-service transformer T2.
CT **Ž** can have normal dimensions



Digital Transformer Differential Protection

I0-correction
+ vector group adaptation

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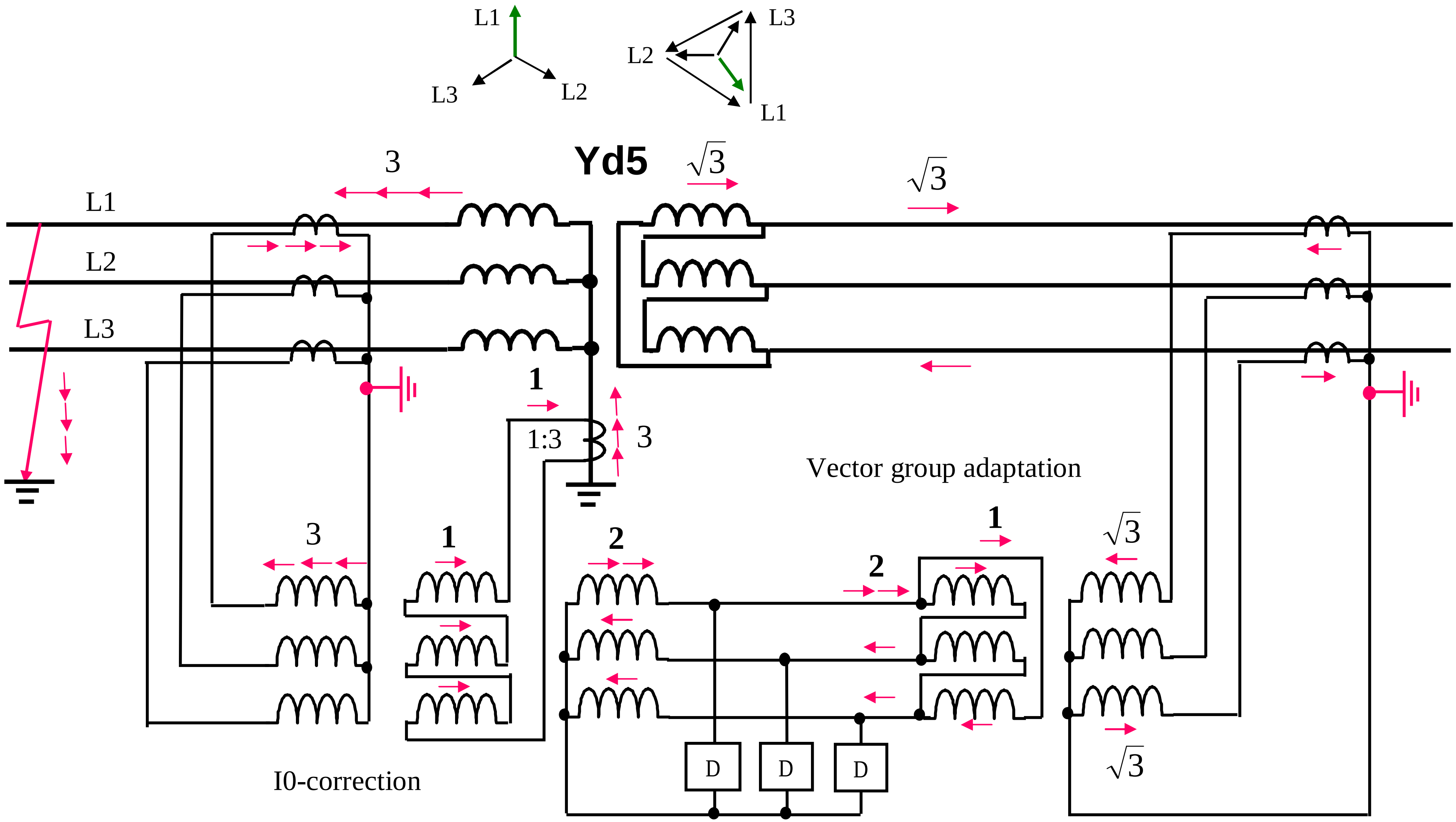
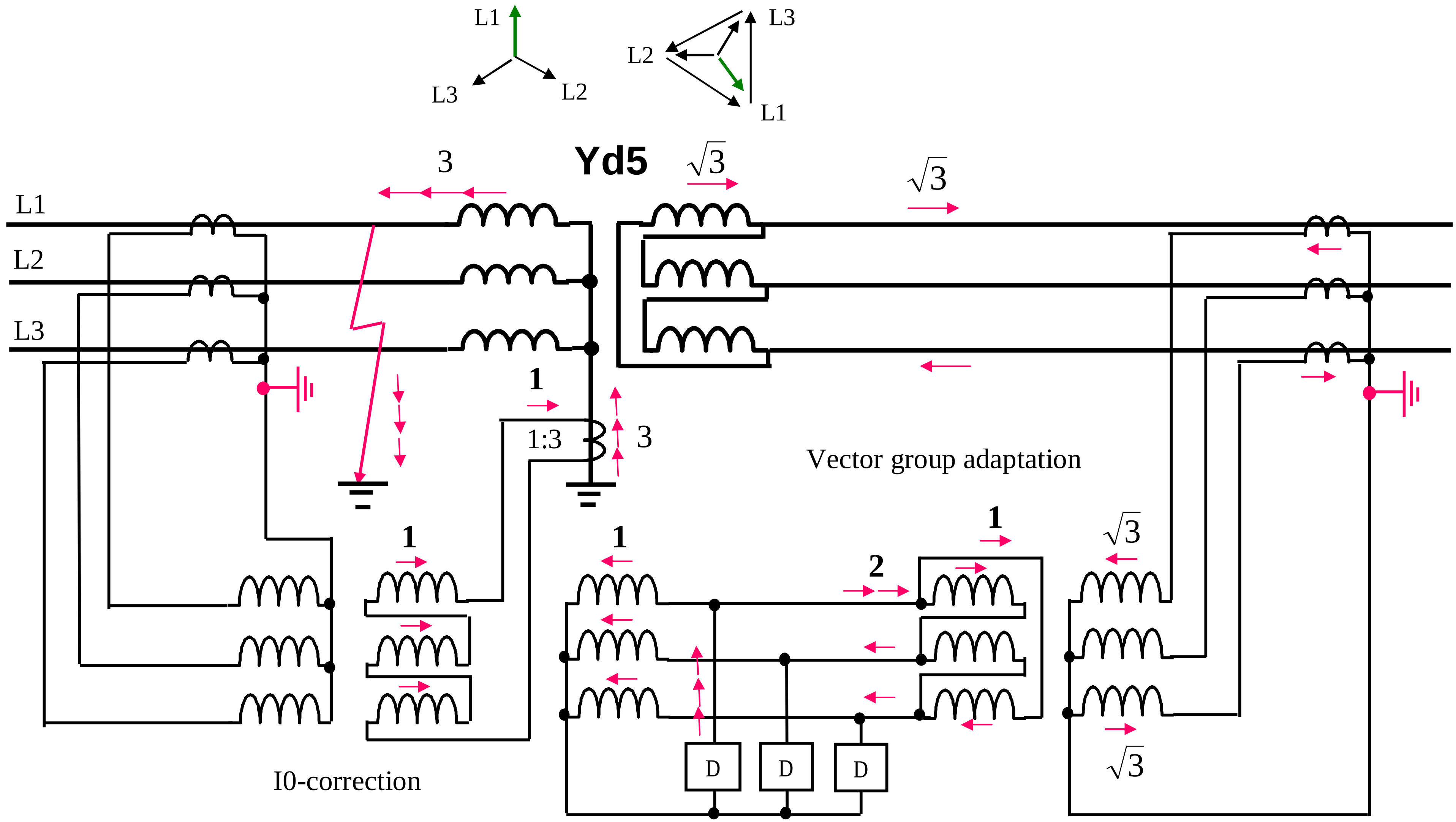
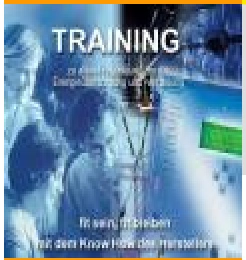
Transformer differential protection with I0-correction
External fault



Transformer differential protection with I0-correction
Internal fault

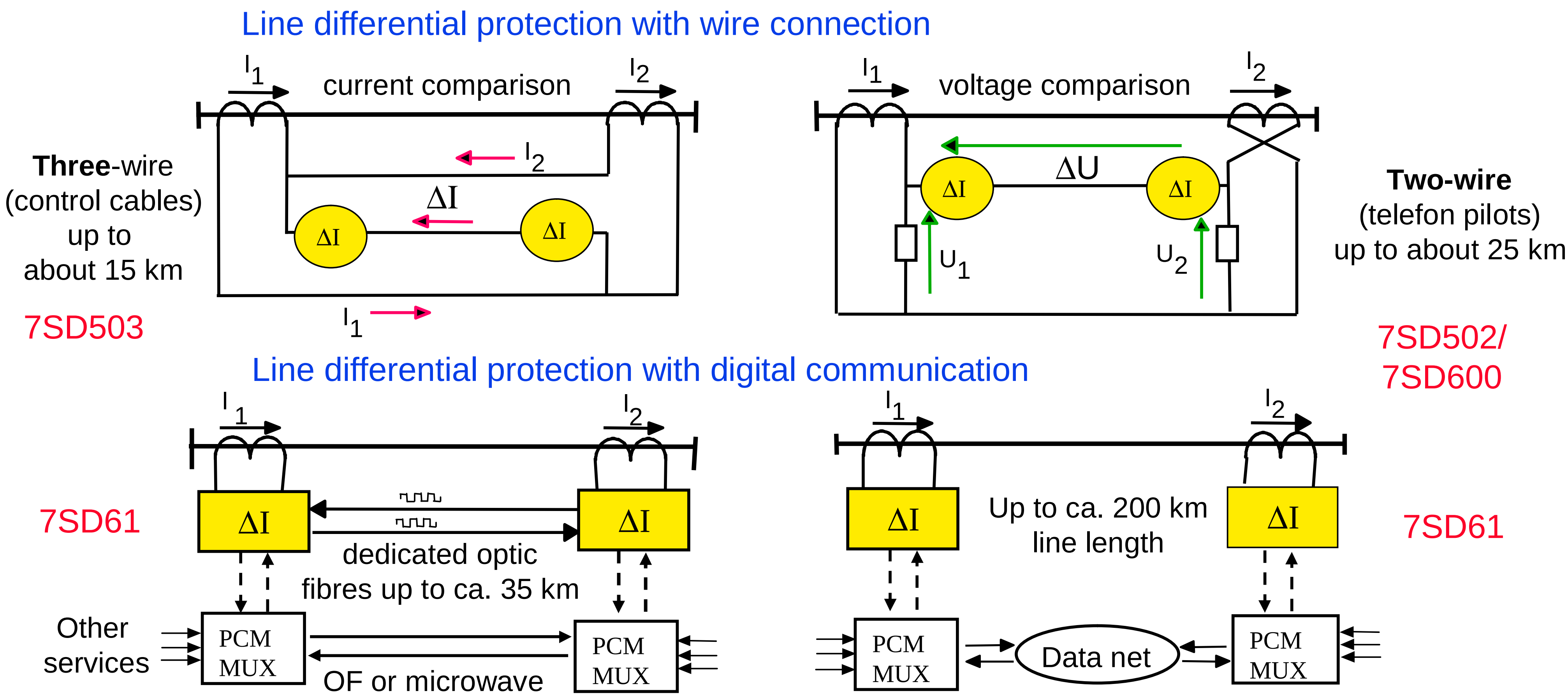




Digital Line Differential Protection

Gerhard Ziegler

Line differential protection, Versions



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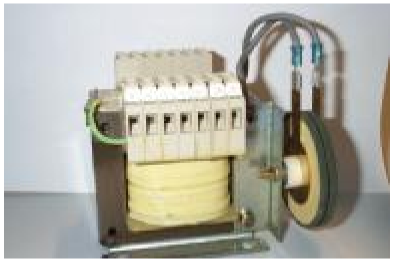
Digital pilot wire relay 7SD600



Combines

- Traditional pilot wire protection principle

with

- Modern digital relay technology

Novel features:

- Self-monitoring and pilot wire supervision
- Saturation detector
- Measurement of pilot loop resistance
- Add-on functions

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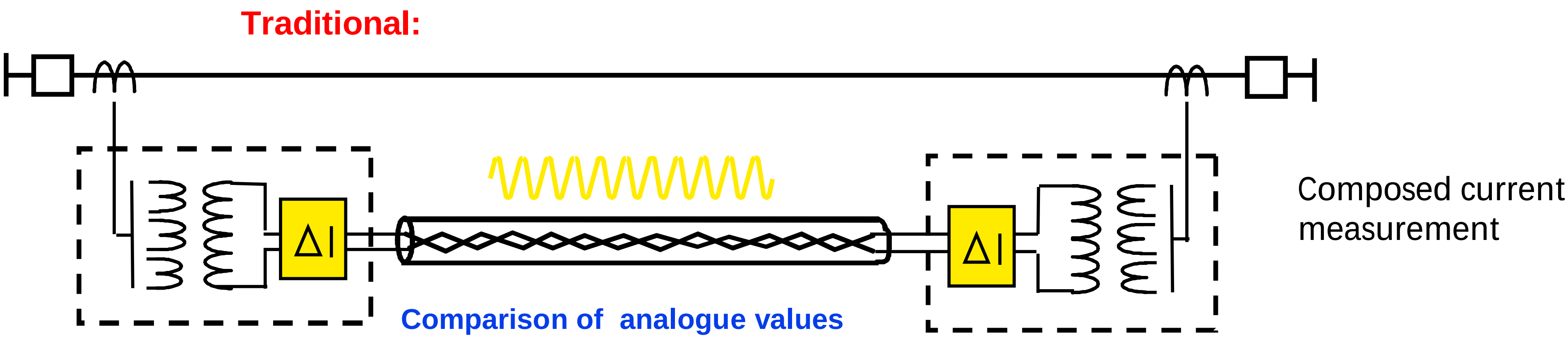
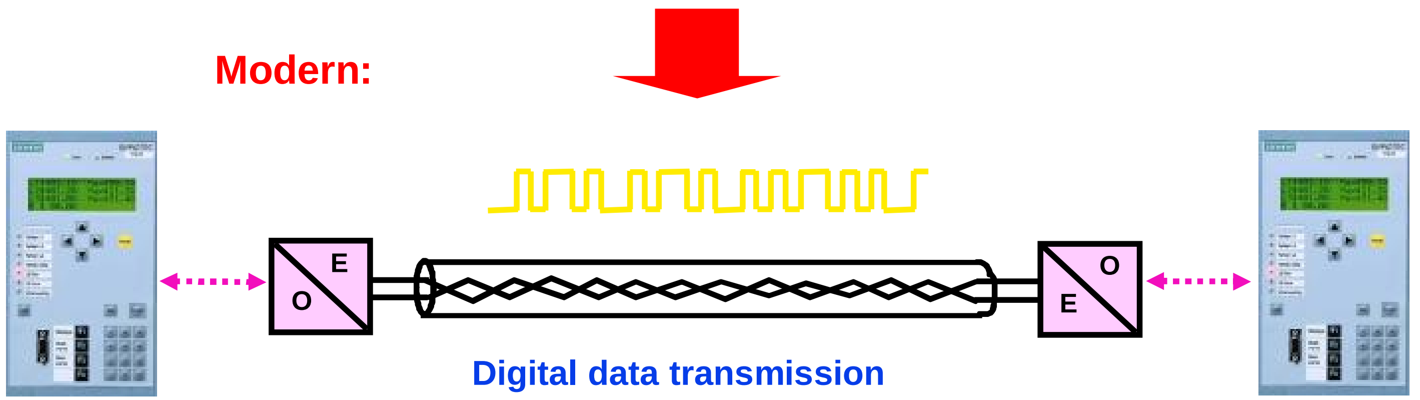
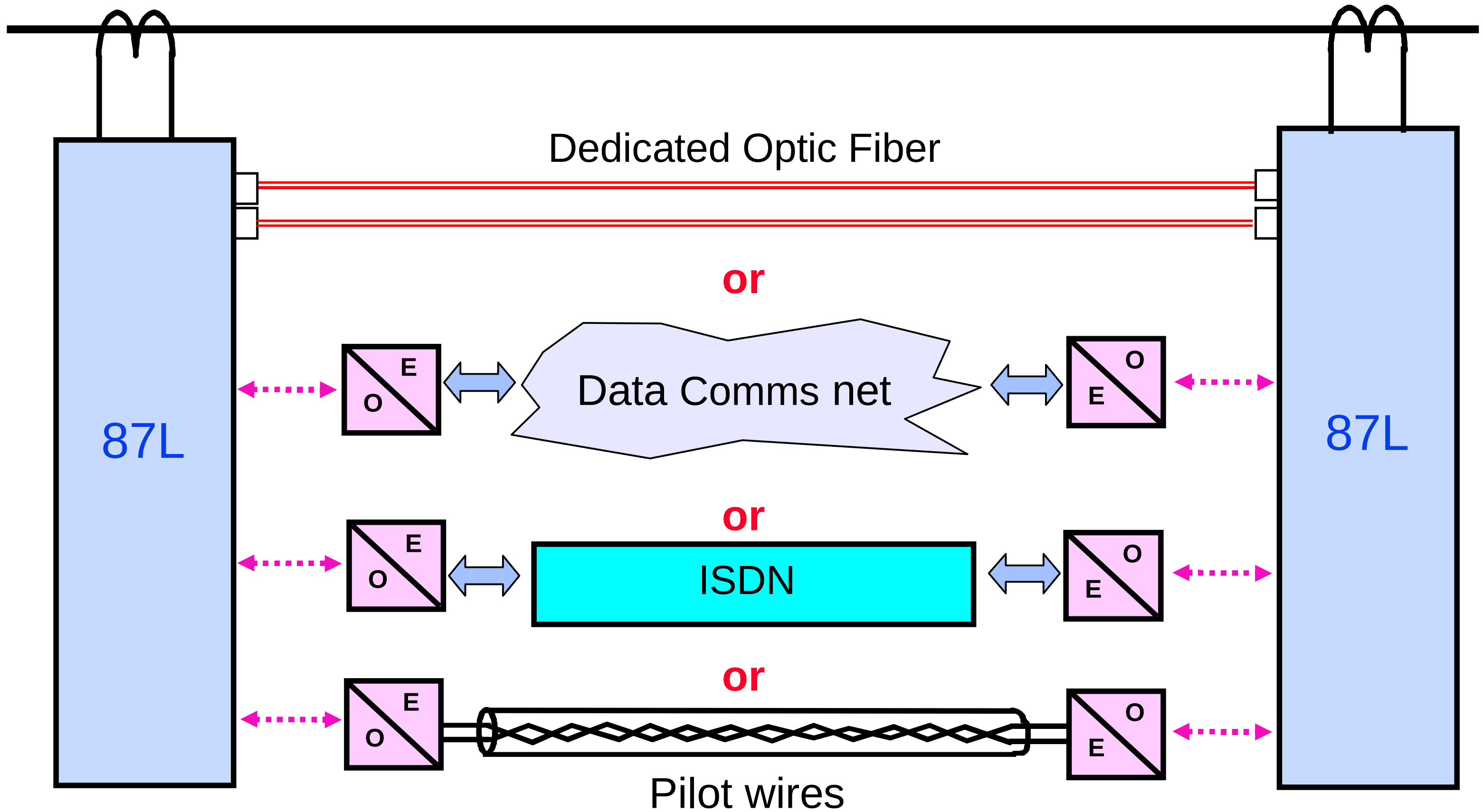
Relay to Relay pilot wires communication
New technology on existing (copper-) pilots





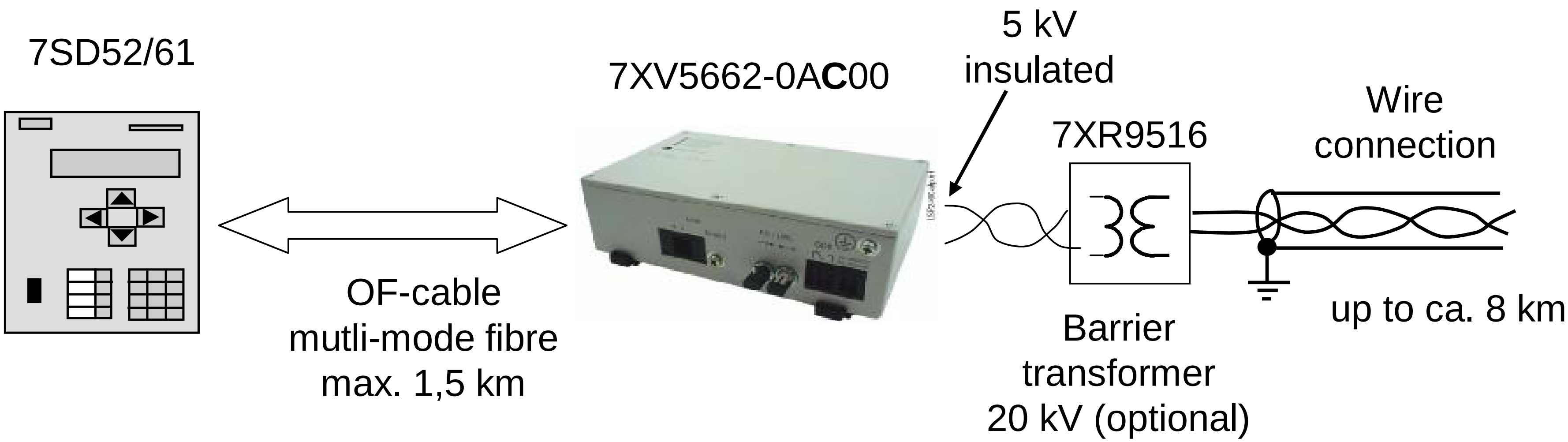
64 kbps bi-directional
4 value digital code (2B1Q)
Amplitude and phase modulation
Spectrum mid frequency: 80 kHz

Digital Relay to Relay Communication (Overview)



Communication according to given possibilities

Converter for digital communication via pilot wire



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Line differential protection
with converter for digital communication

7SD52/61

7XV56

Digital
data
network

OF
Multi-mode fibre
max. 1.5 km

Interface to data network:
X.21 or G.703.1
(wired connection)

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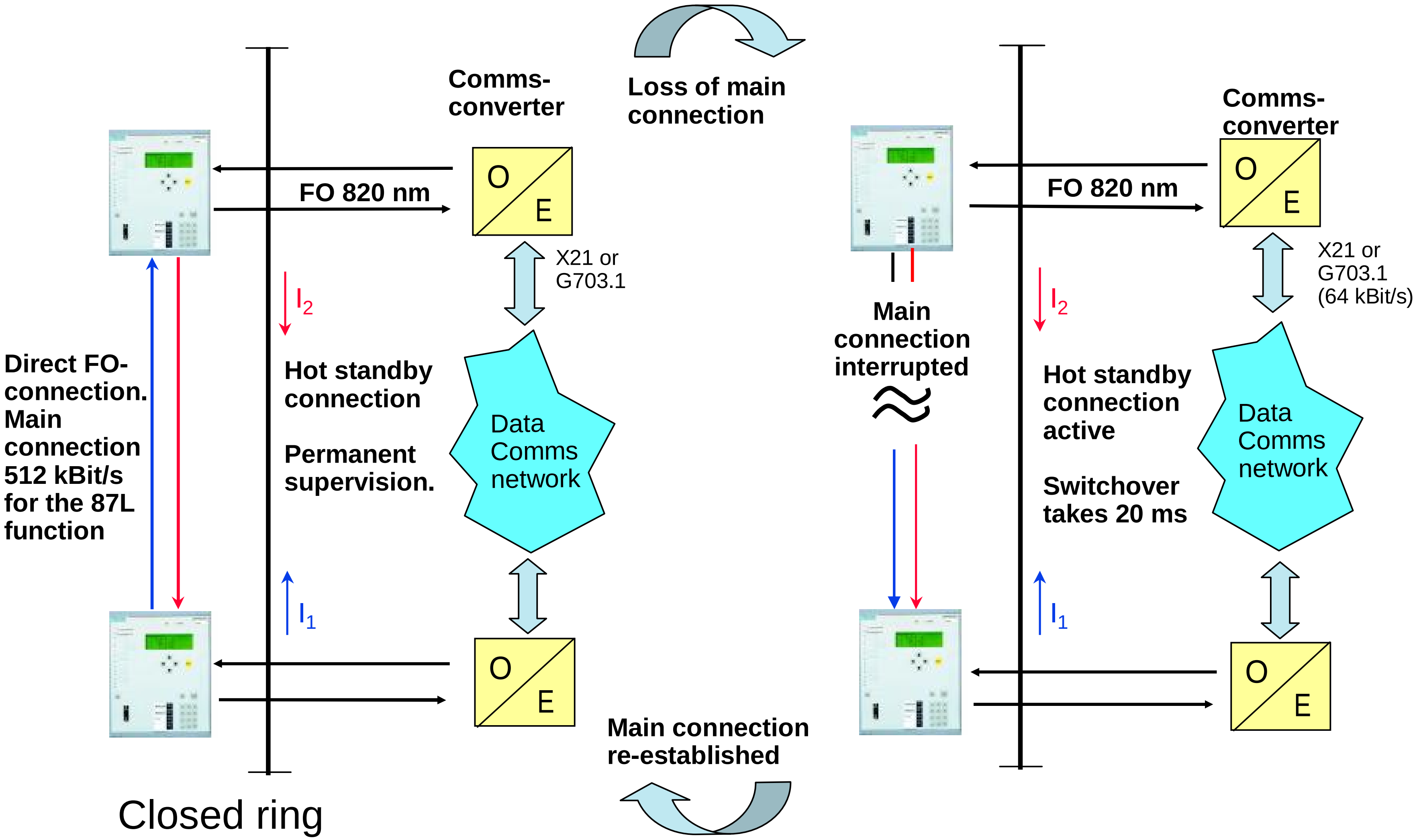
Relay to Relay Communication: Two terminal configuration with hot standby connection



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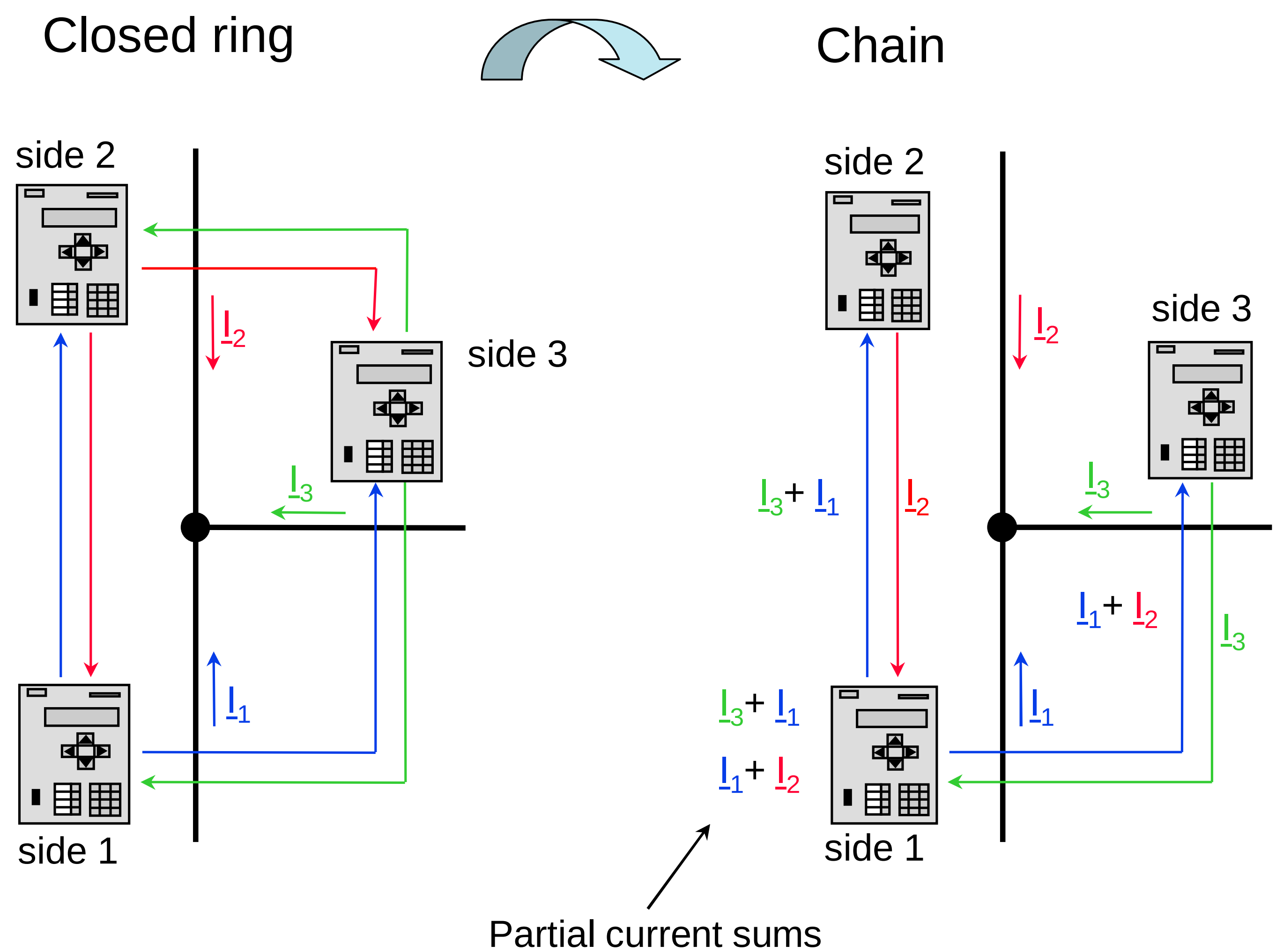
Relay to Relay Communication: Ring- and Chain topology, loss of one data connection tolerated



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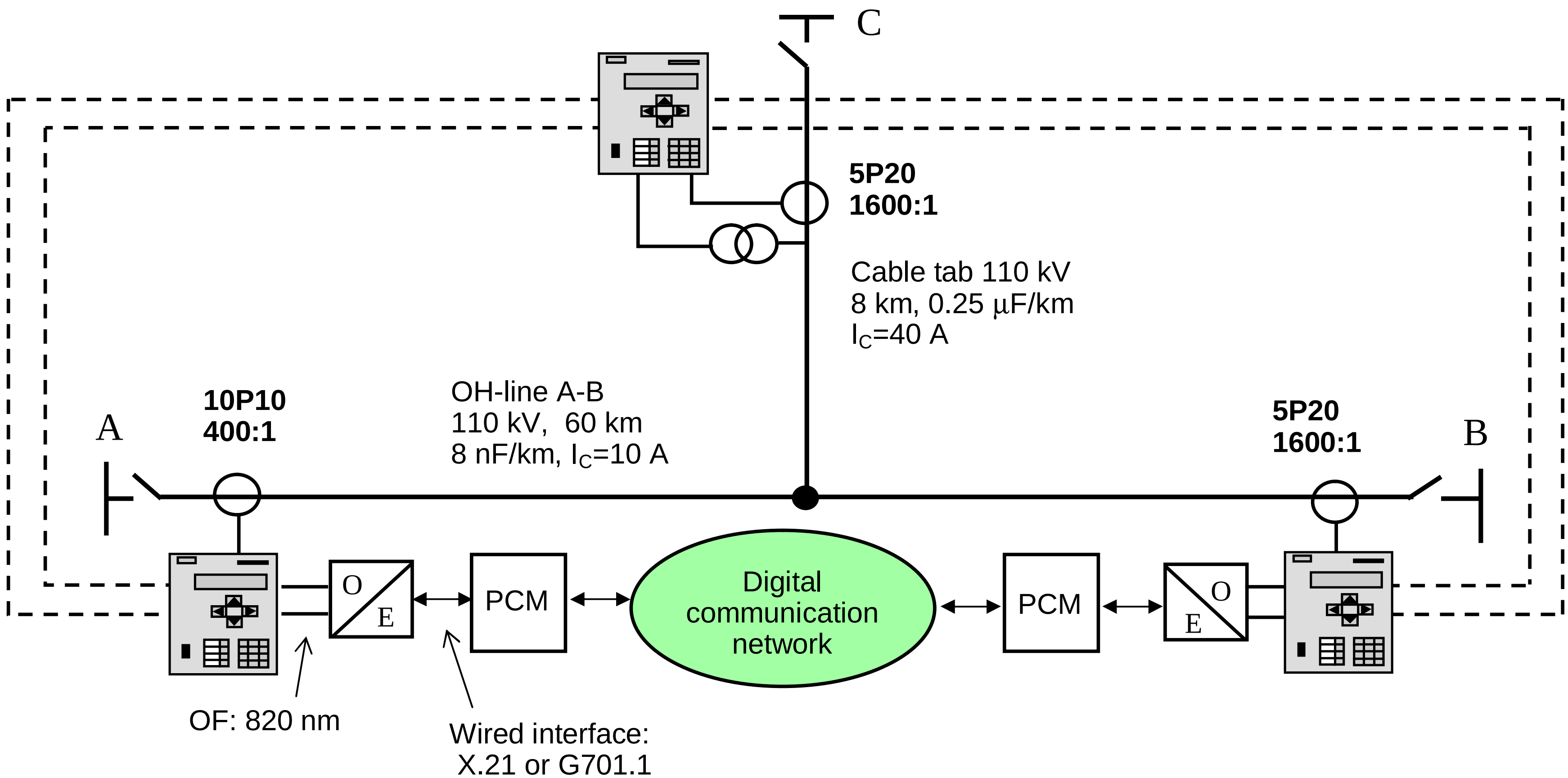
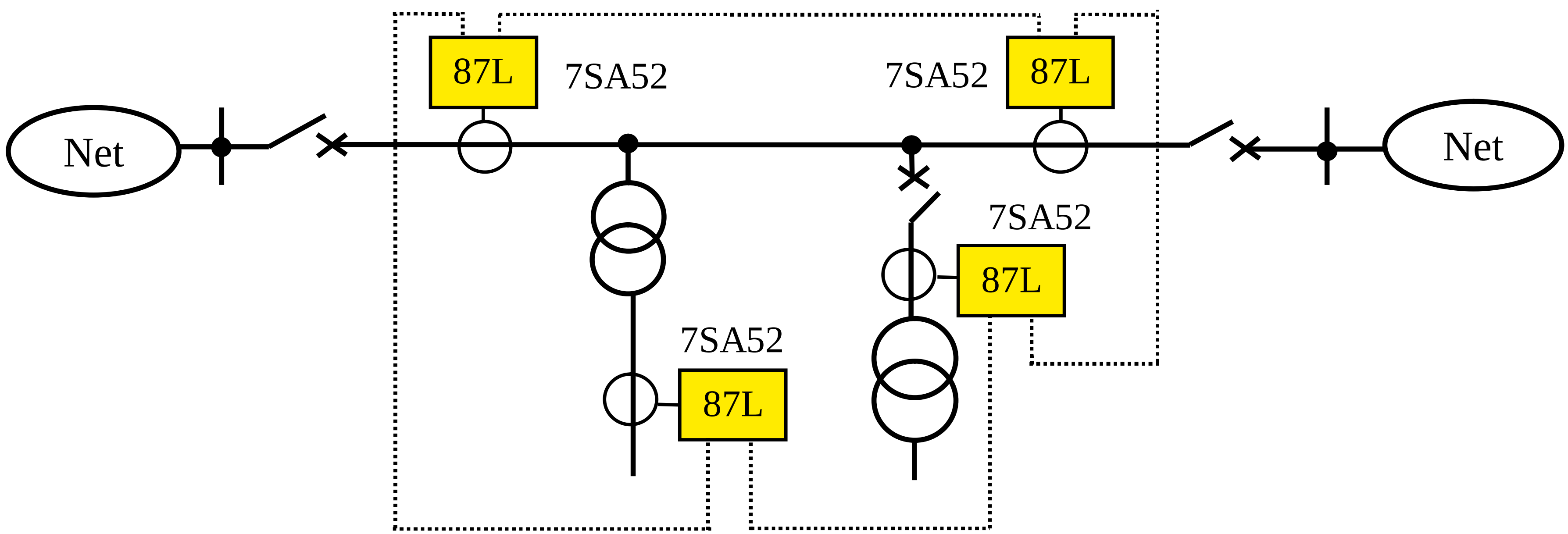
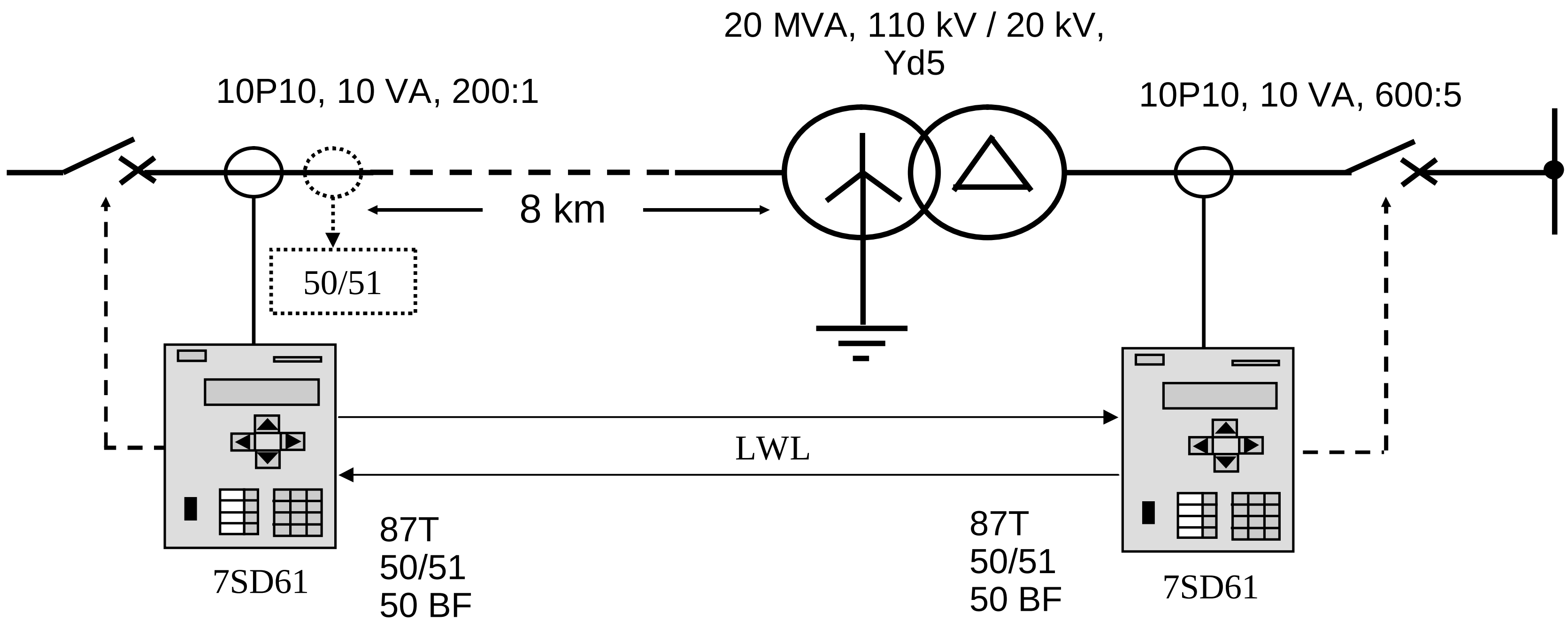
Line differential relay with digital communication (7SD52) Application to 3-terminal line



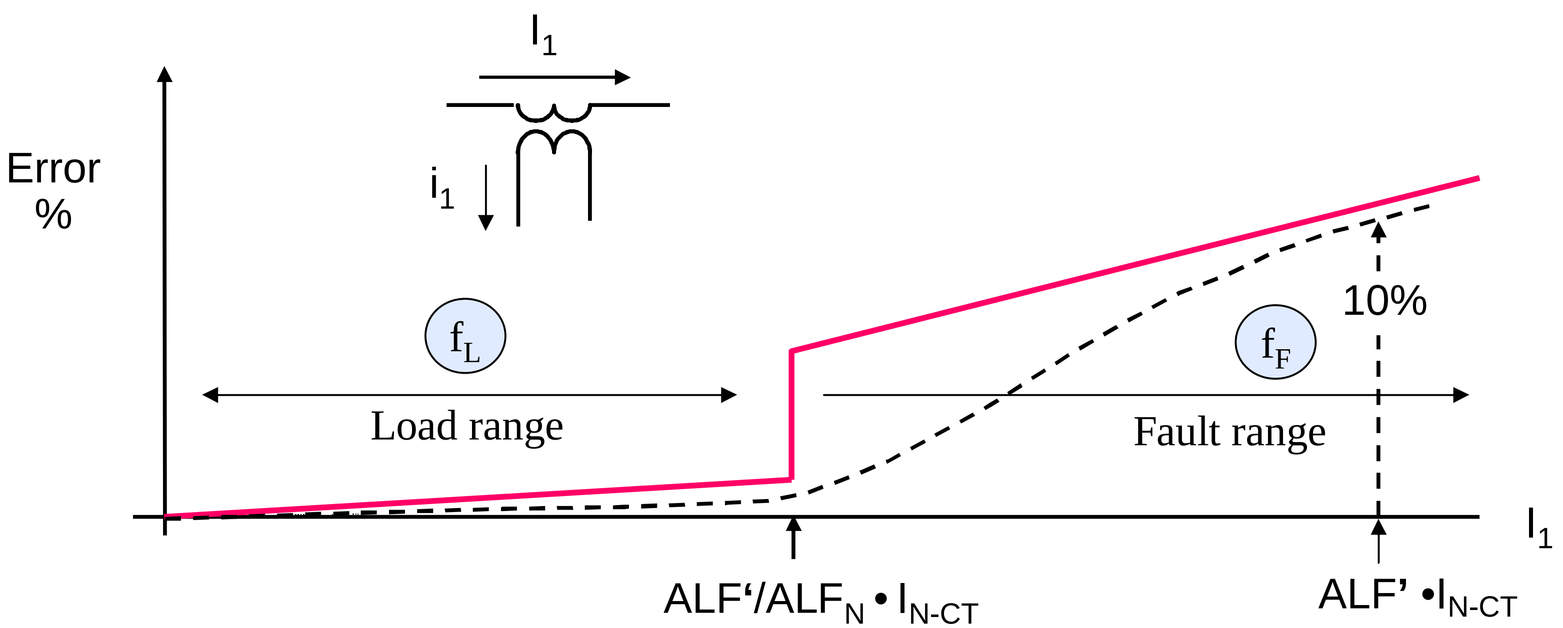
Line differential relay with digital communication (7SD52)
Application to tapped line



Line differential relay with digital communication (7SD61)
Transformer-line protection



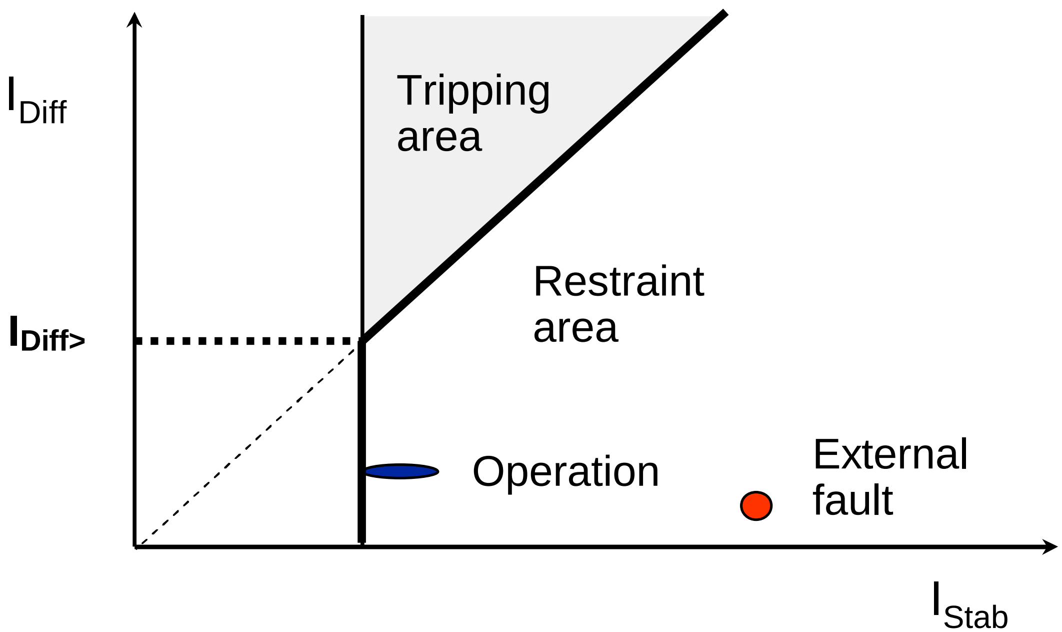
7SD52/61: Bias for CT errors

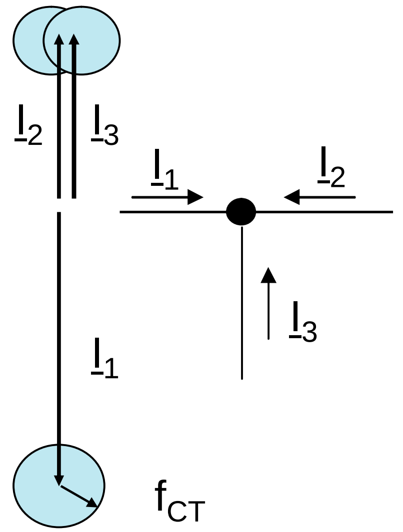


f : relay setting parameters

Example: 10P10, f_L < 3%, f_F = 10% at ALF'•I_{N-CT}

Relays 7SD52/61: Operating characteristic





$I_{Diff} = \underline{I}_1 + \underline{I}_2 + \underline{I}_3$ (Calculated differential current)

$I_{Stab} = I_{Diff>} + \Sigma$ Sync.error $+ |\underline{I}_1| \bullet f_{CT1} + |\underline{I}_2| \bullet f_{CT2} + |\underline{I}_3| \bullet f_{CT3}$

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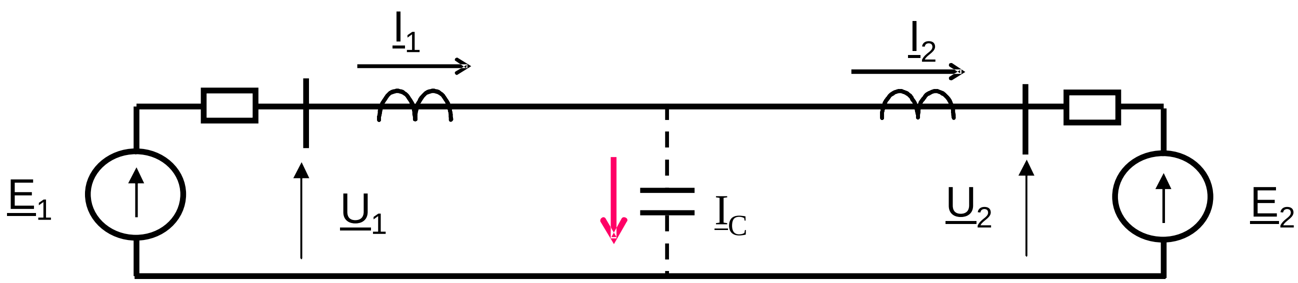
7SD52/61: Impact of line charging current



$\underline{I}_{Diff} = \underline{I}_1 + \underline{I}_2 + \underline{I}_C$ (currents $\underline{I}_1$ and $\underline{I}_2$ counted positive in line direction!)

Without charge current compensation:

Pick-up value: $I_{Diff>} > 2{,}5..\ 4 \bullet I_C$ è Senstive setting only for short cables or lines

With charge current compensation:

Pick-up value: $I_{Diff>} > 0{,}2 \bullet I_N$

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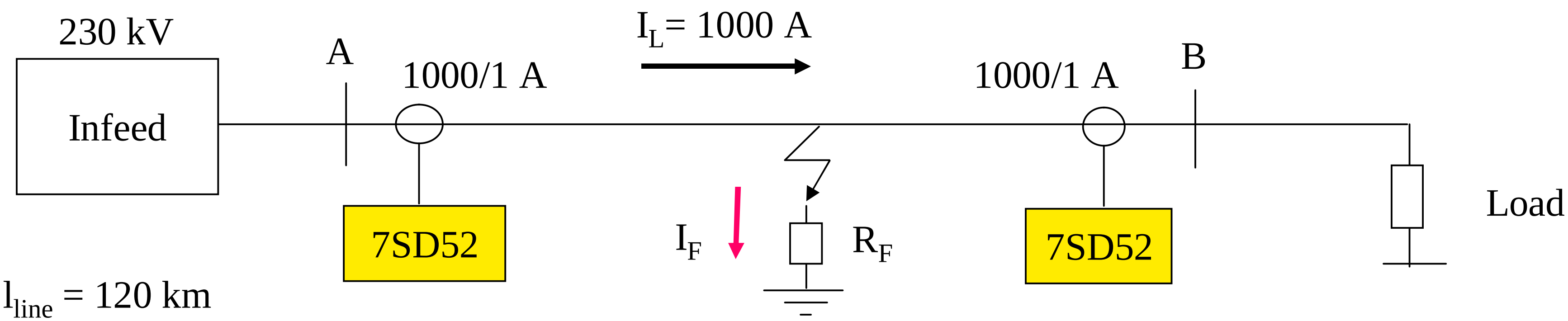
7SD52/61: High resistance fault sensitivity



l_{line} = 120 km
I_c = 72 A

Channel unsymmetry: 0.2 ms = 4.32^{O} ≈ 5^{O} (60 Hz)
5P type CT, i.e. 1% error in the load area, set: f_{CD}= 2%
Relay pick-up setting about 4xI_C: $I_{Diff>}$ = 30% I_n = 300 A

$$I_{Op} = I_A + I_B = 1000\text{ A} + I_F - 1000\text{ A} = I_F$$

$$I_{Res} = I_{Diff>} + F_{sync} + f_{CTA} \cdot I_A + f_{CTB} \cdot I_B = I_{Diff>} + (I_L + I_F) \cdot \sin\frac{\Delta\varphi}{2} + I_L \cdot \sin\frac{\Delta\varphi}{2} + f_{CTA} \cdot (I_L + I_F) + f_{CTB} \cdot I_L$$

$$I_F > \frac{I_{Diff>} + (2 \cdot \sin(\Delta\varphi/2) + f_{CTA} + f_{CTB}) \cdot I_L}{1 - (\sin(\Delta\varphi/2) + f_{CTA})} = \frac{300\text{A} + (2 \cdot \sin 5^{o}/2) + 0.02 + 0.02) \cdot 1000\text{A}}{1 - (\sin(5^{o}/2) + 0.02)} = 457\text{ A}$$

$$R_{F-max.} = \frac{230\text{ kV}}{\sqrt{3} \cdot I_{F-min.}} = \frac{230\text{ kV}}{\sqrt{3} \cdot 457\text{A}} = 290\text{ Ohm}$$

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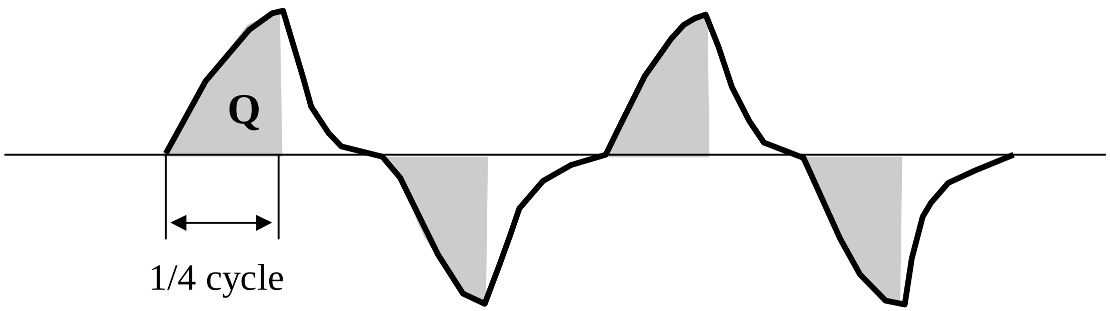
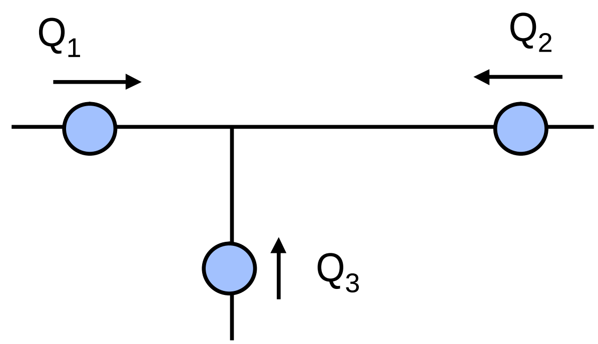
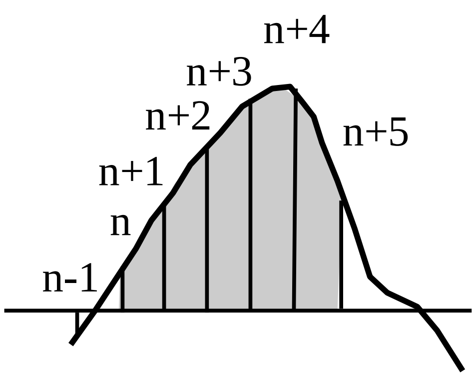
7SD52/7SD61: Charge comparison protection supplement



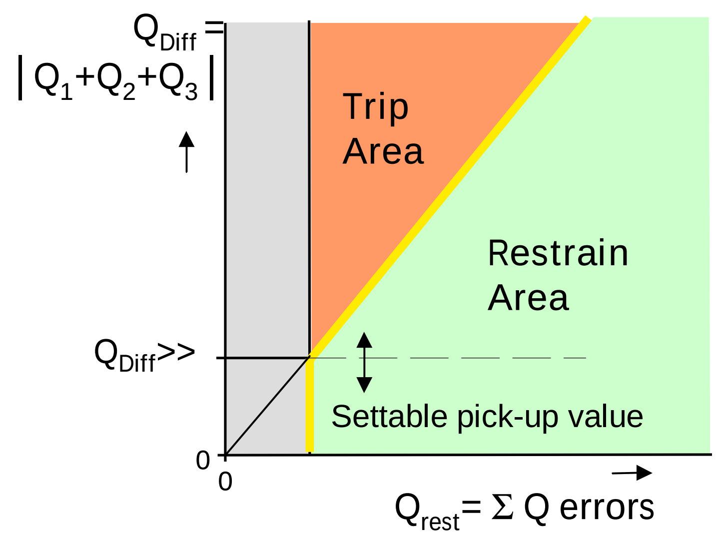




Calculation of the charge

$$Q = \int_{t}^{t+T/4} I(t)\cdot dt \approx \left(\frac{i_n}{2} + \frac{i_{n+5}}{2} + \sum_{n+1}^{n+4} I_n\right)\cdot \Delta T$$

with $\Delta T = 1$ ms (18^{O} el.)



speed	*2 relays*	*3 relays*	*6 relays*
64 kbit/s	21 ms	21 ms	41 ms
128 kbit/s	16 ms	16 ms	24 ms
512 kbit/s (FO)	14 ms	14 ms	17 ms

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Development of IED processing and communication power

Year	Memory	Processing power	Bus width	Communication
1986	192 kB	0.5 MIPS	16 bit	19.2 kbps
1992	768 kB	1.0 MIPS	16 bit	115.2 kbps
1998	8.5 MB	35 MIPS	32 bit	1.5 Mbps (LAN)
2004	28 MB	80 MIPS	32 bit	100 Mbps (LAN)

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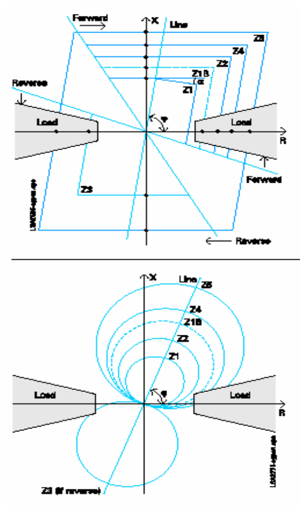
21 & 87 Relay
United full scheme distance and differential protection



21

Copy of well proven features

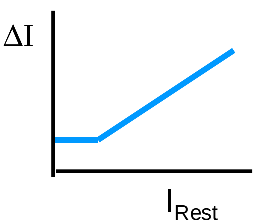
21, 21N	85 - 21
67N	85 - 67N
68, 68T	27 WI

79	25
59	27
49	81
51/51N	50 BF

87

21 & 87

87



Universal line protection relay

87 Differential
21 Distance
67 DEF

} line protection

For all kind of lines

Short to long lines

Parallel lines

Multi-terminal lines

Tapped lines

Transformer lines

Series comp. lines

For all kind of communication:

Traditional : PLC, Pilot wires, Microwave

Dedicated OF

Digital microwave

Comms networks

For all kind of operation

Single and/or three-pole ARC

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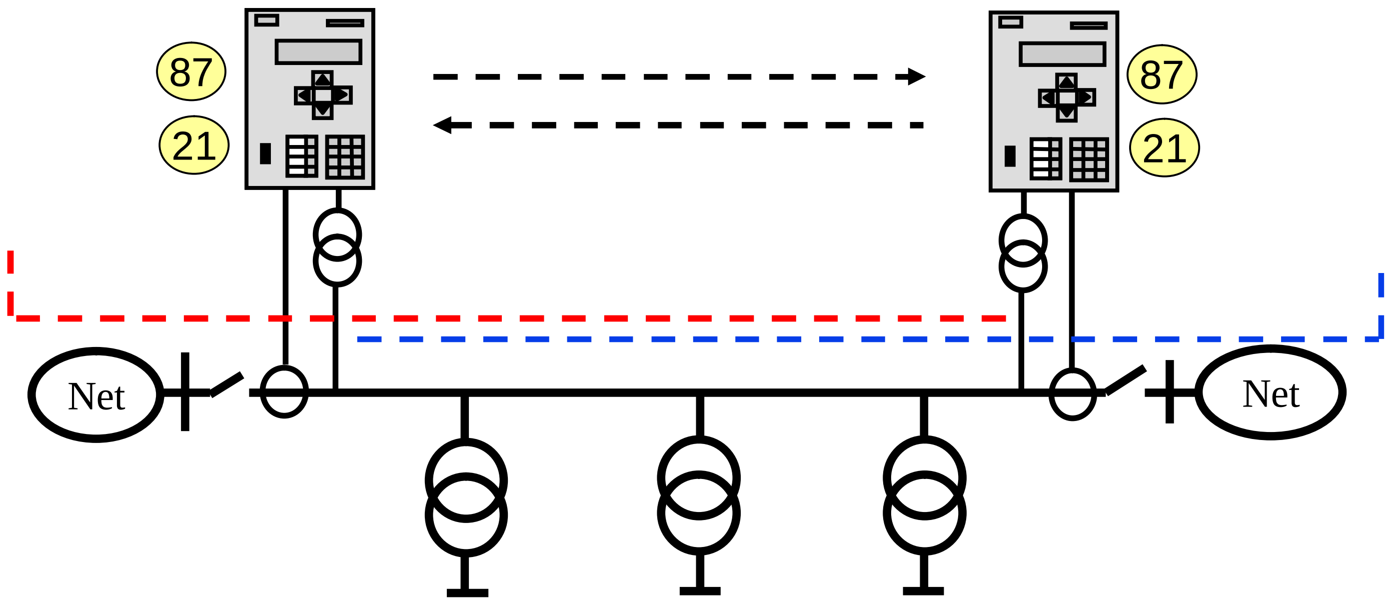
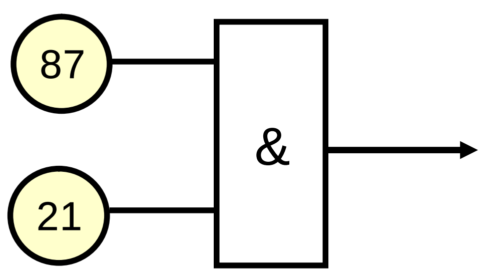
Line with larger transformer taps
Release of 87 by 21 distance overreaching zone





Allows low setting of 87 pick-up!

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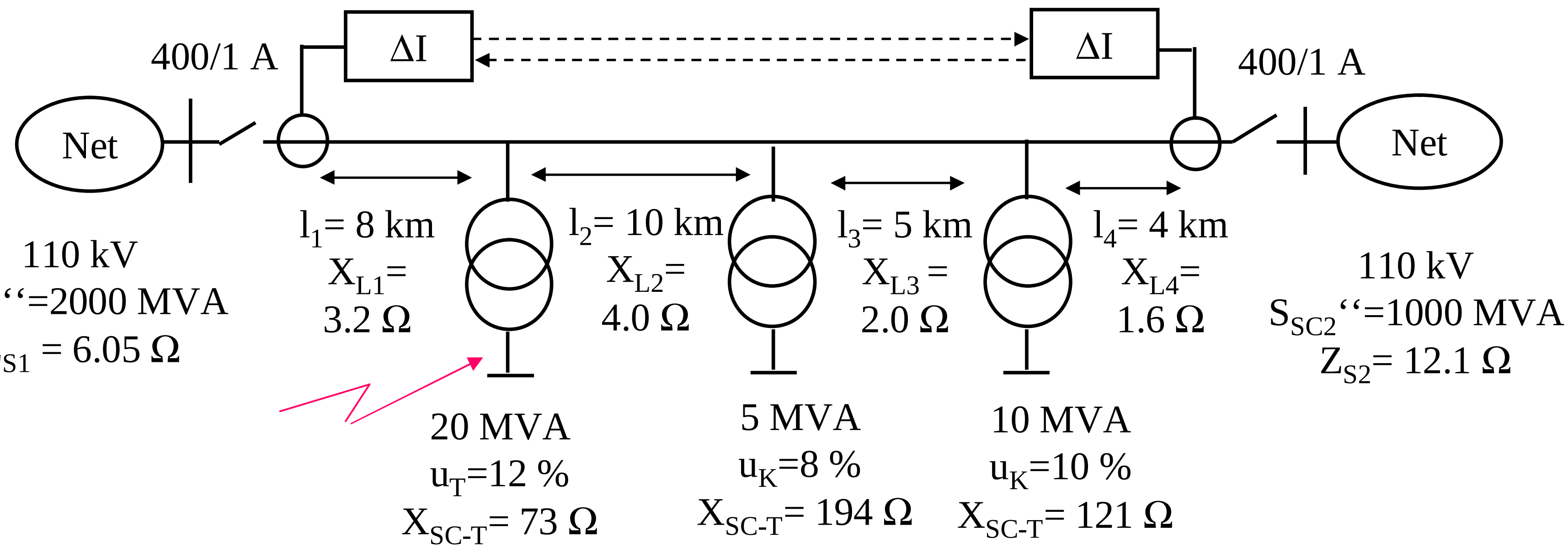
Line differential relay with digital communication (7SD61)
Application to tapped line, Example

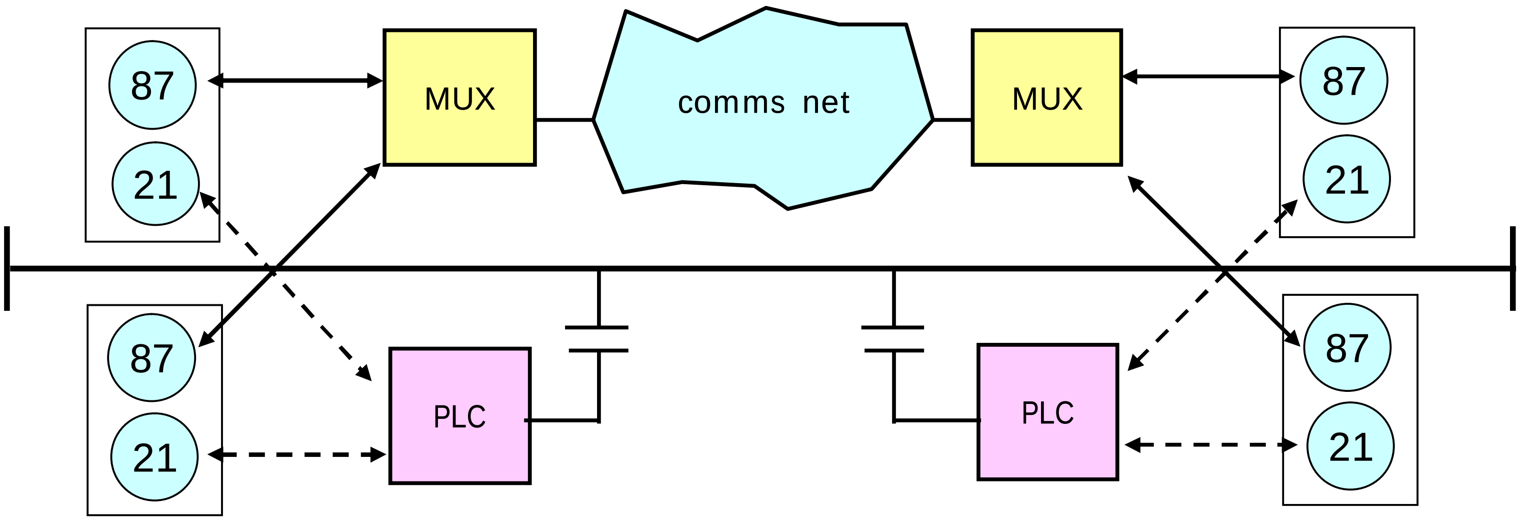


$$I_{SC} \approx \frac{1.1 \cdot U_N/\sqrt{3}}{X_{SC-T}} = \frac{1.1 \cdot 110/\sqrt{3}\ \text{kV}}{73\ \Omega} = 957\ \text{A}$$

$$\Sigma I_{Rush} \approx 5 \cdot \frac{\sum S_{N-T}}{\sqrt{3} \cdot U_N} = 5 \cdot \frac{35\ MVA}{\sqrt{3} \cdot 110\ kV} = 918\ A$$

- Setting pick-up value ΔI > 1.3·957 A
- or blocking ΔI via remote signalling when tap protection operates
- or release of ΔI by an overreaching distance zone

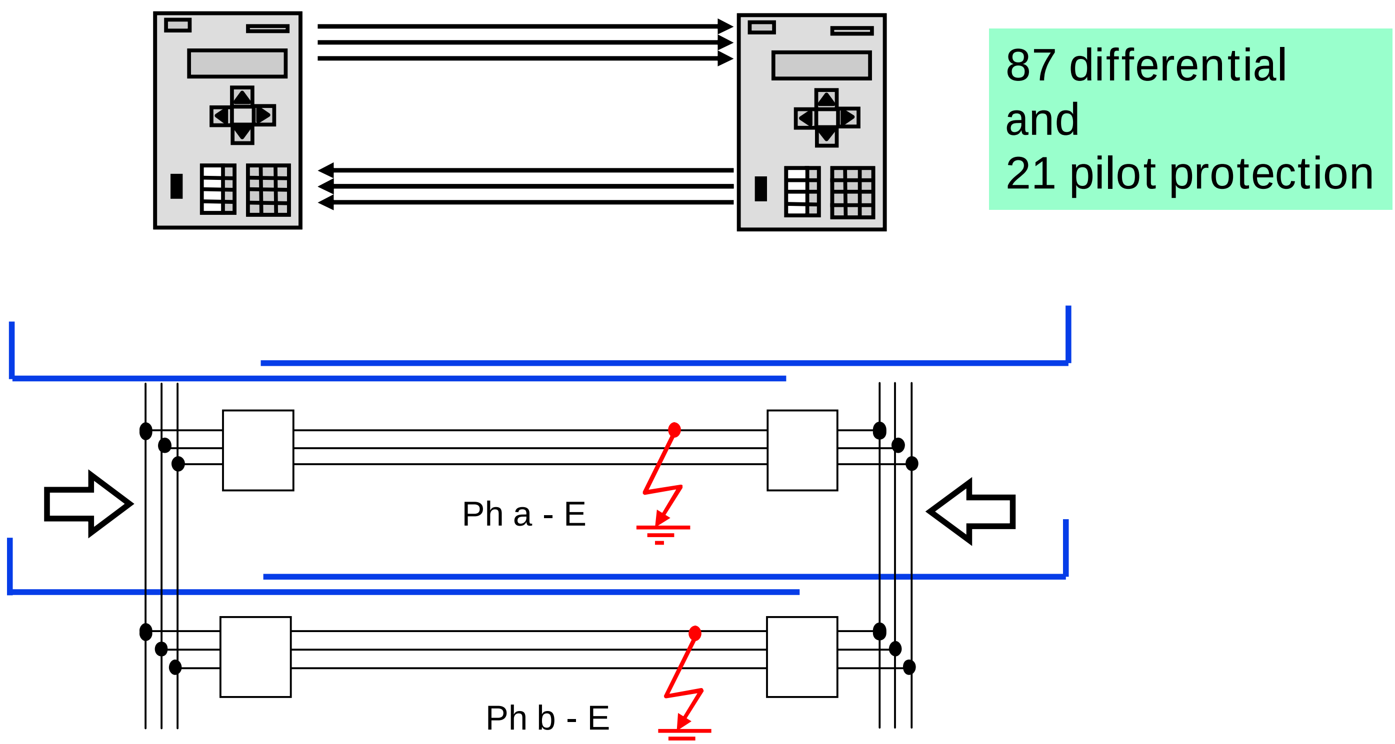
Fully redundant line protection
using dissimilar protection and comms principles



Fully redundant 87 and 21 teleprotection remains in operation

in each combination of relay and communication failure!

Phase segregated 87 differential and 21 distance pilot protection:
Enhanced selectivity with multiple faults



Phase selective fault clearance and auto-reclosing also with multiple-faults

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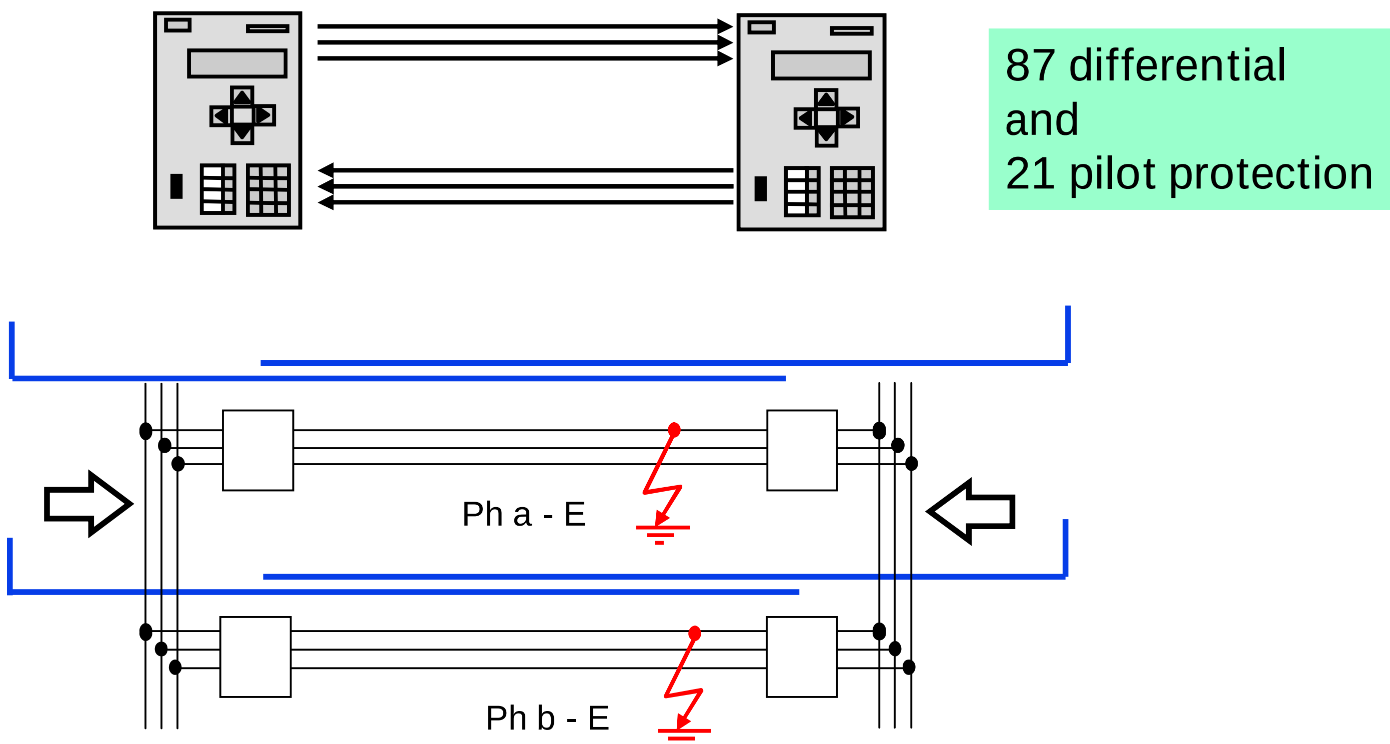
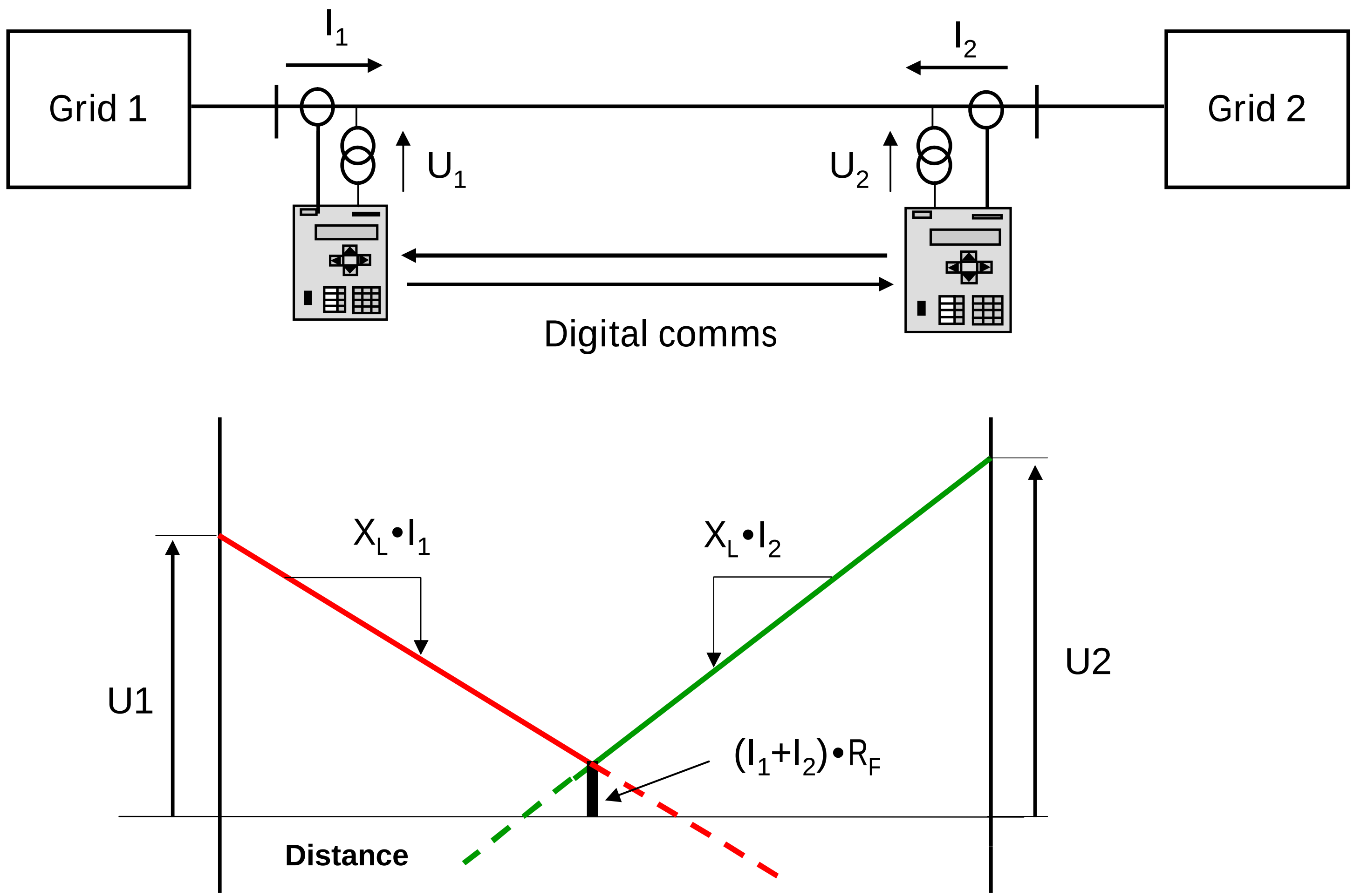
Phase segregated 87 differential and 21 distance pilot protection: Enhanced selectivity with multiple faults



Phase selective fault clearance and auto-reclosing also with multiple-faults

Two-sided fault locator using 87&21 relay communication



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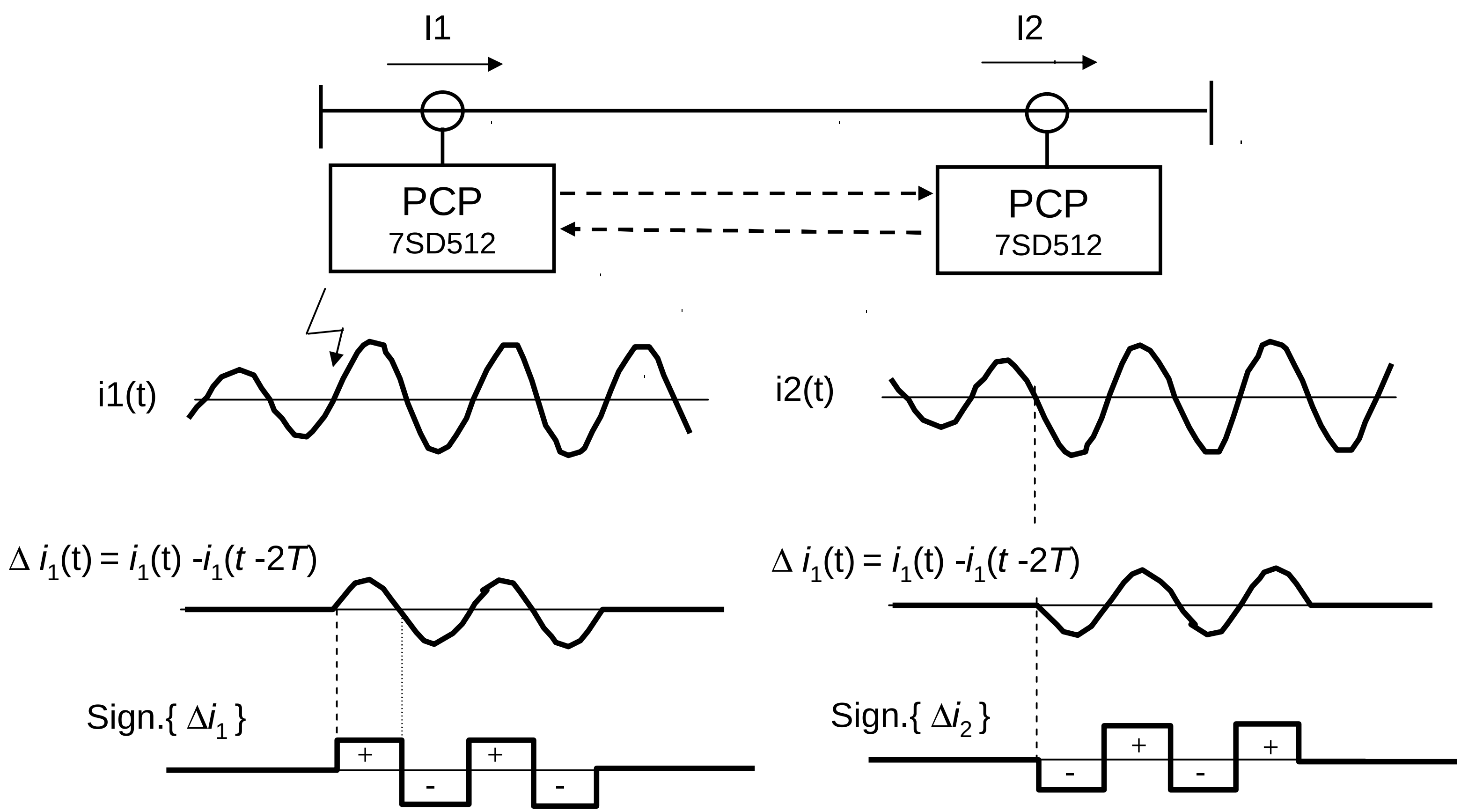
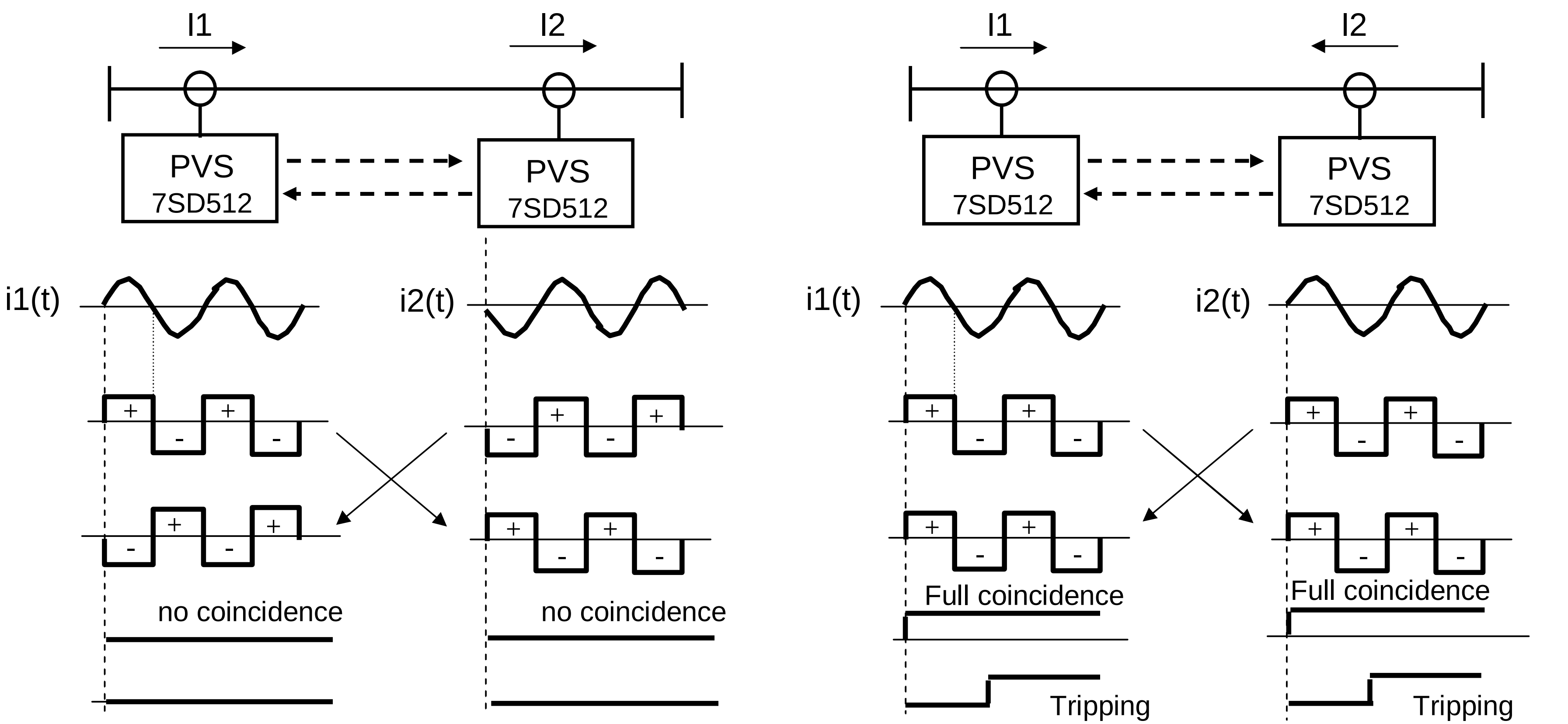
Conclusions

- ü Combined distance and differential protection relays , together with modern comms, allow to enhance line protection in a cost saving way.
- ü The dissimilar protection principles complement each other perfectly.
- ü Distance and differential protection can both be configured as phase segregated teleprotection schemes allowing absolute phase selective fault clearance and autoreclosure even with complex cross county and inter-circuit faults.
- ü Digital relay to relay comms allows to exchange data for upgraded two sided fault locating.
- ü Using a single relay type for distance and/or differential protection also saves on cost in investment and operation.

7SD51: Phase comparison, Dynamic supplement based on delta-quantities



7SD51: Phase comparison



External fault

Internal fault,

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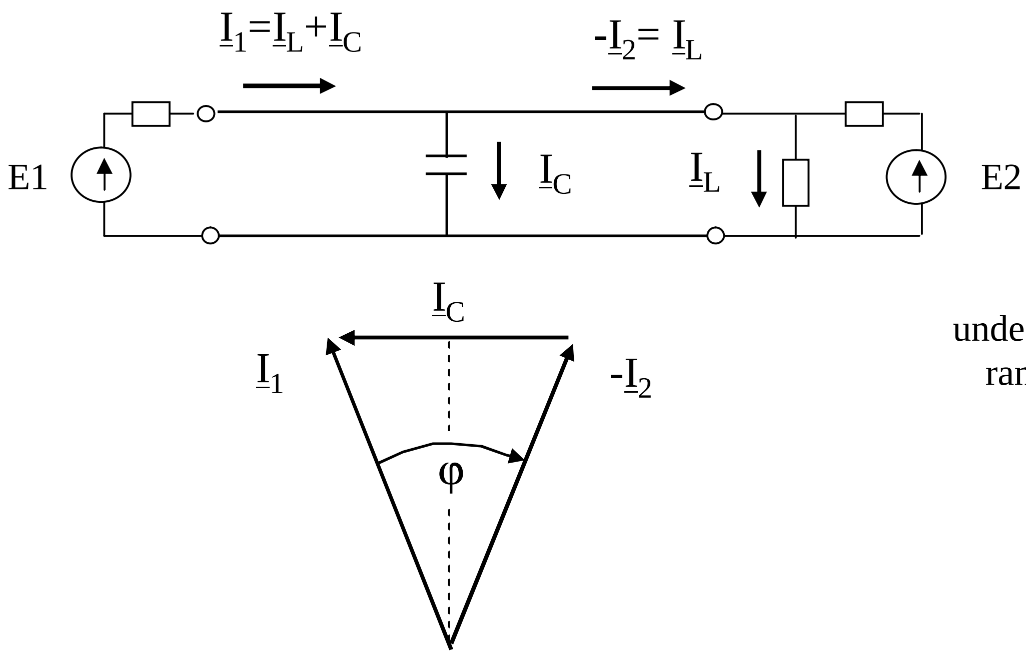
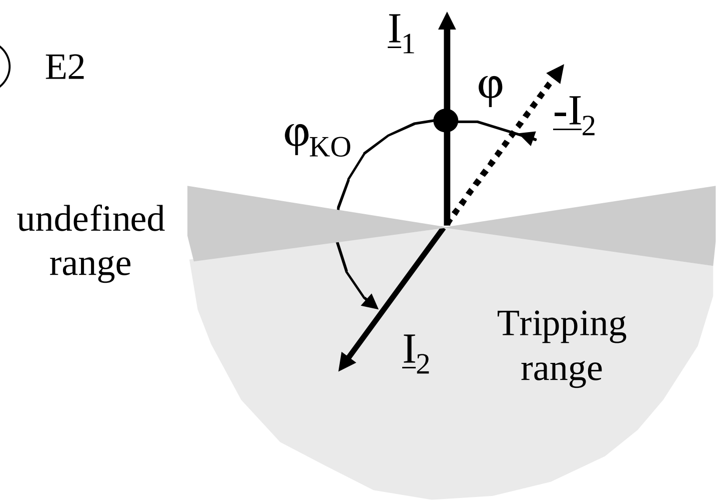
7SD51: Phase comparison: Impact of charging current



Phase shift φ caused by charging current $\underline{I}_C$



undefined range due to discrete sampling :
$\pm 1/2\Delta T = \pm\ 1{,}66/2$ ms$= \pm\ 15^{O}$

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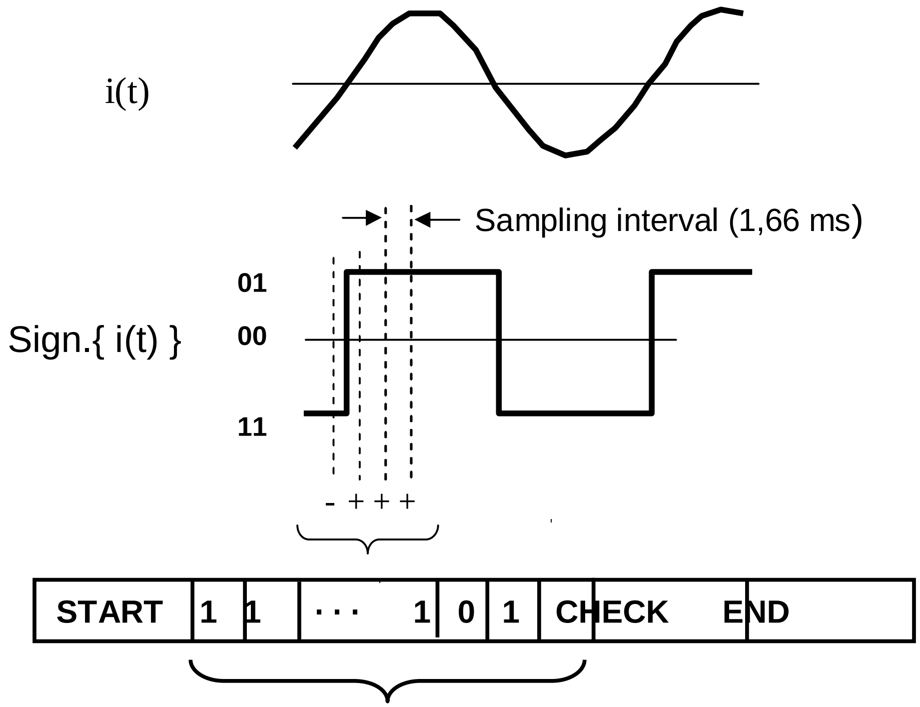
Phase comparison protection 7SD51:

Sampling of the rectangular sign wave and data transmission telegram



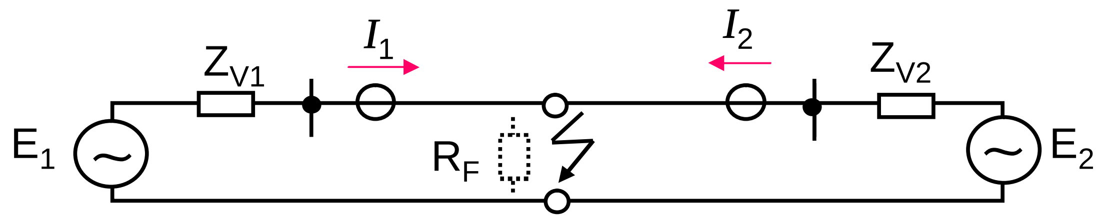
4 directional signs per phase = 12 binary digits

Telegram acc. to IEC 60870-5
Hamming distance d= 4

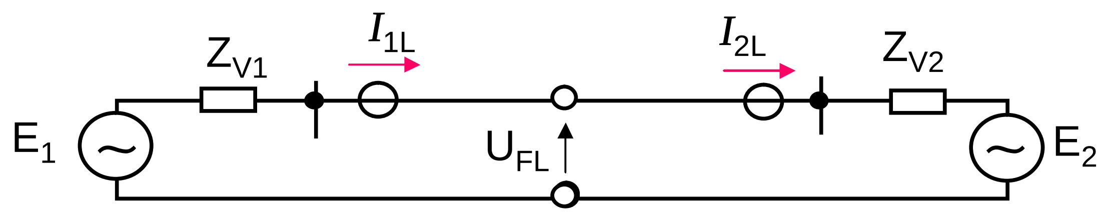
Measurement based on delta quantities, Principle

ΔI_1, ΔI_2: DELTA-quantities

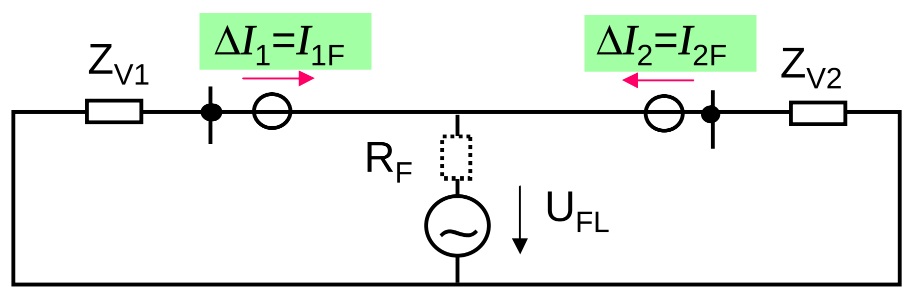
Total situation after fault inception:

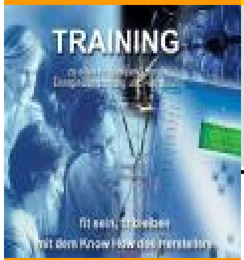


⊖ Load before fault inception:



⊜ Pure fault part :





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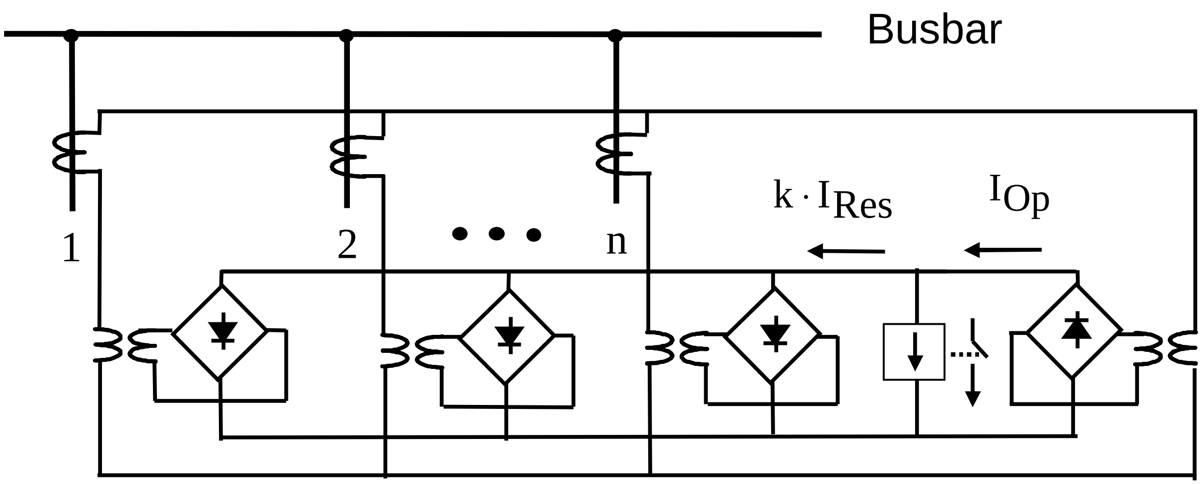
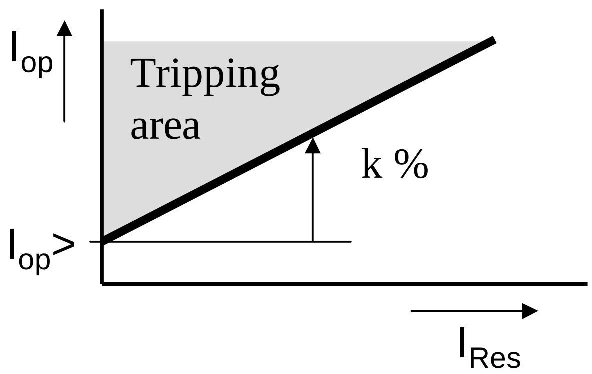
Digital Busbar Protection

Gerhard Ziegler

Busbar differential protection, Principle (Analog technique)



Measuring circuit



Operating characteristic

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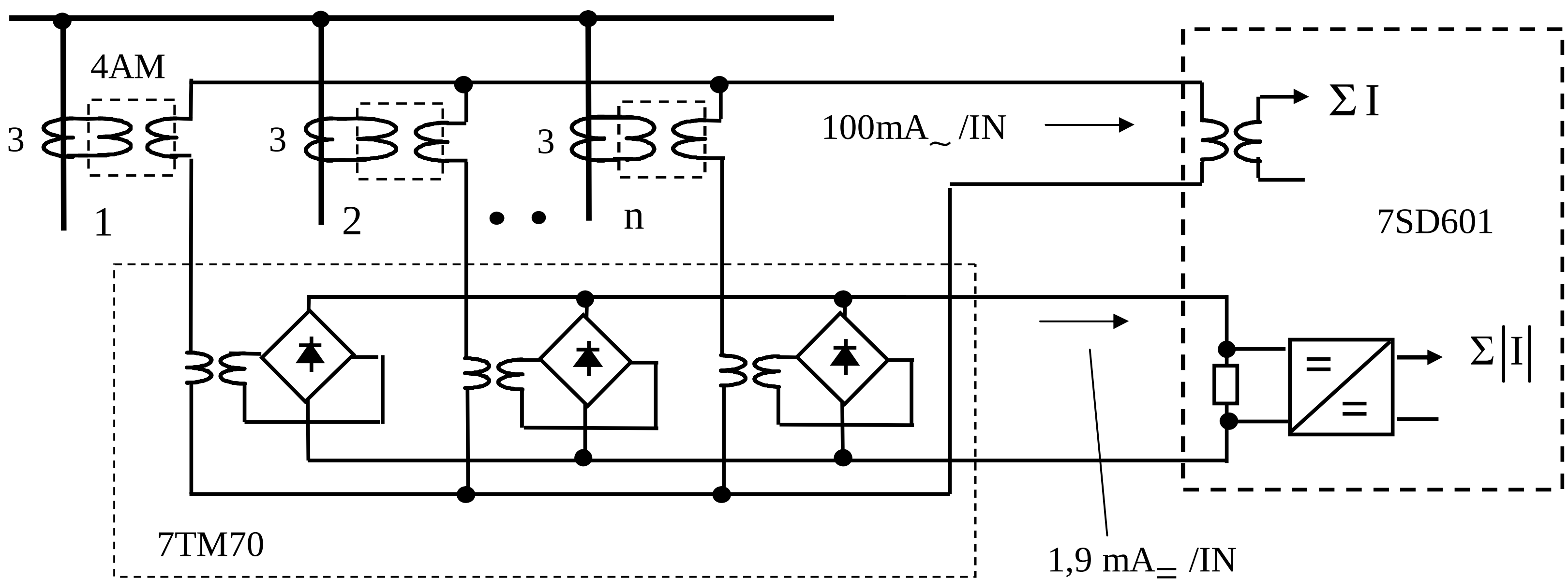
Part-digital Busbar protection 7SS6



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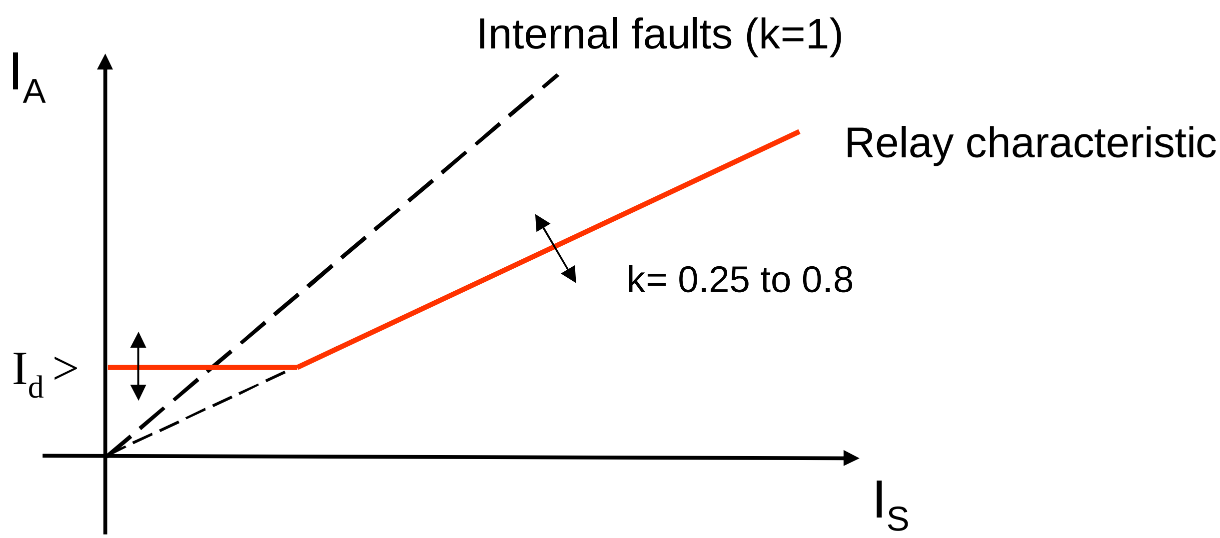
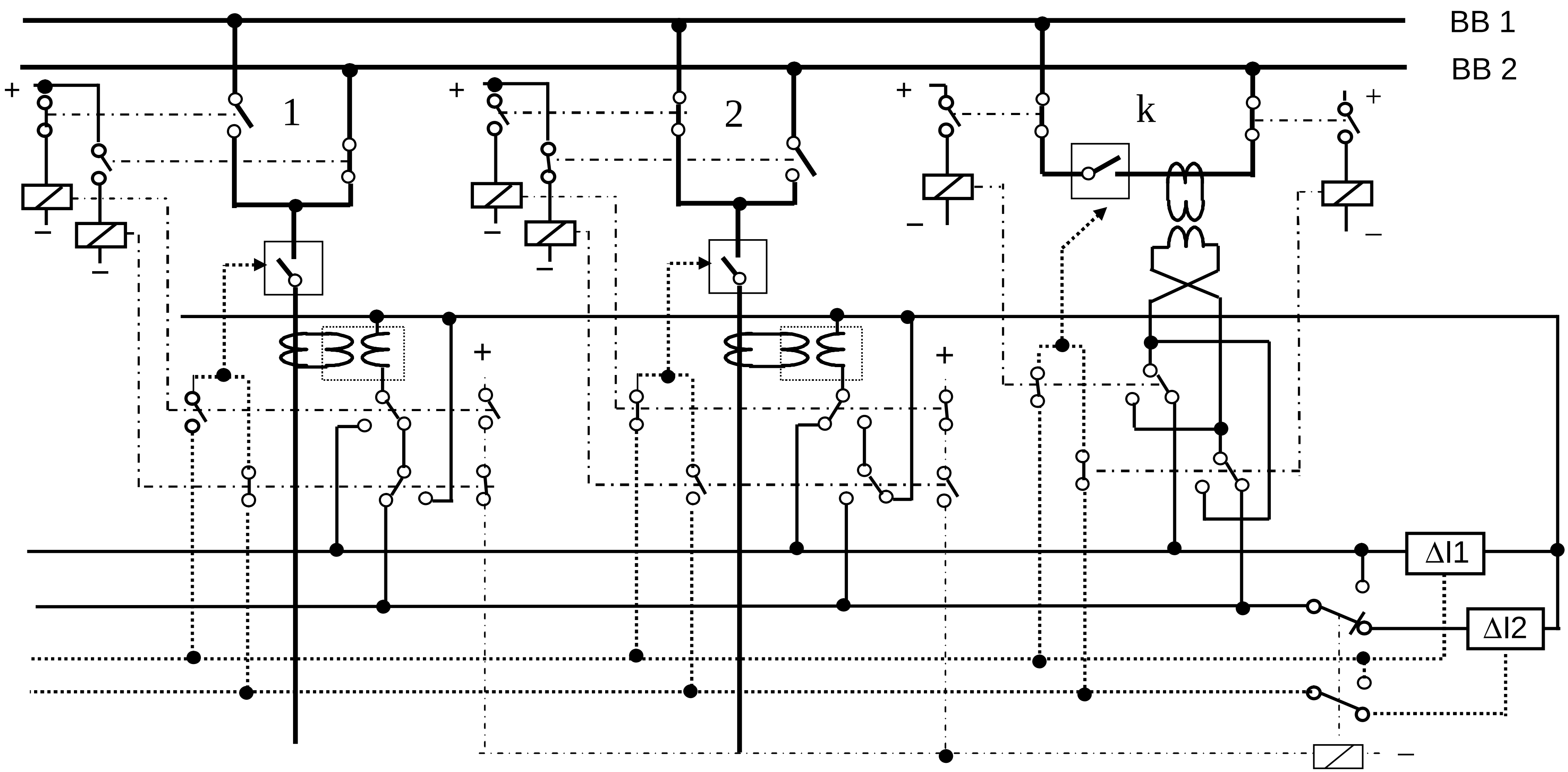
7SS6: Operating characteristic



Isolator replica, Principle, (stabilising circuit not shown)



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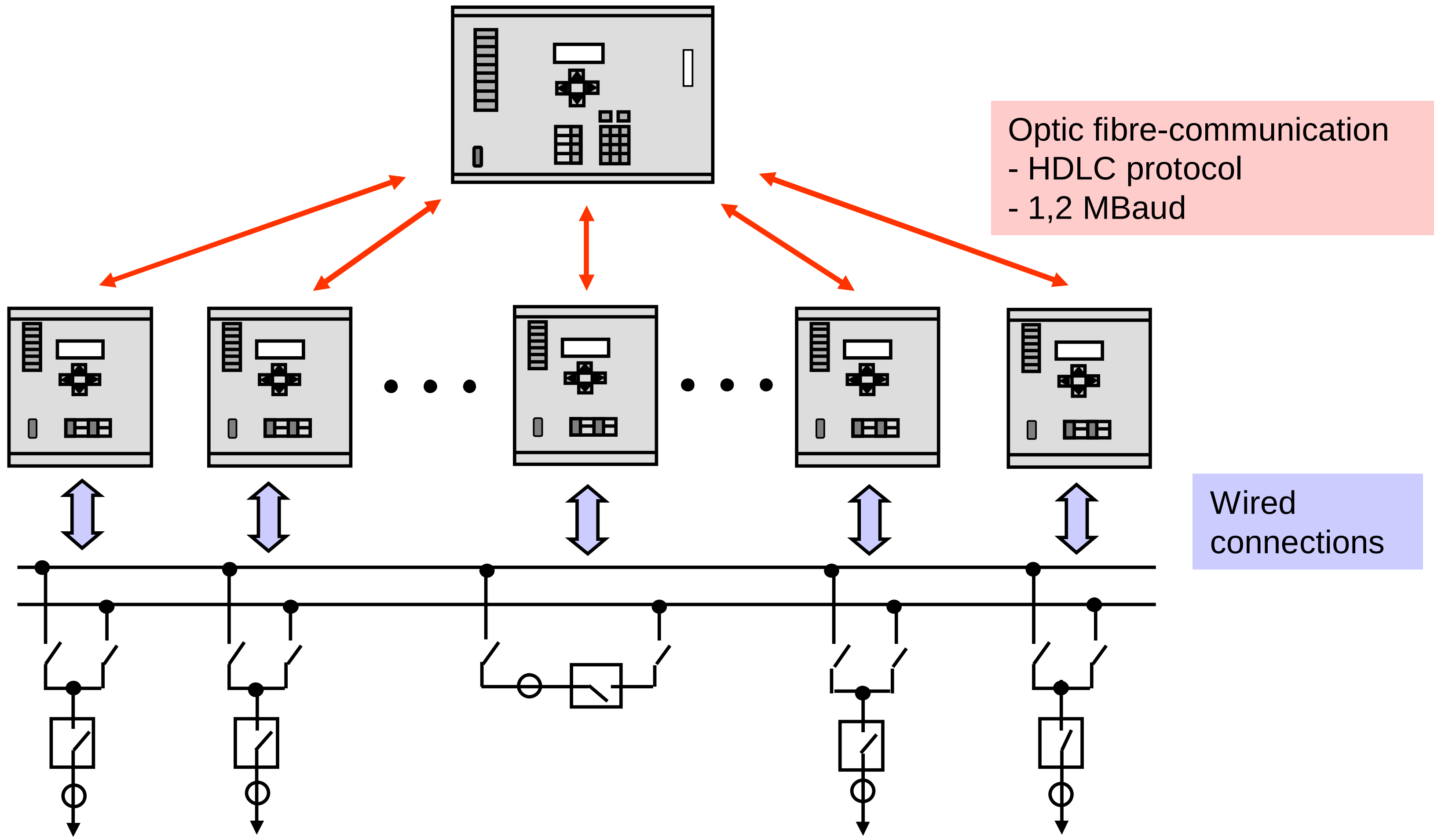
Decentralised BB-protection 7SS52, Structure



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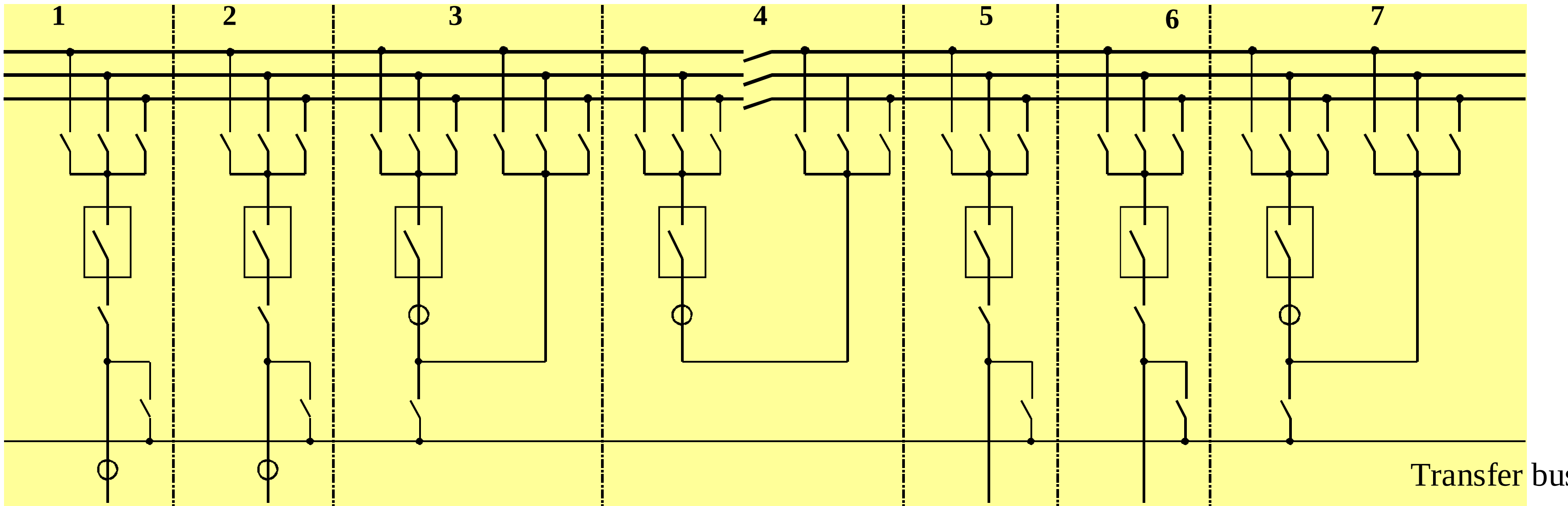
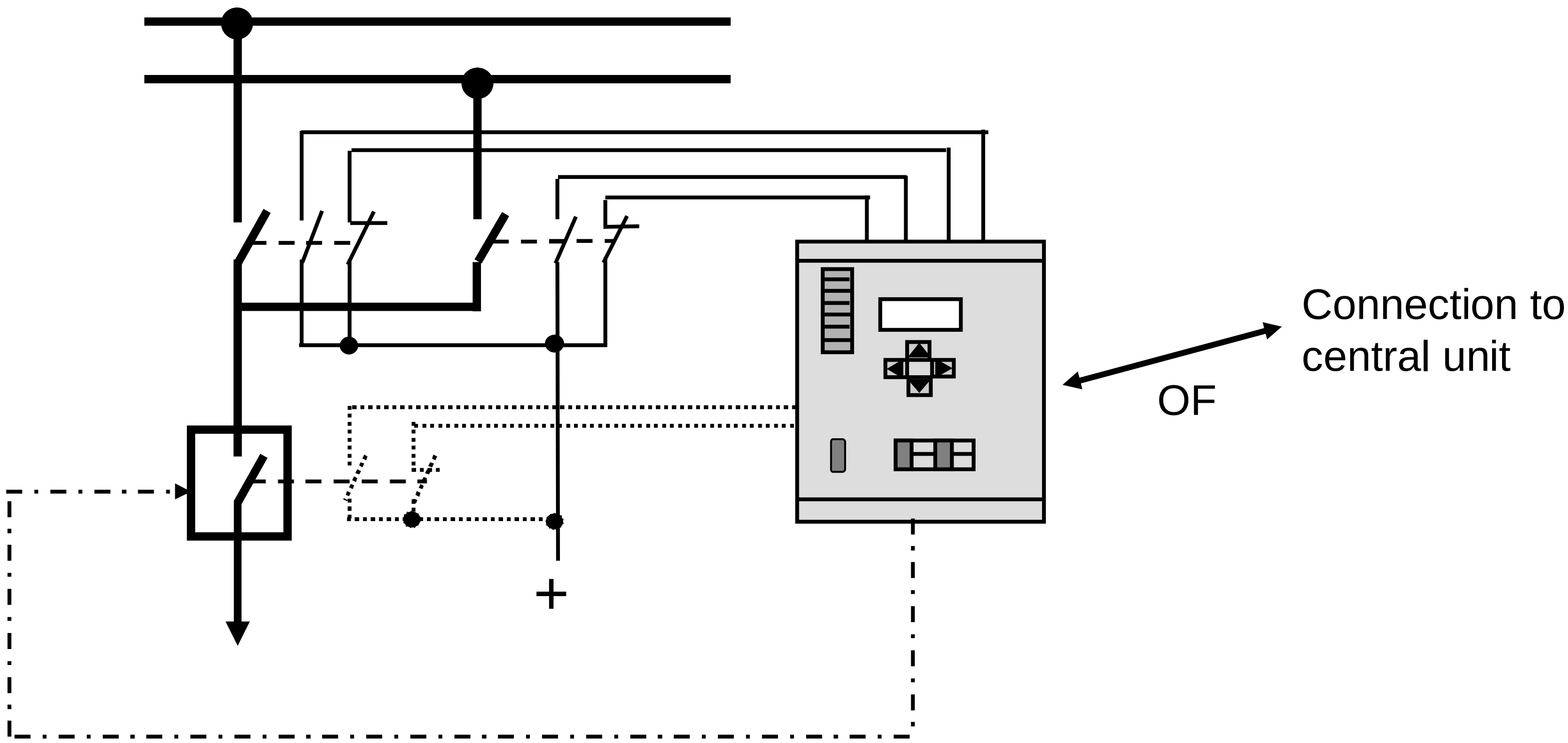
7SS50/52: Maximum configuration

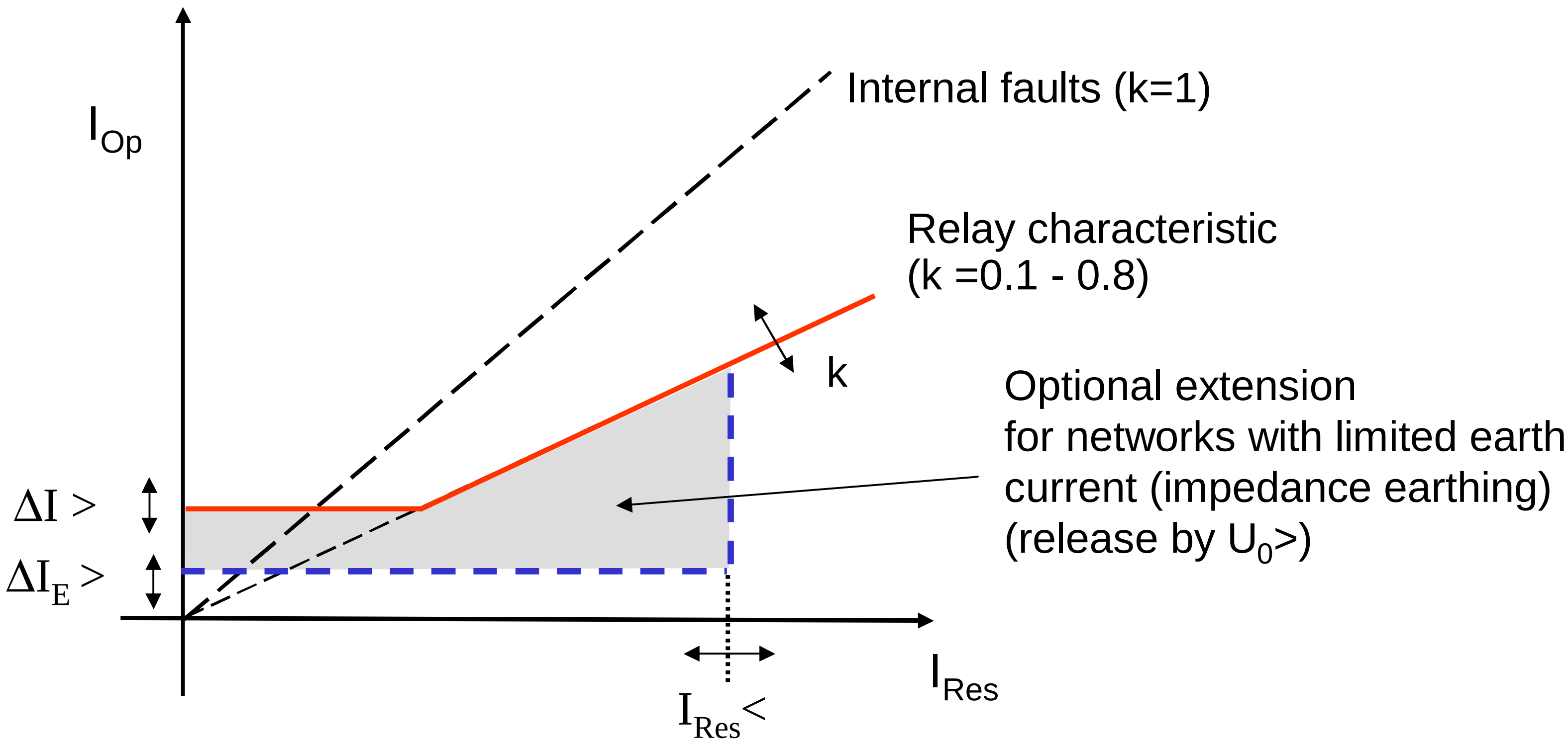


	7SS50 centralised	7SS52 decentralised
Bays	32	48
BB-zones	8	12
couplings	4	16

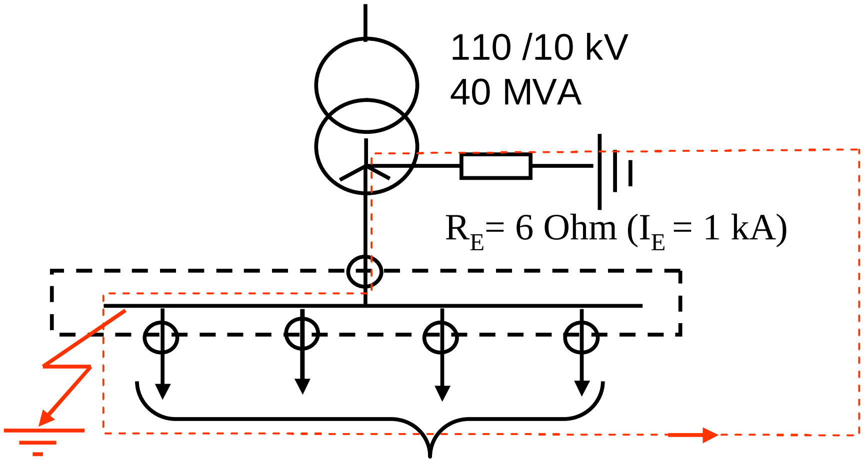
7SS50/52: Acquisition and supervision of isolator positions



Operating characteristic of BB protection 7SS52



BB-Protection 7SS52
Performance in networks with earth current limitation



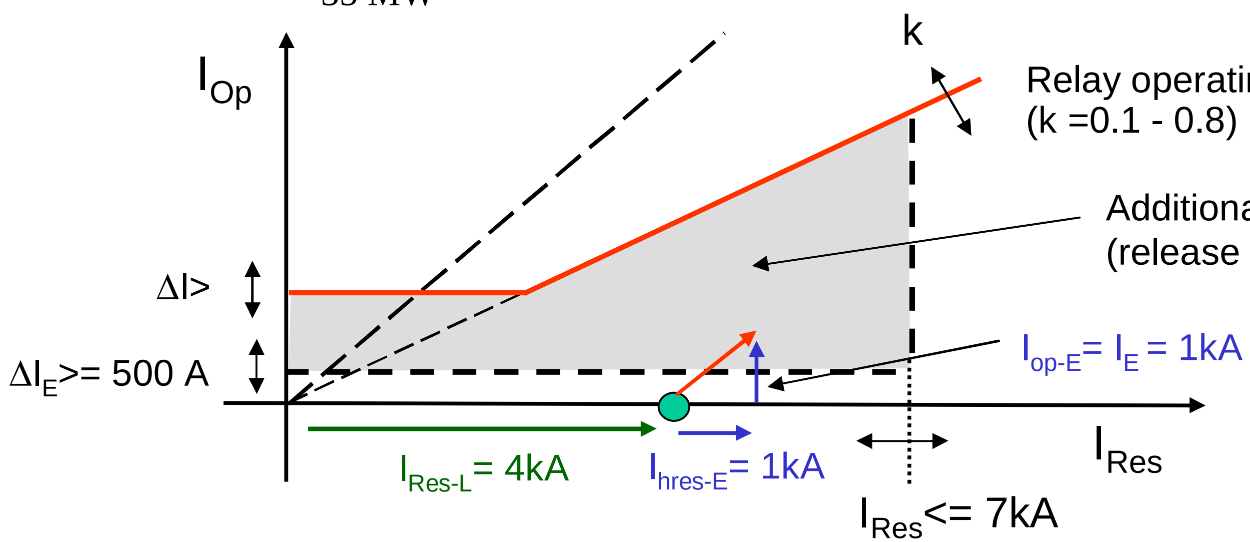
$$I_L = \frac{35MVA}{10kV \cdot \sqrt{3}} = 2\ kA$$

$$I_F = I_E = 10/\sqrt{3}kV/6\Omega \approx 1\ kA$$

Restraint current: $I_{Res} = \Sigma|I| = (2+1) + 2\ kA$

Operating current: $I_{Op} = |\Sigma I| = I_E = 1\,kA$

$$k = \frac{I_{Op}}{I_{Res}} = \frac{1}{5} = 0.2$$



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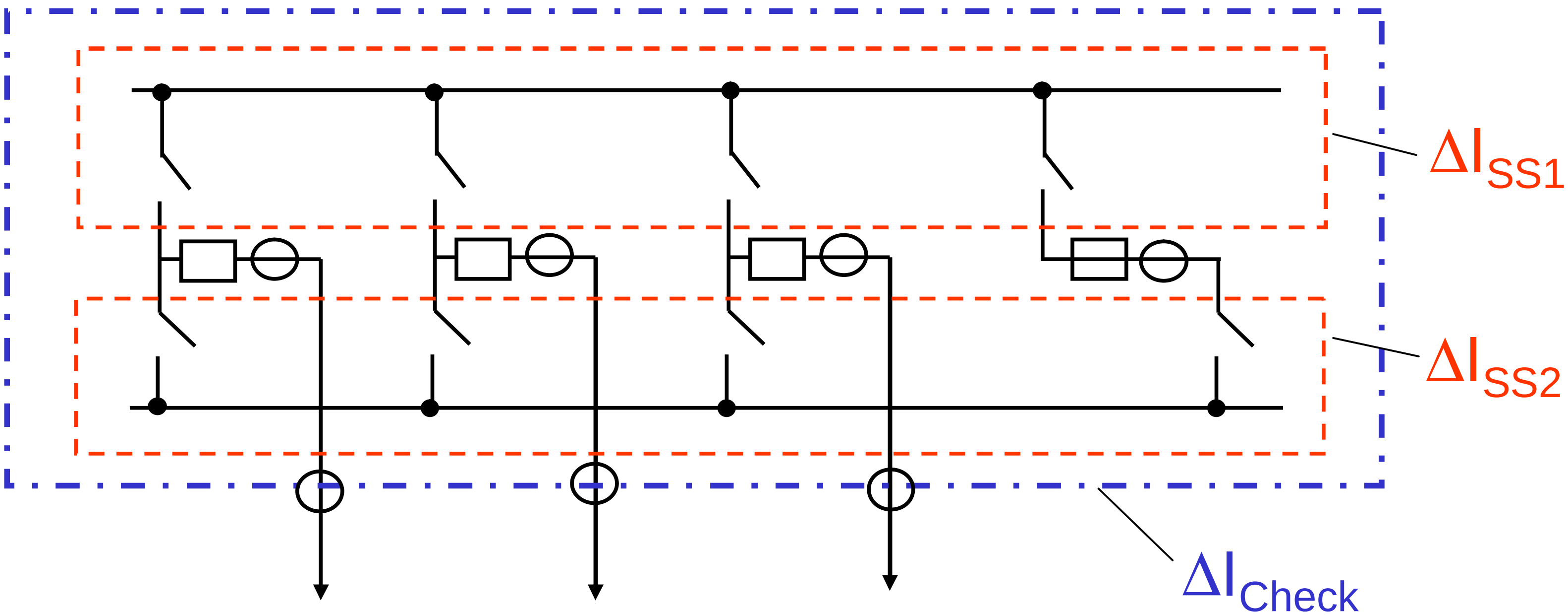
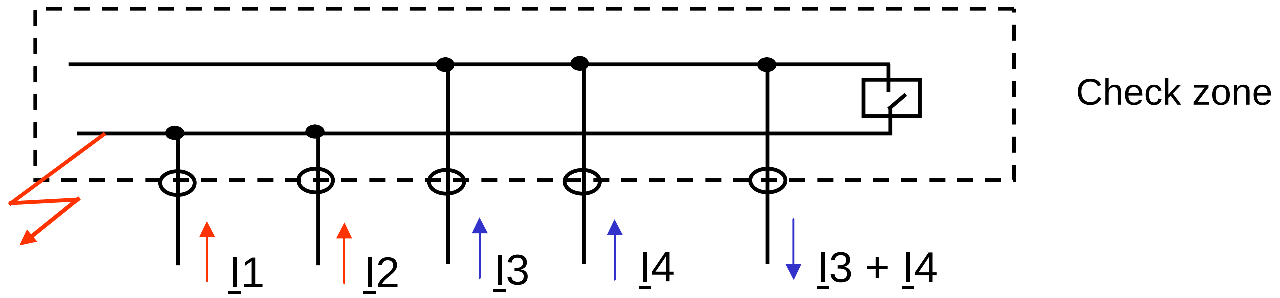
Check zone of busbar protection

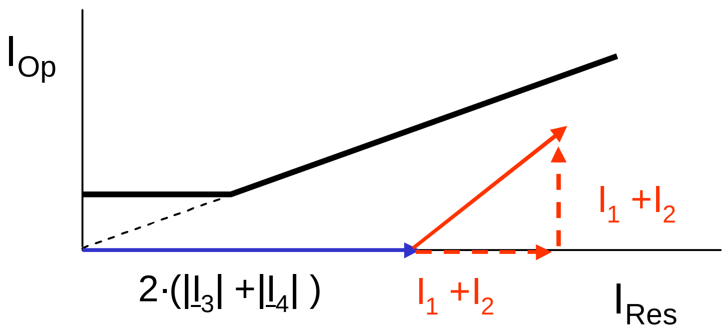


Check zone:

- in the past used with HI protection on EHV level (needs separate CT cores)
- in general not used with traditional low impedance busbar protection (too expensive)
- However, now integrated as software function in full scheme versions 7SS51 and 7SS52

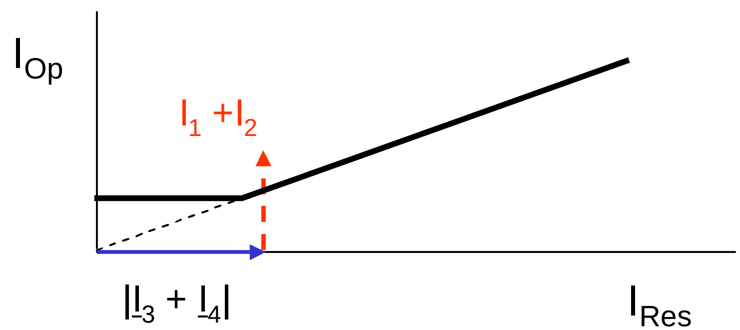
7SS52: special restraint algorithm avoids over-stabilisation





Normal restraint:
Sum of all current magnitudes

$$I_{Res} = \Sigma|\underline{I}| = |\underline{I}1| + |\underline{I}2| + |\underline{I}3| + |\underline{I}4| + |\underline{I}3| + |\underline{I}4|$$



Special restraint algorithm:
Positive and negative currents are added separately.

$$\Sigma|\underline{I}_p| = |\underline{I}1| + |\underline{I}2| + |\underline{I}3| + |\underline{I}4| \qquad \Sigma|\underline{I}_n| = |\underline{I}3| + |\underline{I}4|$$

Smaller value is then taken:

$$I_{Res} = \Sigma|\underline{I}_n| = |\underline{I}3| + |\underline{I}4|$$

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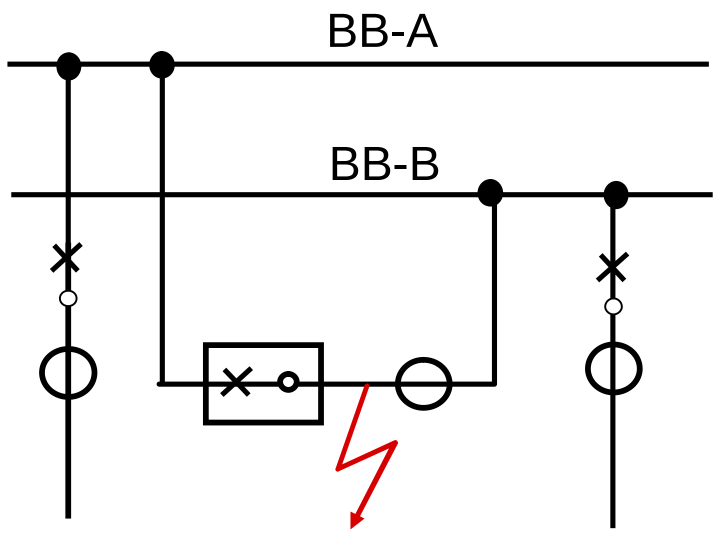
7SS52: Special treatment of dead zone faults (1)



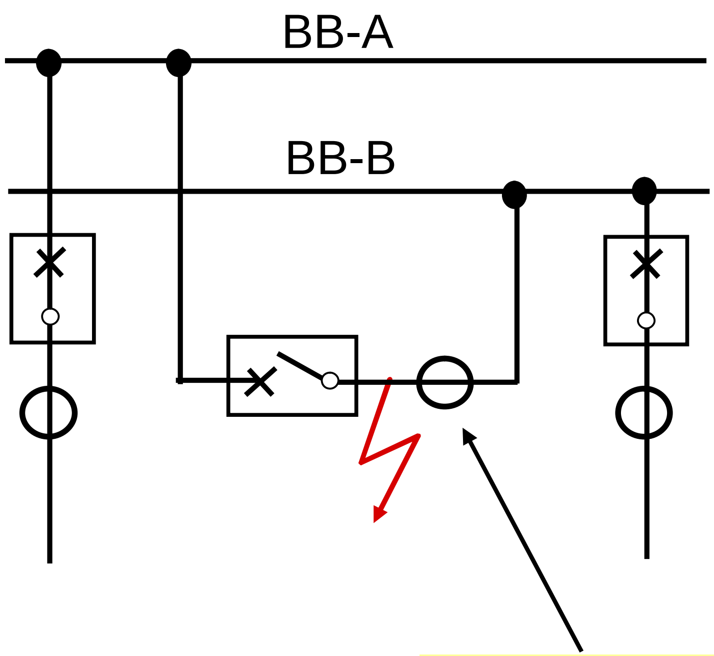
Bus coupler CB aux. contacts **not** connected:

- 87-A trips bus coupler
- Current inverted in 87-B after T-BF. Subsequently 87-B trips BB-B

Coupler CB auxiliary contacts connected:

- 87-B trips immediately after opening of bus coupler CB because coupler current is removed from bus protection.
  $\rightarrow$ time reduction (T-BF saved)

7SS52: Special treatment of dead zone faults (2)



A) Bus coupler CB aux. contacts not connected:

- 87-A overfunctions and trips unnecessarily.
- 87-B „sees“ an external fault and only trips finally through BF function (delay T-BF!)

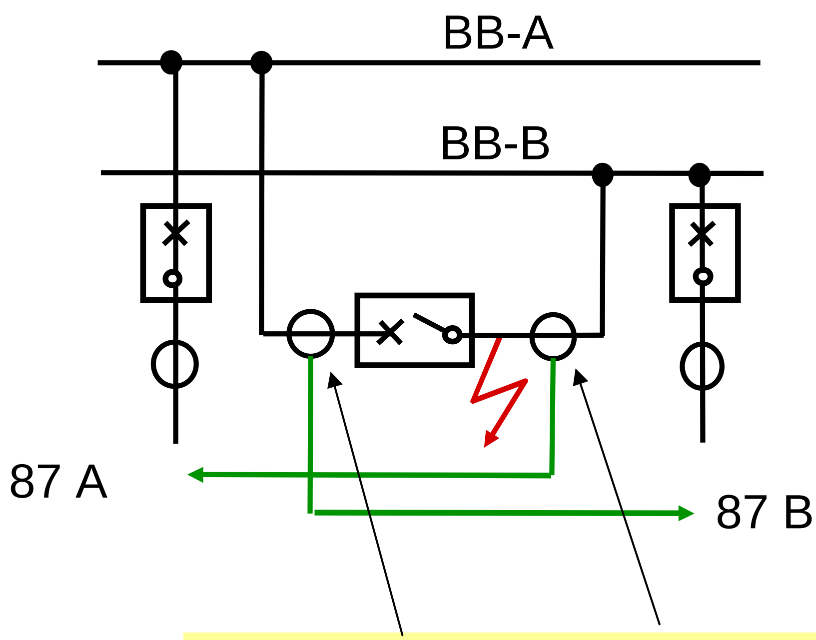
B) Bus coupler CB aux. contacts connected:

- 87-A remains stable („sees“ no fault current)
- 87-B trips immediately

Coupler CB auxiliary contacts connected to 7SS52:
Coupler current is removed from 87-A and 87-B current comparison with open coupler CB.

7SS52: Special treatment of dead zone faults (3)

Two CTs in coupling bay, overlapping protection zones

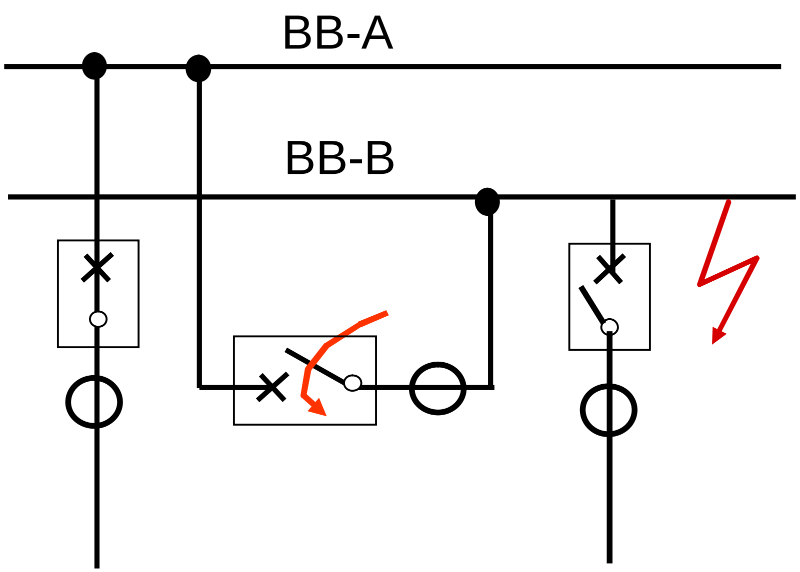


Coupler CB auxiliary contacts connected:

- 87-A „sees“ external fault and remains stable
- 67-B correctly trips BB-B

Coupler CB auxiliary contacts connected to 7SS52:
Coupler currents are removed from 87-A and 87-B current comparison with open coupler CB.

7SS52: Treatment of switch onto a faulted (earthed) bus



Coupler CB close command is detected by bus protection (change of biary input signal):

- Coupler current is immediately re-included in the 87 current comparison before CB contacts close.
- Selective tripping of BB-B by 87-B.

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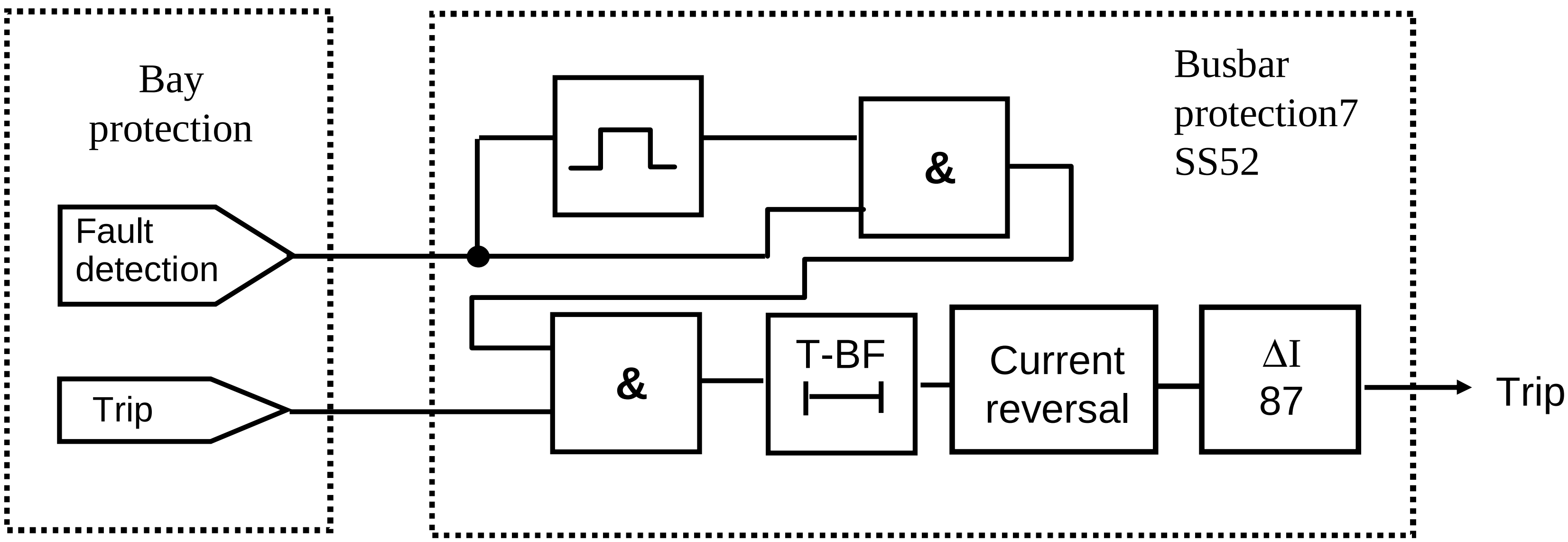
7SS52 : Integral breaker fail protection

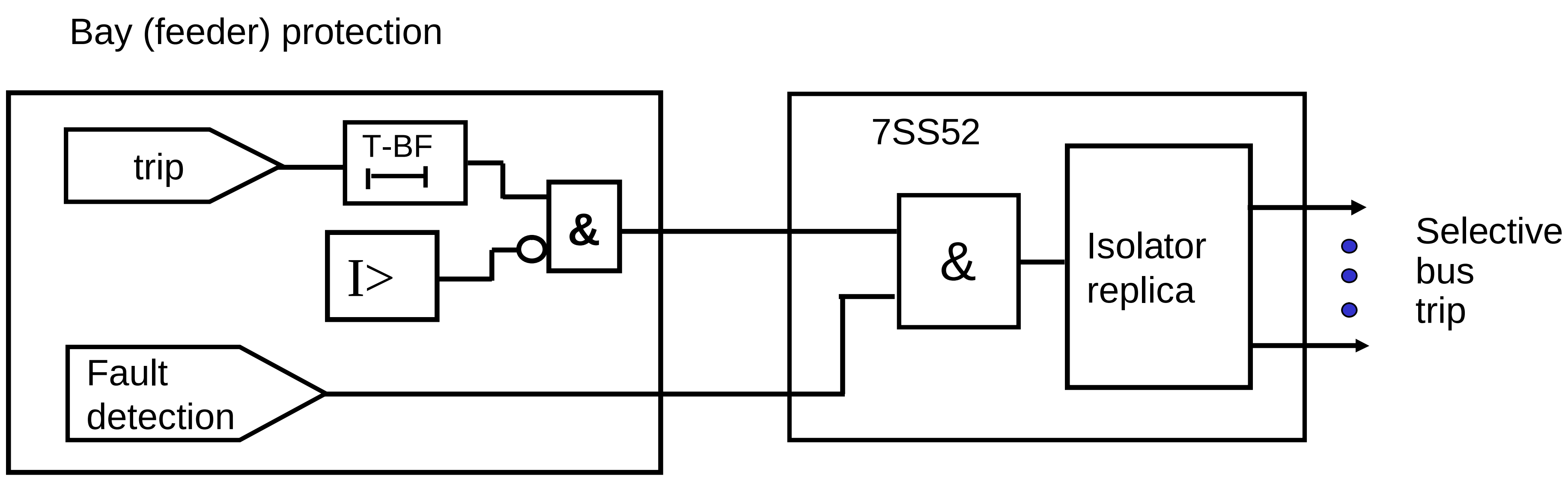


With line fault and CB failure:

- Trip command of bay protection hangs on at BB protection
- Forced current reversal of the current of concerned bay after T-BF
- Zone selective tripping only of the concerned busbar
- Advantage: Reset time (overtravel time) of bay protection does not matter

External bay dedicated BF protection

Zone selective tripping via isolator replica of 7SS52 busbar protection



- BF trip command to busbar protection binary input
  (for security: fault detection signal as second criterion)
- Distribution of trip commands via isolator replica to breakers of concerned busbar
- è zone selective tripping of concerned busbar

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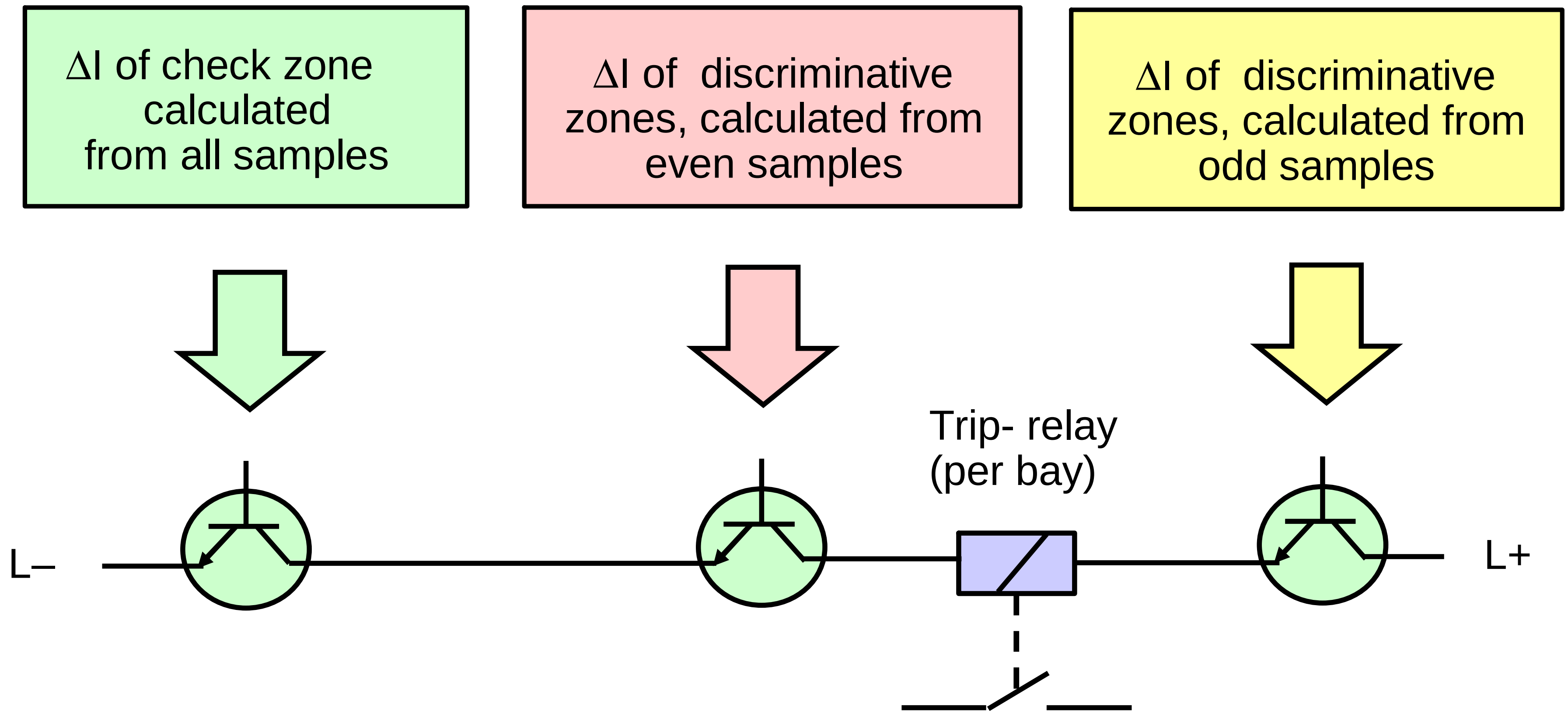
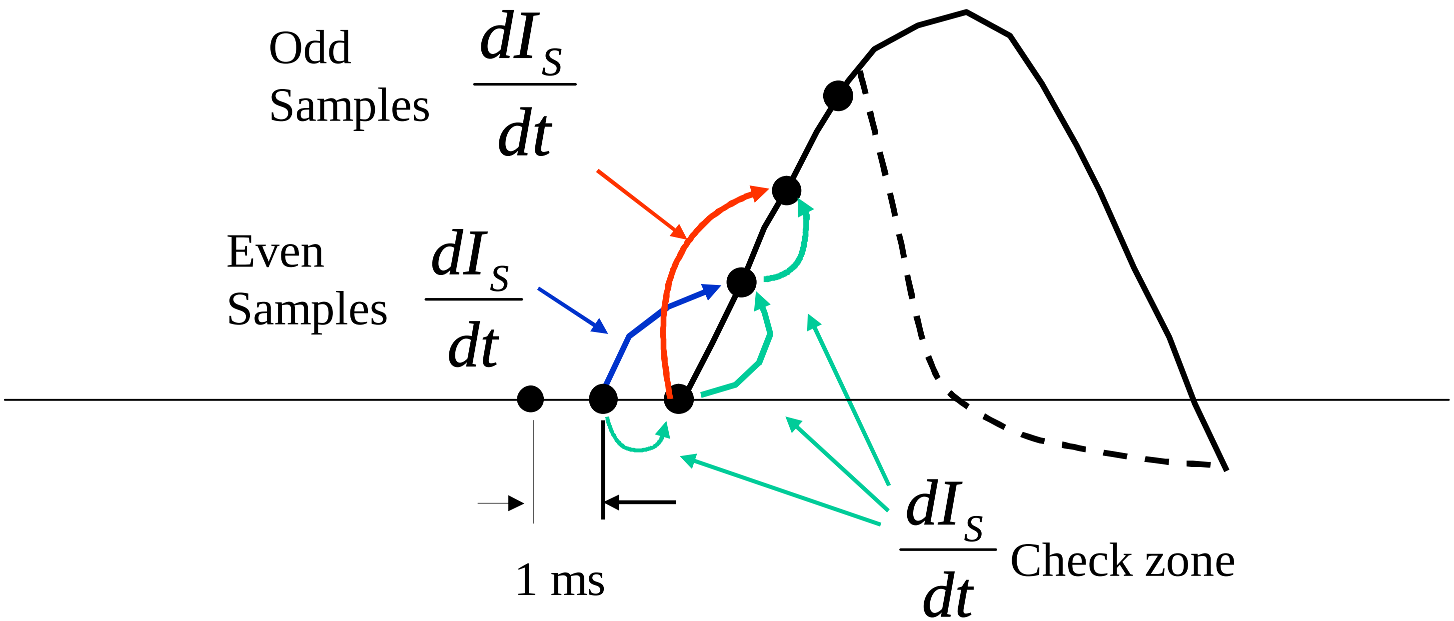
Fail safe design: 3-out-of-3 decision per bay



Adaptive measurement (Booster circuit) (7SS5)



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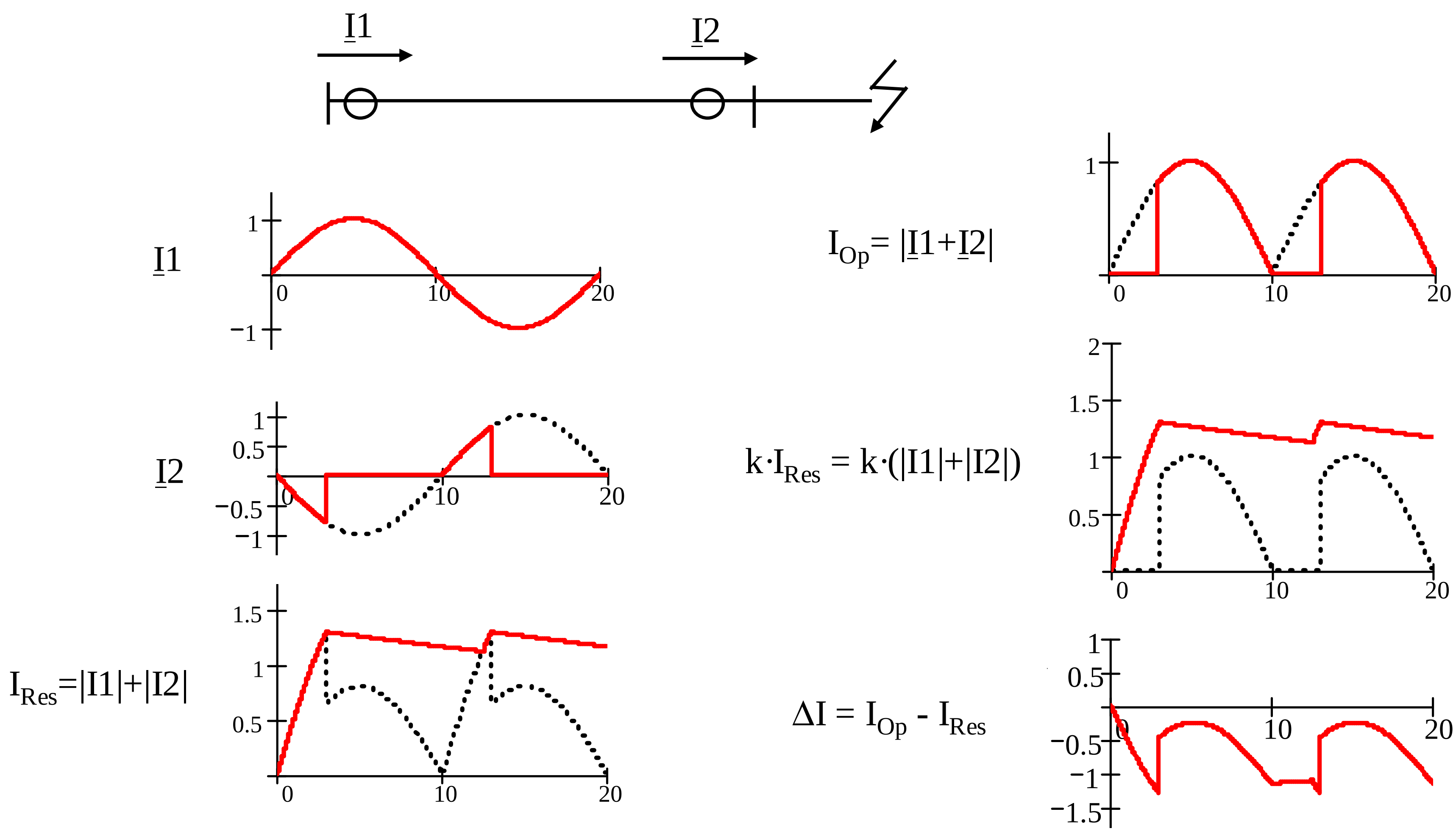
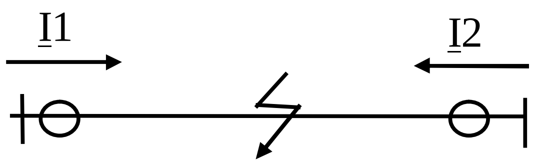
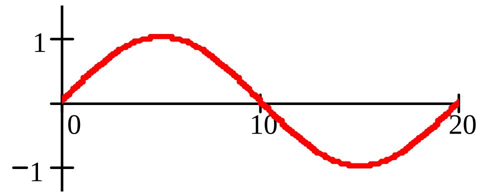
Digital busbar protection 7SS5, Measuring technique
External fault, symmetrical fault current



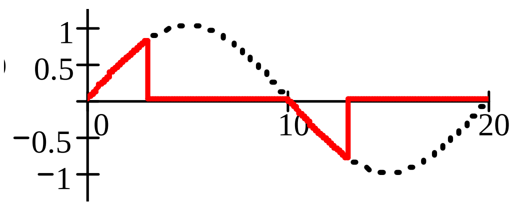
Digital busbar protection 7SS5, Measuring technique
Internal fault, symmetrical fault current



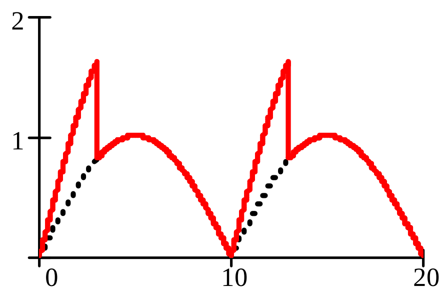
I1



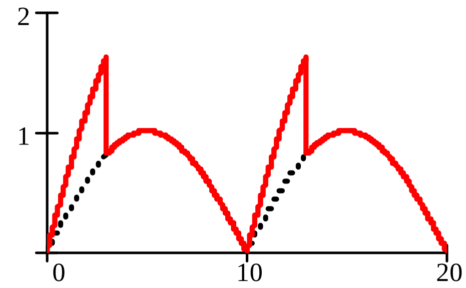
I2



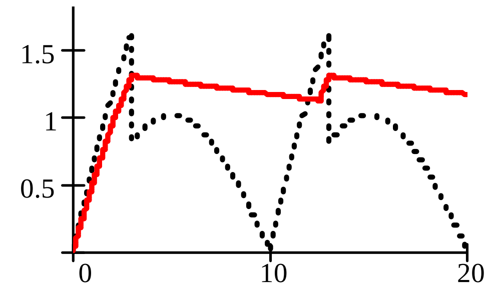
$I_{Res}=|I1|+|I2|$



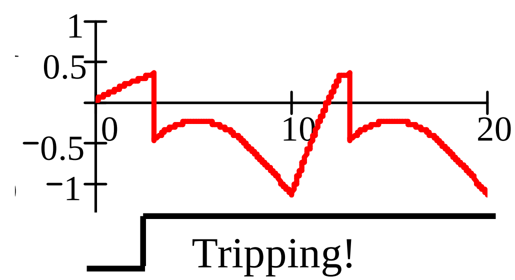
$I_{Op}= |I1+I2|$



$k \cdot I_{Res} = k \cdot (|I1|+|I2|)$



$\Delta I = I_{Op} - I_{Res}$



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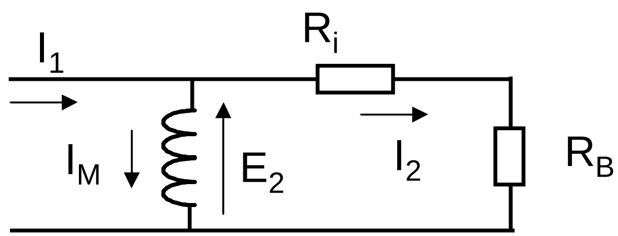
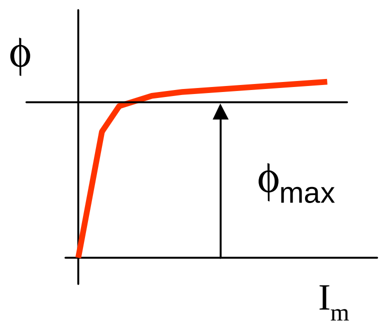
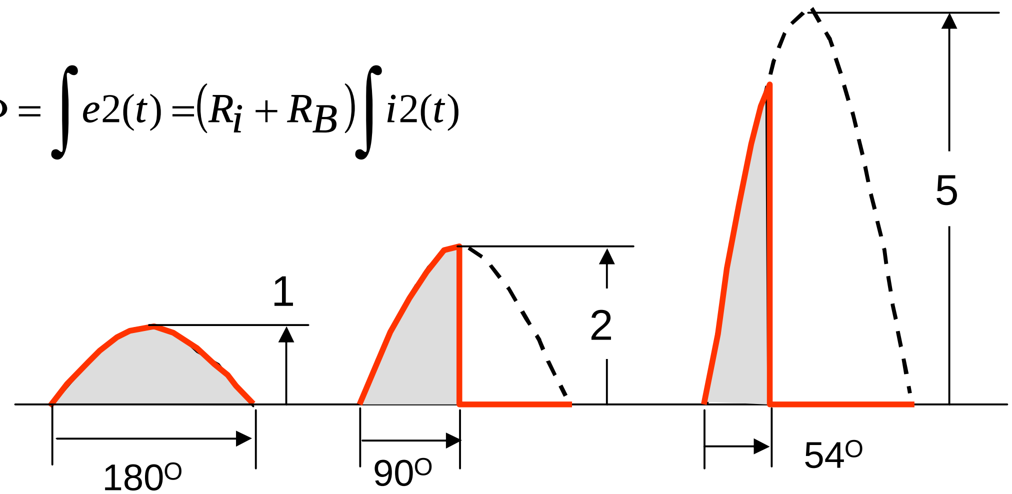
7SS5/6: Admissible over-burdening - Necessary dimensioning of CTs with regard to symmetrical fault currents



$$\Phi = \int e2(t) = (R_i + R_B)\int i2(t)$$





$$\Phi_{max} \cong \int_0^{180^O} ALF' \cdot u_{2N}(t) \cdot dt = (R_i + R_B)\int_o^{180^O} ALF' i_{2N}(t) \cdot dt = (R_i + R_B) \cdot ALF' \cdot \hat{I}_2 \cdot \int_o^{180^O} \sin x \cdot dt = (R_i + R_B) \cdot ALF' \cdot \hat{I}_{2N} \cdot 2$$

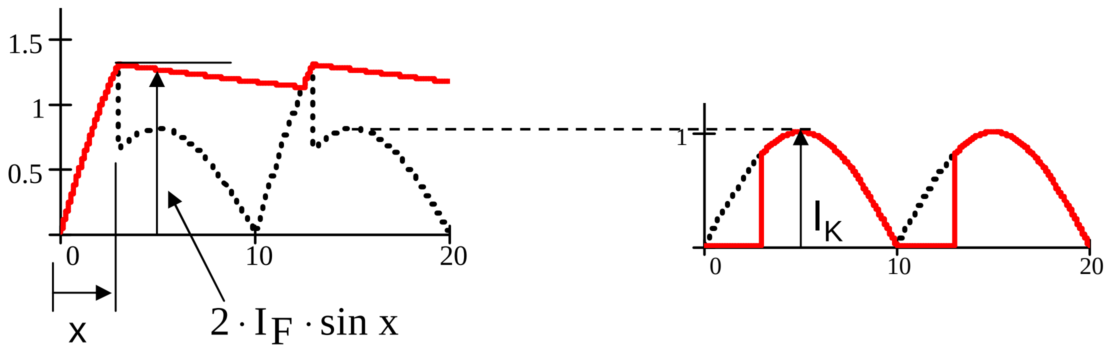
$$\hat{I}_{2F}\int_o^{x} \sin x \cdot dt = ALF' \cdot \hat{I}_{2N} \cdot \int_o^{180^O} \sin x \cdot dt = ALF' \cdot \hat{I}_{2N} \cdot 2$$

$$\frac{I_{2F}}{I_{2N}} = ALF' \cdot \frac{2}{\int_o^{x} \sin x}$$

$$k_{OB} = \frac{I_{2F}/I_{2N}}{ALF'} = \frac{2}{\int_o^{x} \sin x}$$

Required restraining factor k dependent on over-burdening factor K_{OB} (over-dimensioning factor K_{TF})

$I_{Res} = |I1|+|I2|$



$I_{Op} = |\underline{I}1+\underline{I}2|$

Condition for stability: $I_{Op} < k \cdot I_{Res}$ $\qquad I_F < k \cdot 2 \cdot I_F \cdot \sin x$ (1)

(1') $\sin x > \dfrac{1}{2 \cdot k}$

(2) $\ddot{u} = \dfrac{I_{2K}/I_{2N}}{n'} = \dfrac{2}{\int_o^x \sin x} = \dfrac{2}{1-\cos x}$

from previous transparency)

$$k > \frac{K_{OB}}{4 \cdot \sqrt{K_{OB} - 1}} \quad \text{or} \quad k > \frac{1}{4 \cdot \sqrt{K_{TF} - K^2_{TF}}}$$

K_{OB}= CT over-burdening factor

K_{TF}= 1/K_{OB} = CT over-dimensioning factor

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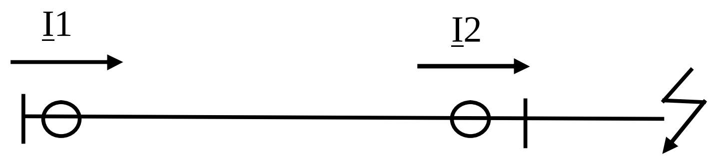
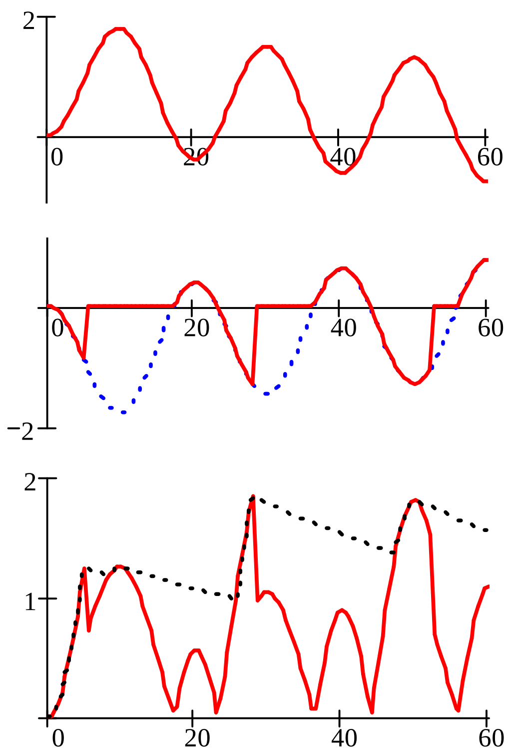
Digital busbar protection 7SS5, Measuring technique
External fault, fault current with DC offset



$\underline{I}1$

$\underline{I}2$

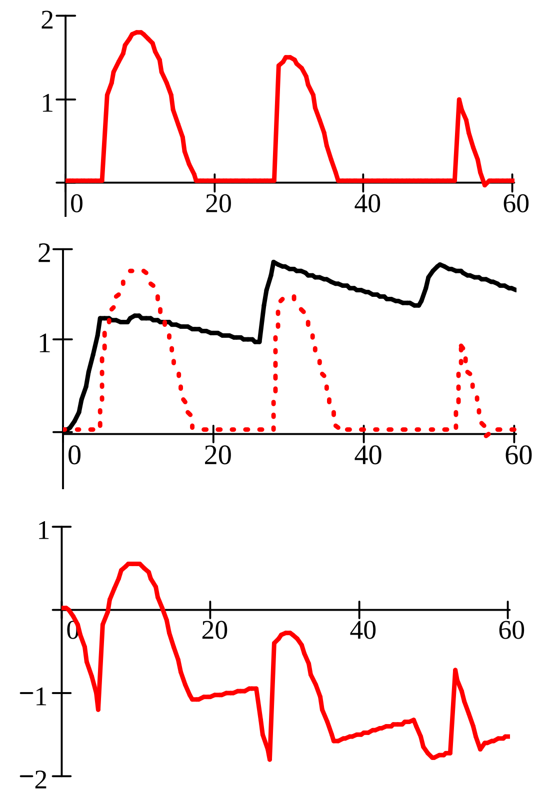
$I_{Res}=|I1|+|I2|$



$I_{Op}= |\underline{I}1+\underline{I}2|$

$k \cdot I_{Res} = k \cdot (|I1|+|I2|)$

$\Delta I = I_{Op} - I_{Res}$



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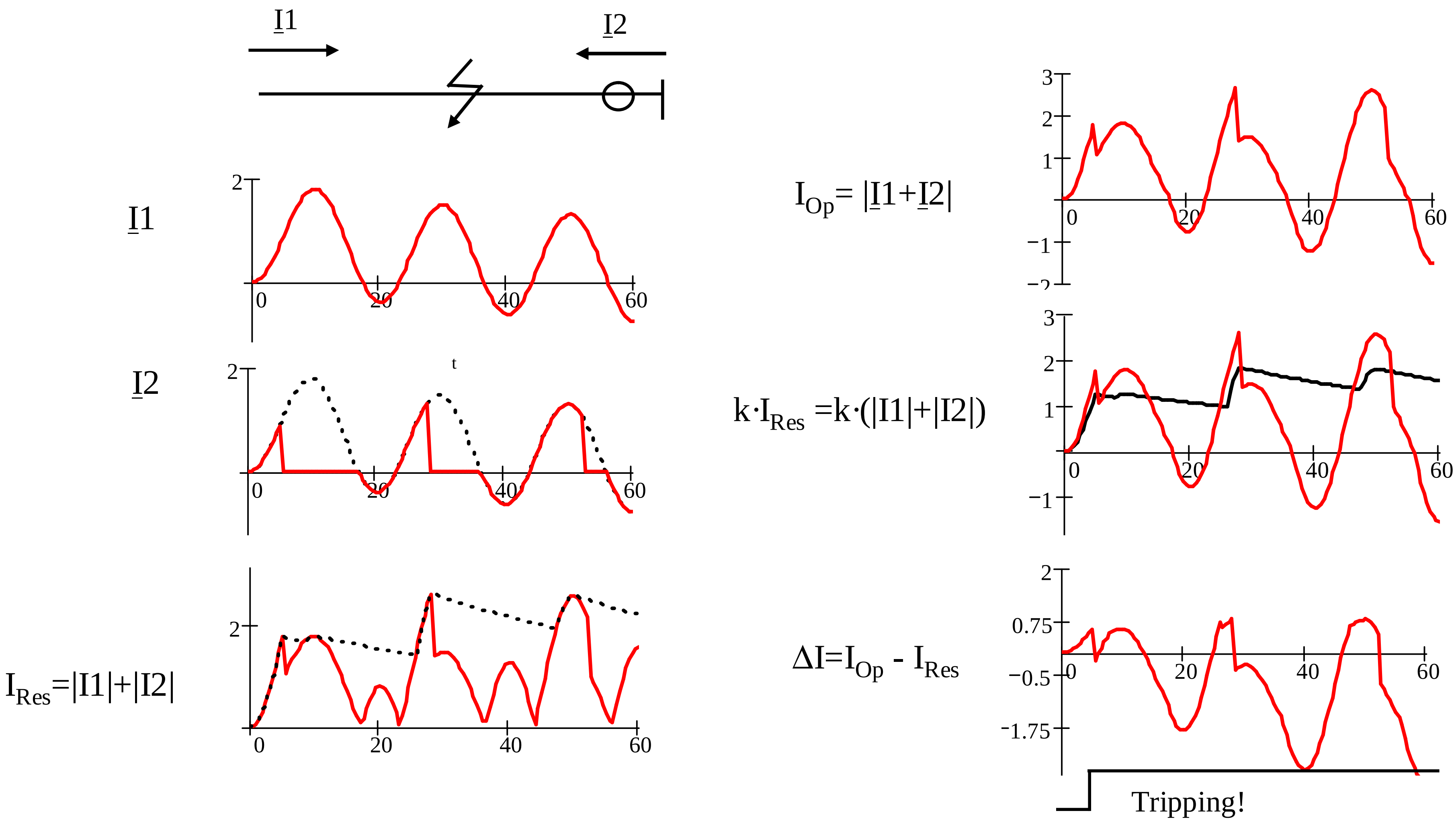
Digital busbar protection 7SS5, Measuring technique
Internal fault, fault current with DC offset



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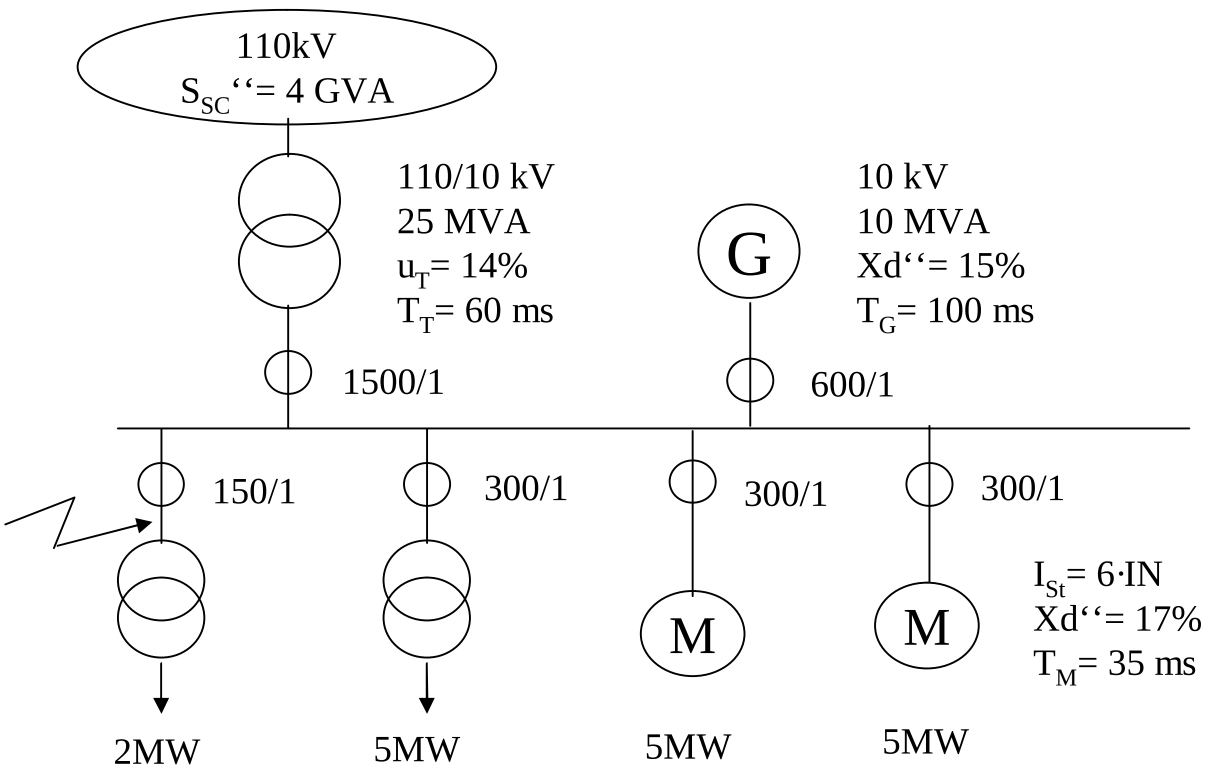
CT dimensioning for busbar protection 7SS5, Example (1)



$$I_{N-T} = \frac{25 \cdot 10^6}{10 \cdot 10^3 \cdot \sqrt{3}} = 1440A$$

$$I_{N-G} = \frac{10 \cdot 10^6}{10 \cdot 10^3 \cdot \sqrt{3}} = 577A$$

$$\Sigma I_{N-M\text{-}HV} = 2 \cdot \frac{5 \cdot 10^6}{10 \cdot 10^3 \cdot \sqrt{3}} = 577A$$

$$I_{F-T} = \frac{1.1 \cdot 1440}{0.14} = 11.3 \text{ kA}$$

$$I_{F-G} = \frac{1.1 \cdot 577}{0.15} = 4.2 \text{ kA}$$

$$\Sigma I_{F-M} = \frac{1.1 \cdot 577}{0.17} = 3.7 \text{ kA}$$

CT dimensioning for busbar protection 7SS5 and 7SS6, Example (2)

As worst case, the CT 150/1 A in bay 1 is considered.

Total fault current with a fault at the transformer HV terminals:

$$\Sigma I_F = I_{F-T} + I_{F-G} + \Sigma I_{F-M} = 11{,}3 + 4{,}2 + 3{,}7 = 19{,}2 \text{ kA}$$

Equivalent time constant:

$$T_{Equiv.} = \frac{I_{F-T} \cdot T_T + I_{F-G} \cdot T_G + \Sigma I_{F-M} \cdot T_M}{I_{F-T} + I_{F-G} + \Sigma I_{F-M}} = \frac{11.3 \cdot 60 + 4.2 \cdot 100 + 3.7 \cdot 35}{11.3 + 4.2 + 3.7} = 64 \text{ ms}$$

We consider a CT type 5P?, 30 VA, internal burden Pi= 15% (4.5 VA):

Connected burden Pa= 1 VA
CT over-dimensioning factor for 3ms saturation free time: K_{TF} ca. 0.45
Corresponding to an overburdening factor of $k_{OB} = 1/K_{TF} = 2.2$

Checking of the k-setting
(Stability with symmetrical fault currents):

$$k > \frac{k_{OB}}{4 \cdot \sqrt{k_{OB} - 1}} = \frac{2{,}2}{4 \cdot (2.2 - 1)} = 0.5 \quad \text{(chosen: k=0.6)}$$

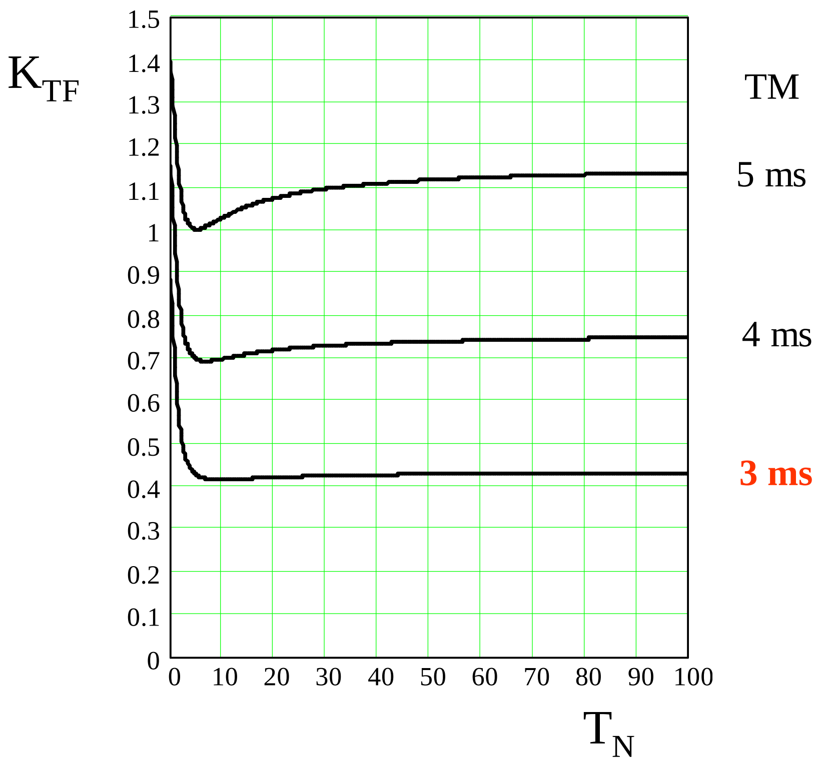
$$ALF' = \frac{\Sigma I_F}{I_{N-CT}} \cdot K_{TF} = \frac{19.200}{150} \cdot 0.45 = 58$$

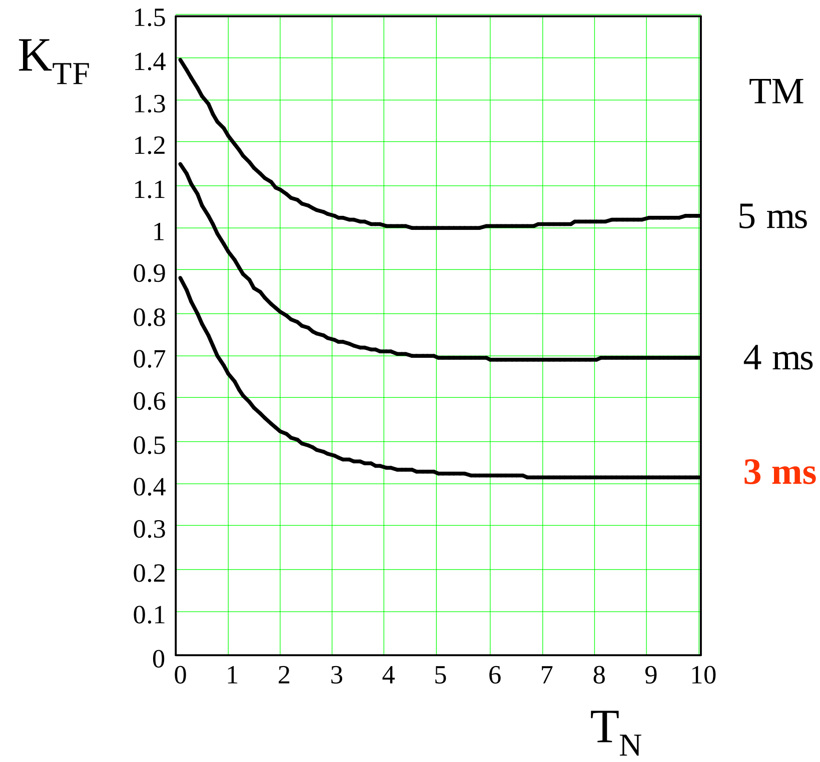
$$ALF = \frac{P_a + P_i}{P_N + Pi} \cdot ALF' = \frac{1 + 4.5}{30 + 4.5} \cdot 58 = 9.3$$

We finally choose: CT 5P10, 150/1, 30 VA, R2≤ 4.5 Ohm

Transient performance of iron closed CT cores (type TPX)

Over-dimensioning factor K_{TF} for short time to saturation





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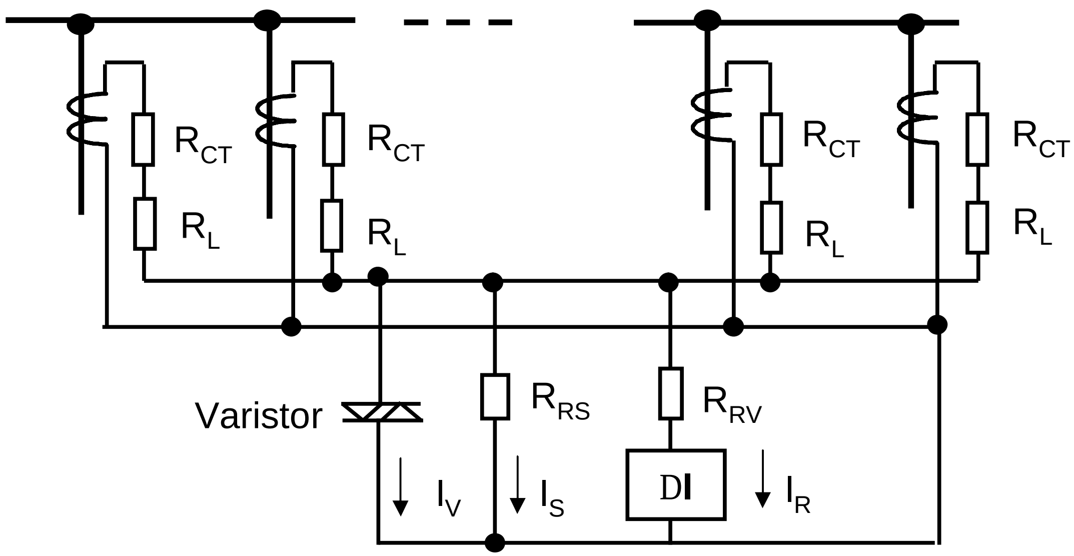
High impedance busbar protection



R_{CT}: Resistance of CT secondary winding

R_L: Connection cable resistance

R_{RV}: Relay series resistance

R_{RS}: Relay shunt resistance

HI busbar protection, calculation example

Given: :n = 8 feeders

r_{CT} = 600/1 A

U_{KN} = 500 V

R_{CT} = 4 Ohm

I_{mR} = 30 mA (at relay pick-up voltage)

R_L= 3 Ohm (max.)

I_R=20 mA (fixed value)

R_{RV} = 10 kOhm

R_{RS} = 250 Ohm

I_v = 50 mA (at relay pick-up voltage)

Primary pick-up current:

$$I_{F-min} = r_{CT} \cdot (I_R + I_S + I_V + n \cdot I_{mR})$$

$$I_{F-min} = \frac{600}{1} \cdot (0.02 + 0.89 + 0.05 + 8 \cdot 0.03)$$

$$I_{F-min} = 666A \cdot (111\% I_{N-CT})$$

Stability with external faults:

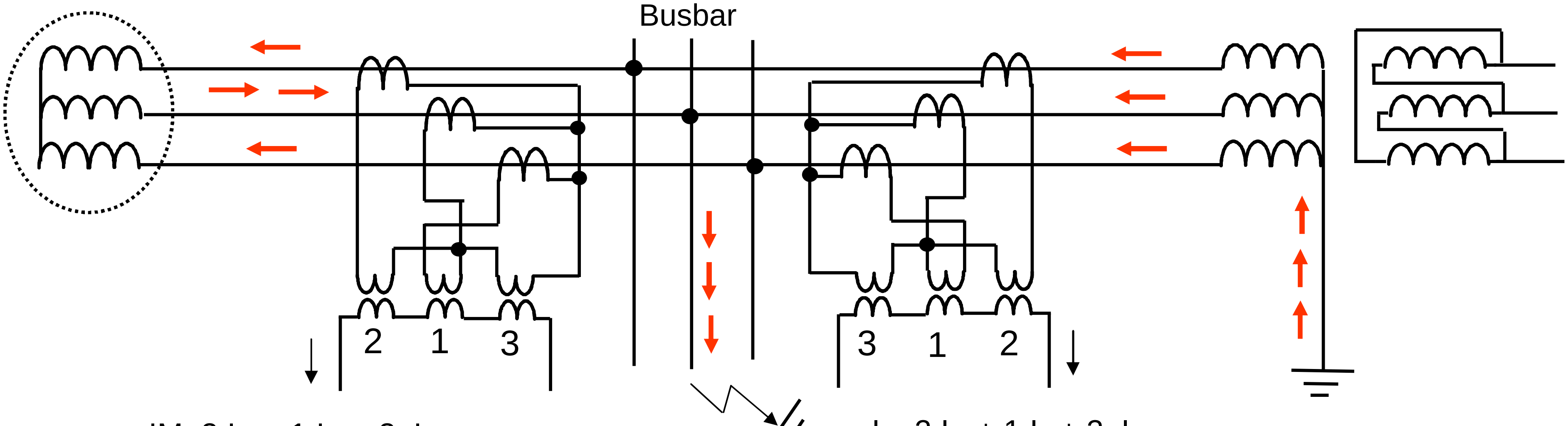
$$I_{F-through-max} < r_{CT} \cdot \frac{R_R}{R_L + R_{CT}} \cdot I_R$$

$$I_{F-through-max} < \frac{600}{1} \cdot \frac{10.000}{3+4} \cdot 0.02$$

$$I_{F-through-max} < 17\ kA = 28 \cdot I_n$$

Busbar protection, Composite current type (7SS600):

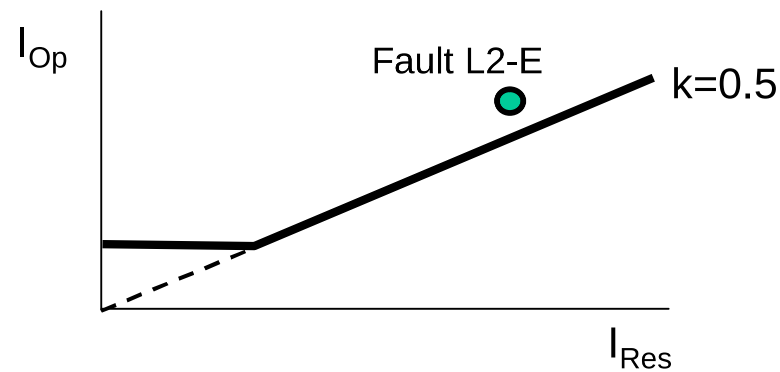
Performance under unfavourable system earthing conditions



$I_M = 2 \cdot I_{L1} + 1 \cdot I_{L3} + 3 \cdot I_E$
$= 2 \cdot (-I_F) + 1 \cdot (-I_F) + 3 \cdot 0 = -3 \cdot I_F$

$I_M = 2 \cdot I_{L1} + 1 \cdot I_{L3} + 3 \cdot I_E$
$= 2 \cdot I_F + 1 \cdot I_F + 3 \cdot 3 I_F = +12 \cdot I_F$

$I_{Op} = | I_{M1} + I_{M2} | = 9 \cdot I_F$
$I_{Res} = |I_{M1}| + |I_{M2}| = 15 \cdot I_F$
} k=9/15 = 0.6



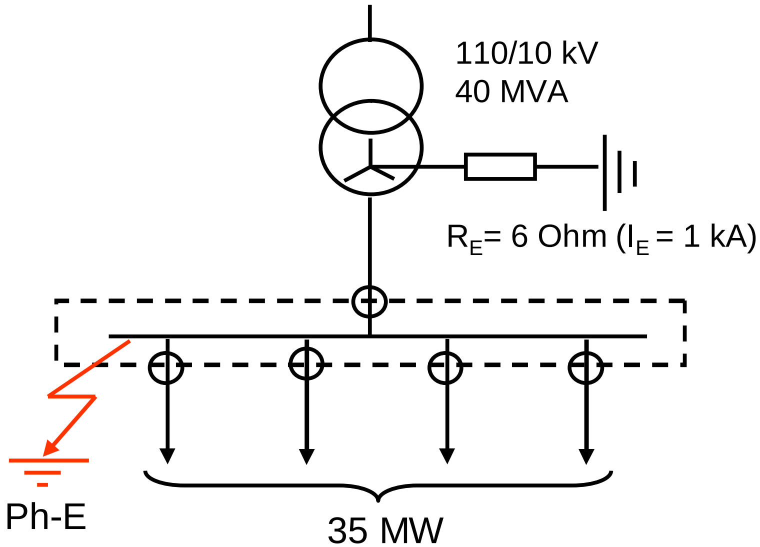
Faults in other phases:

Fault L1-E: $I_{Op} = (3+12) \cdot I_F = 15 \cdot I_F$,
$I_{Res} = (3+12) \cdot I_F = 15 \cdot I_F$,
} k=1

Fault L3-E: $I_{Op} = (0+12) \cdot I_F = 12 \cdot I_F$,
$I_{Res} = (0+12) \cdot I_F = 12 \cdot I_F$,
} k=1

Busbar protection, Composite current type (7SS600):

Performance in networks with earth current limitation



$$I_L = \frac{35\text{MVA}}{10\text{kV}\cdot\sqrt{3}} = 2\ \text{kA}$$

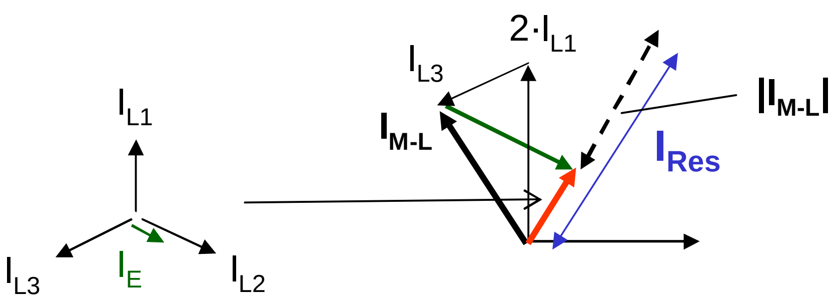
$$I_F = I_E = 10/\sqrt{3}\text{kV}/6\Omega \approx 1\ \text{kA}$$

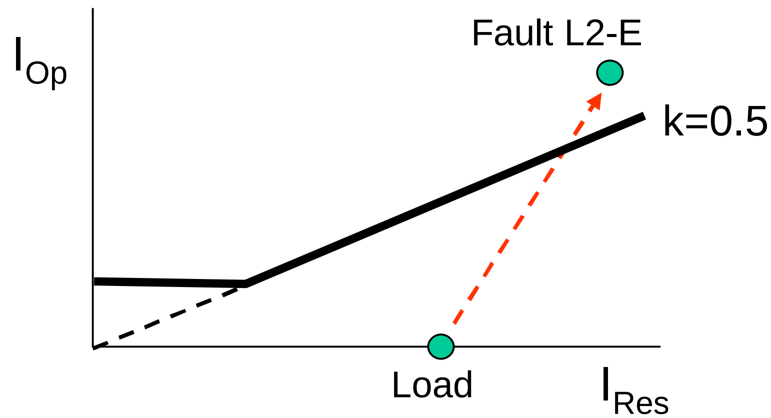
Worst case: Fault in phase L2

Restraint current: $I_{Res} = 3\cdot\sqrt{3}\ \text{kA}$

Operating current: $I_{Op} = 3\cdot\left|\underline{I}_{KE}\right| = 3\ kA$

$$k = \frac{I_{Op}}{I_{Res}} = \frac{3}{3\cdot\sqrt{3}} = 0{,}57$$





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Differential Protection 7UT6

Remarkable Features

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The 7UT6 Family

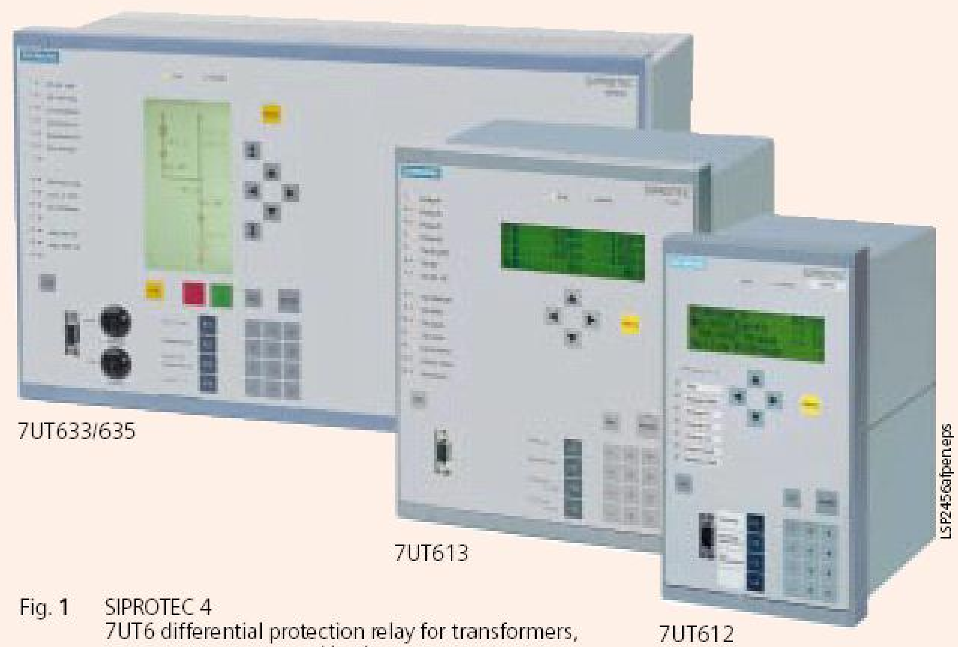

Fig. 1 SIPROTEC 4
7UT6 differential protection relay for transformers, generators, motors and busbars

7UT6 differential protection for

- Transformers
- Generators
- Motors
- Busbars

7UT612: for protection objects with 2 ends (1/3 x 19" case 7XP20)
7UT613: for protection objects with 3 ends (1/2 x 19" case 7XP20)
7UT633: for protection objects with 3 ends (1/1 x 19" case 7XP20)
7UT635: for protection objects with 5 ends (1/1 x 19" case 7XP20)

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7UT6: Hardware options

Relay version	7UT612	7UT613	7UT633	7UT635
current inputs (normal)	7 (7)[1]	11 (6) [1]	11 (6) [1]	14 (12 [1])
(sensitive)	1	1 [2]	1 [2]	2 [2]
voltage inputs (Uph / UE)	---	3 / 1	3 / 1	---
Binary inputs	3	5	21	29
Output contacts	4	8	24	24
Life contact	1	1	1	1
LC Display	4 rows[3]	4 rows[3]	Graphic	Graphic

[1] 1A, 5A, (1A, 5A, 0.1A)

[2] link selectable normal/sensitive

[3] alpha-numeric

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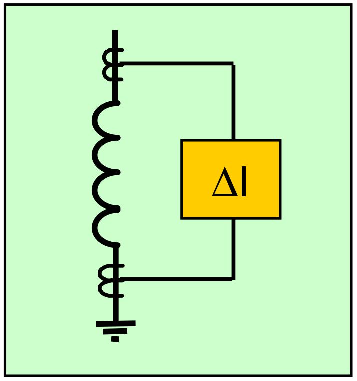
7UT6: Scope of functions

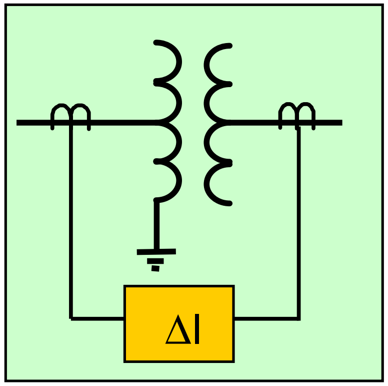
Function	ANSI No.
Differential	87T/G/M/L
Earth differential	87 N
Phase overcurrent,	50/51
Neutral overcurrent I_N>, t	50N/51N
Ground overcurrent (I_E, t)	50G/51G
Unbalanced current I_2>, t	46
Thermal overload IEC 60255-8	49
Therm. OL IEC 60354 (hot spot)	49

Function	ANSI No.
Overfluxing V/Hz	24
Breaker failure	50BF
Temperature monitoring	38
Hand reset trip	86
Trip circuit supervision	74TC
Binary inputs for tripping commands	

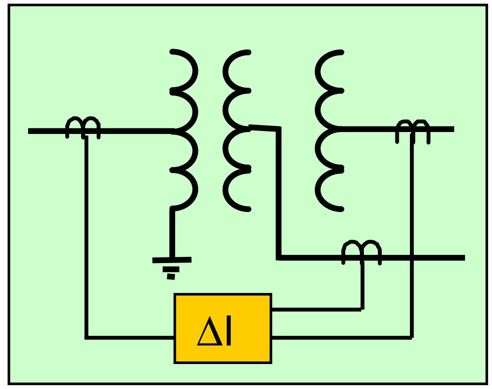
7UT6: Application (1)



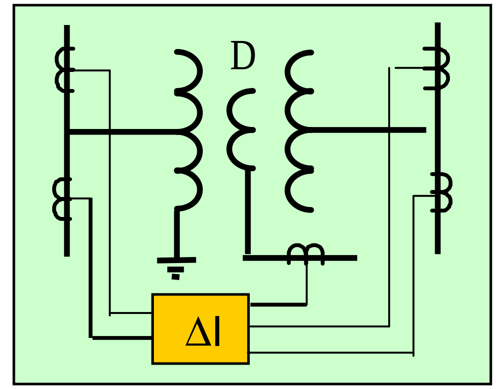
Shunt Reactor



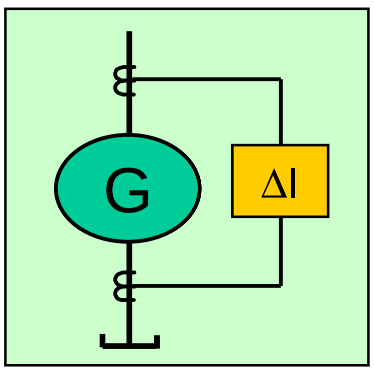
Two winding transformer



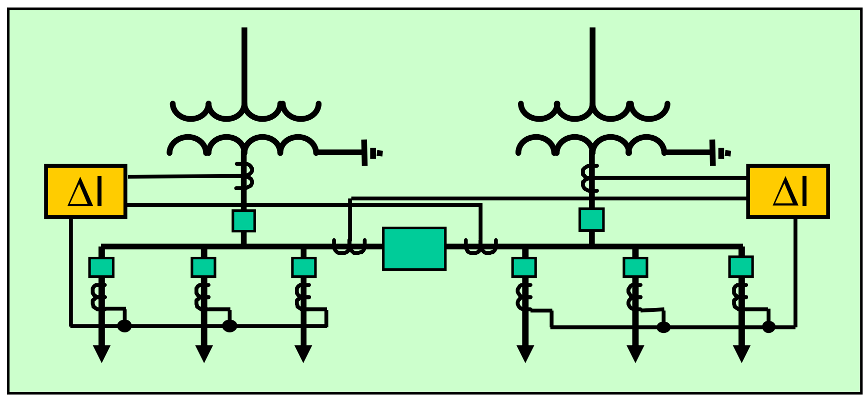
Three winding transformer



Transformer bank (1-1/2-LS)



Generator / Motor



Busbars

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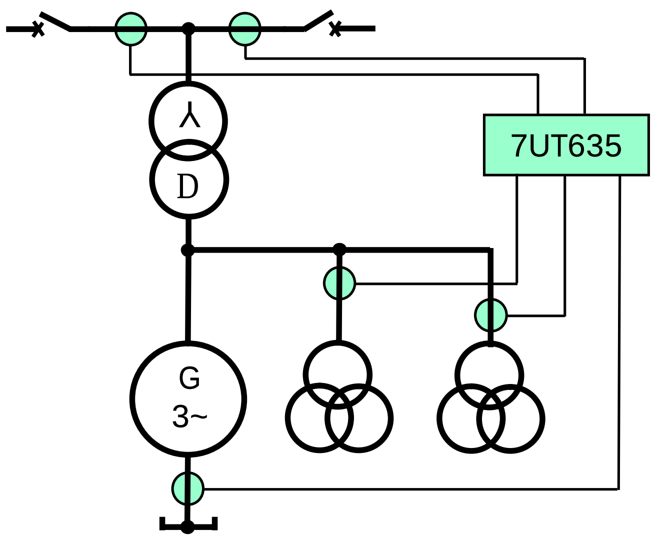
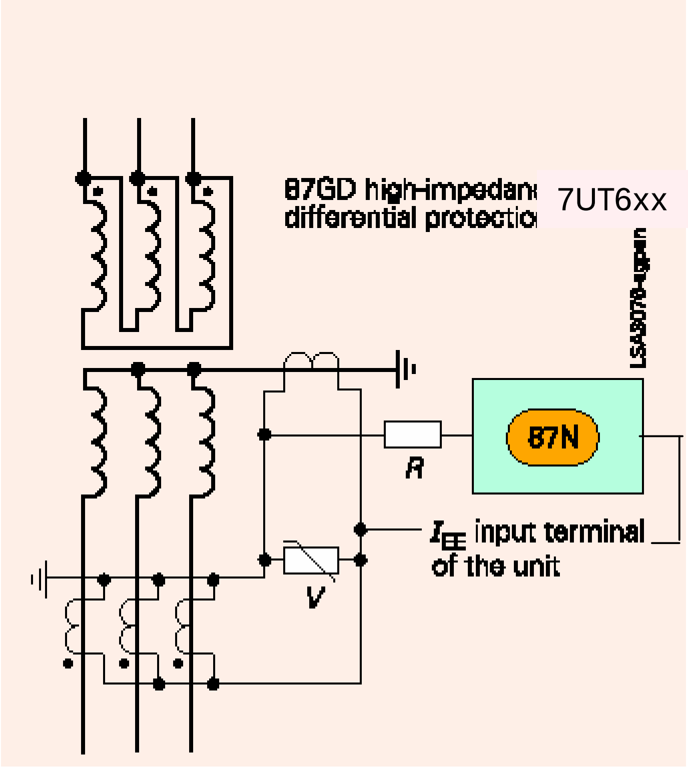
7UT6: Application (2)

Generation Unit protection (overall differential)



HI restricted earth fault protection



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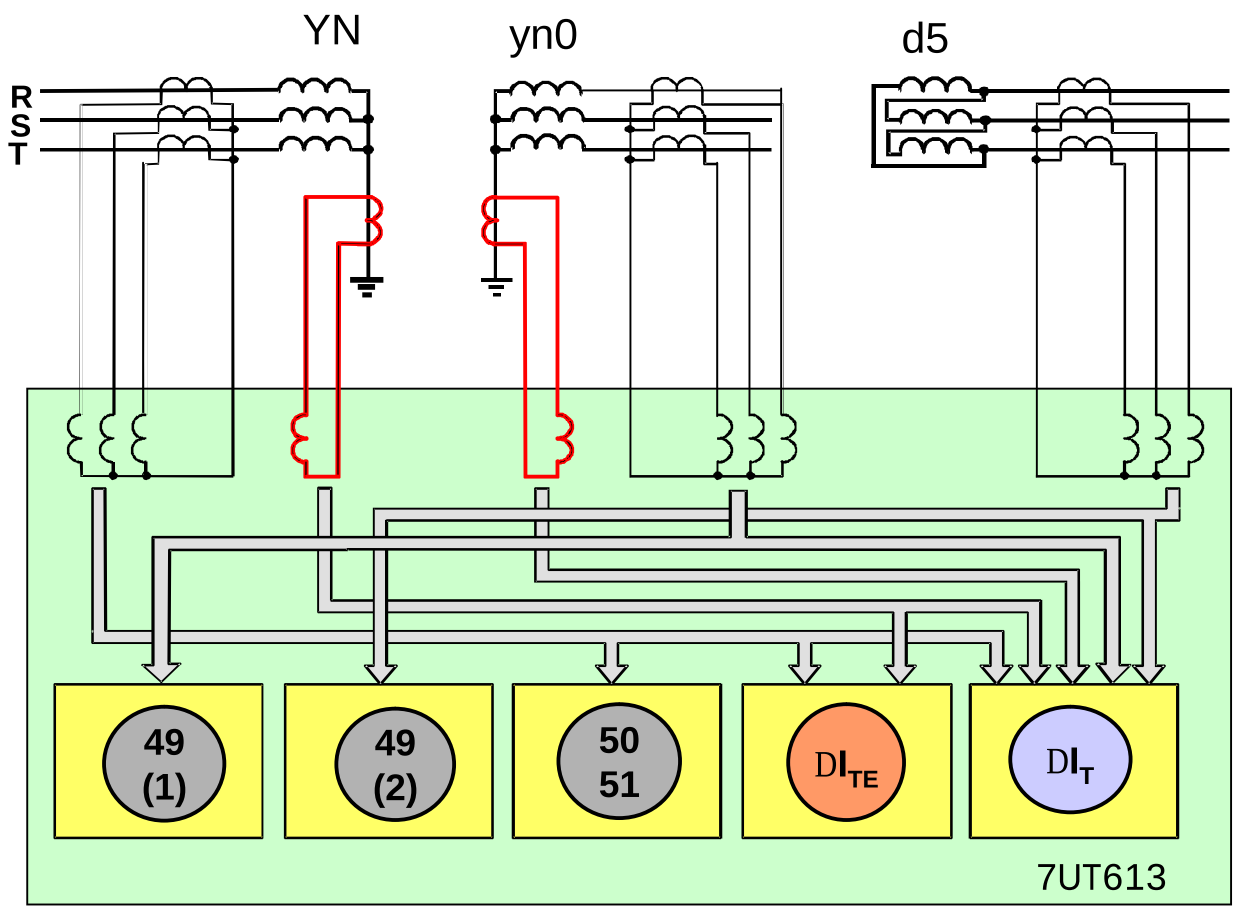
7UT6:

selectable: I_0-correction or restricted earth fault protection



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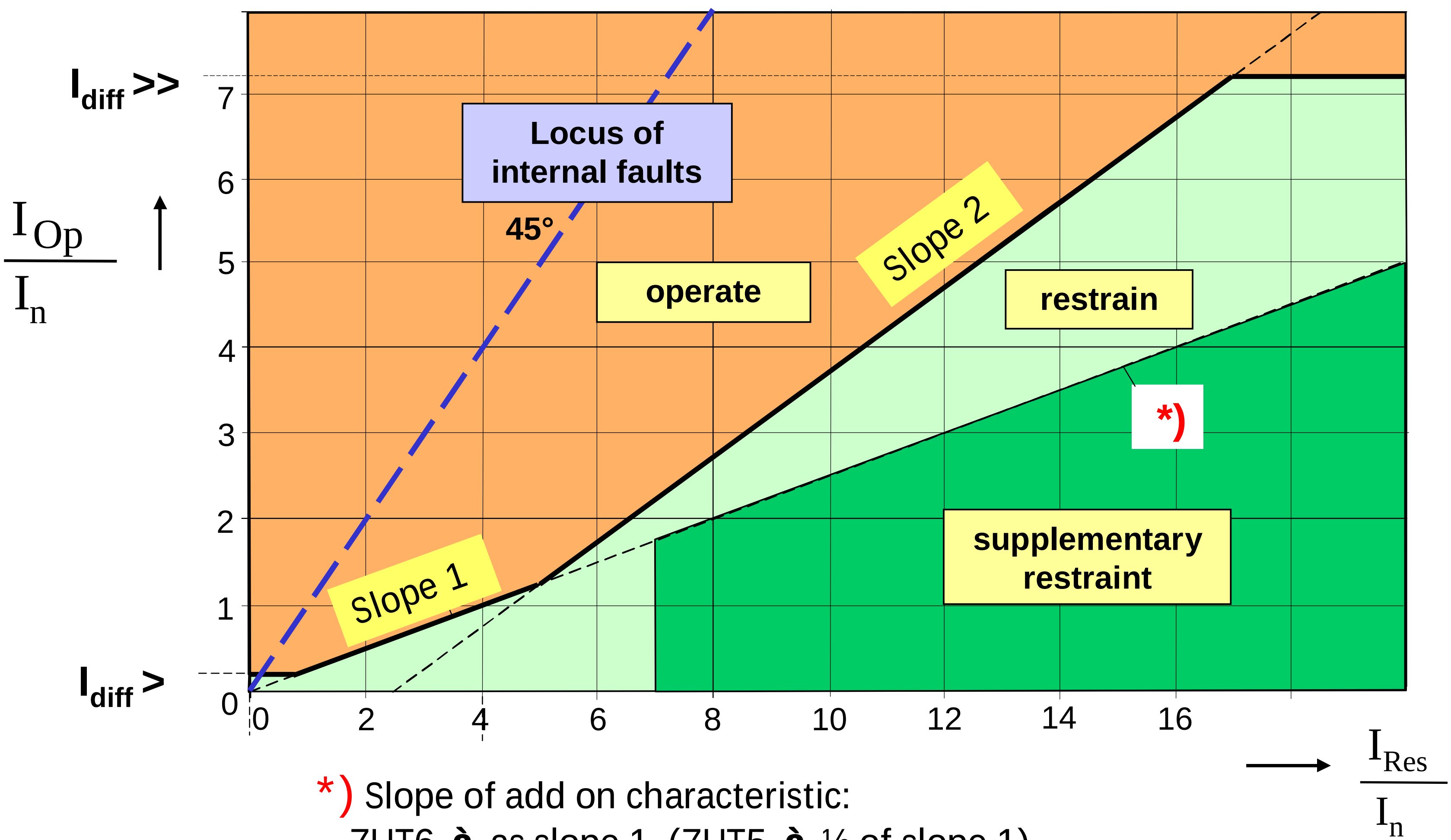
7UT6: operating characteristic



*) Slope of add on characteristic:
7UT6 à as slope 1 (7UT5 à ½ of slope 1)

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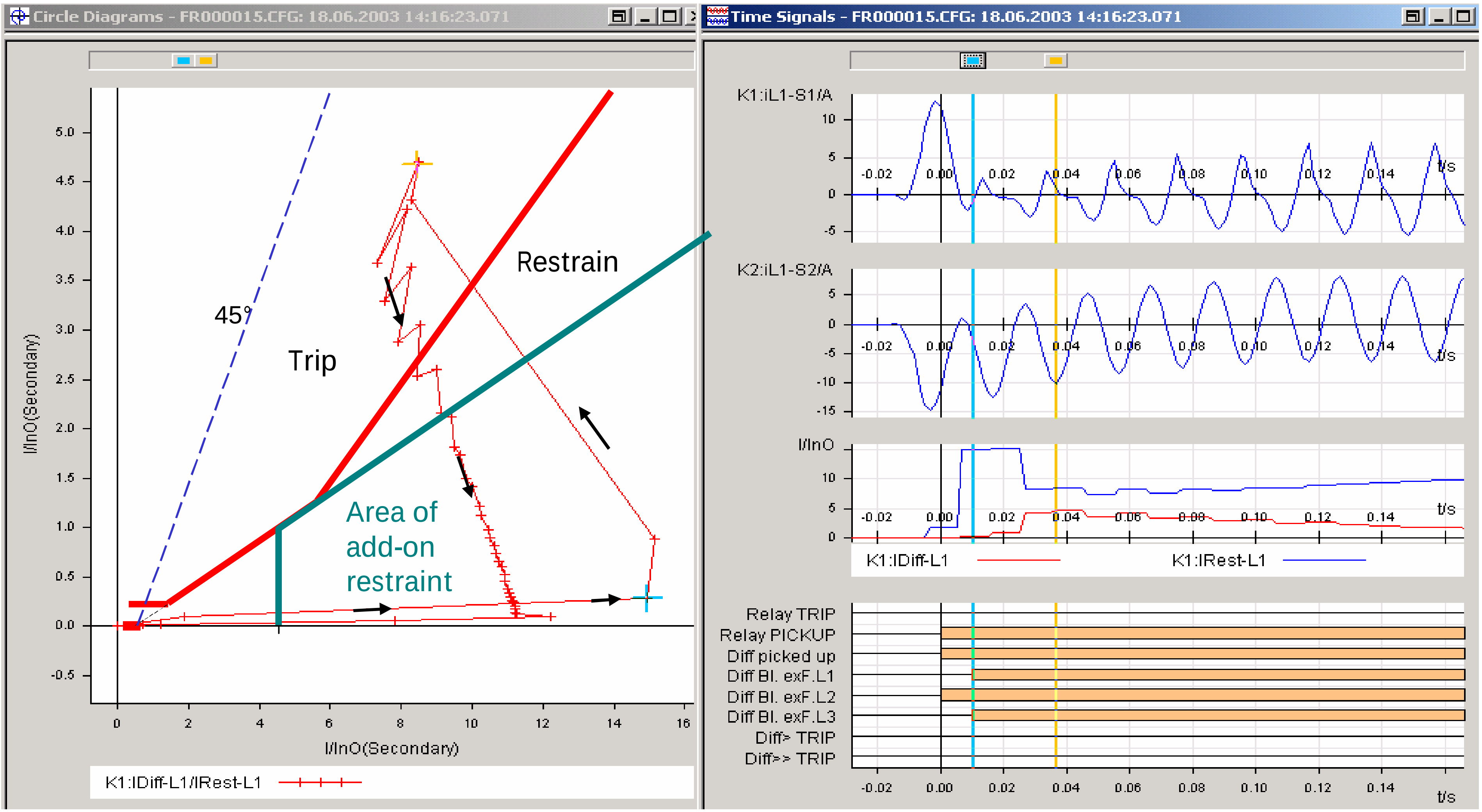
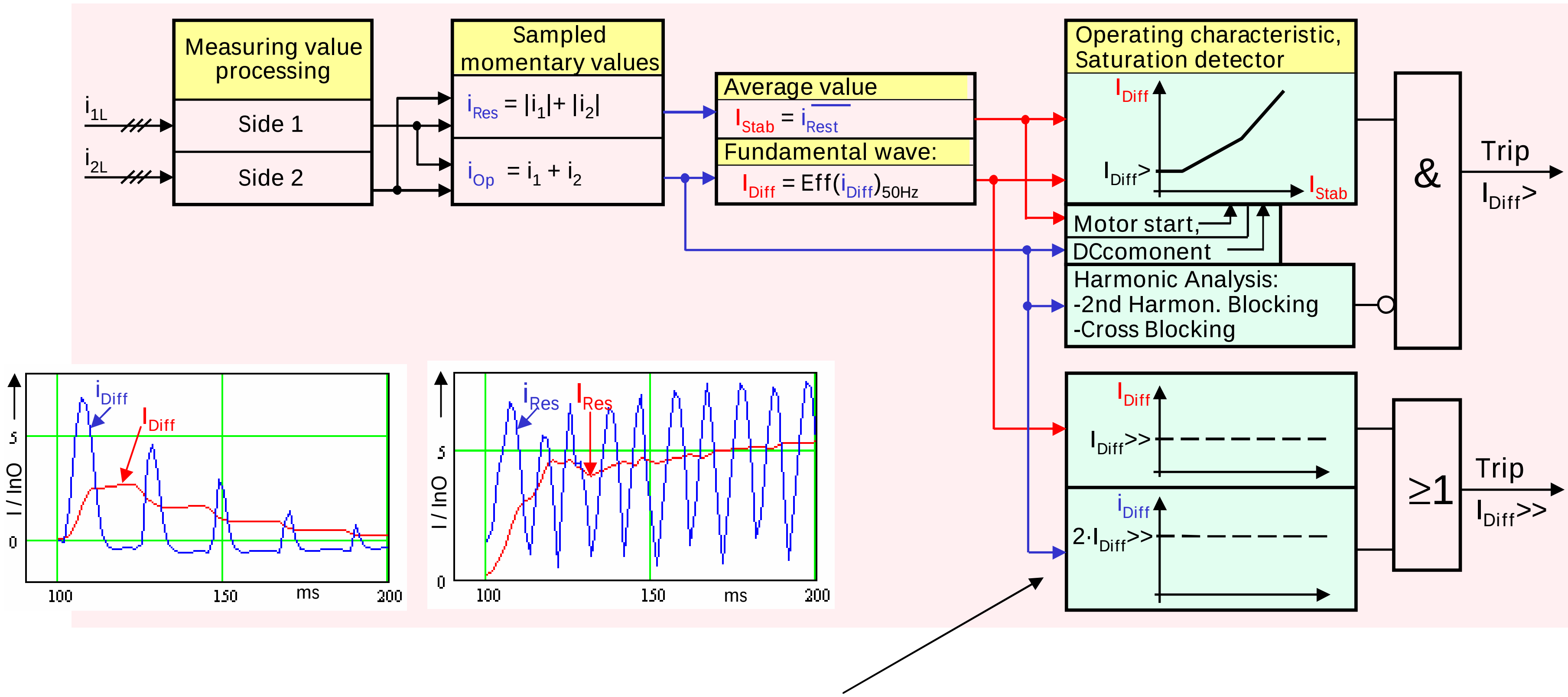
7UT6: Effect of supplementary restraint in case of CT saturation

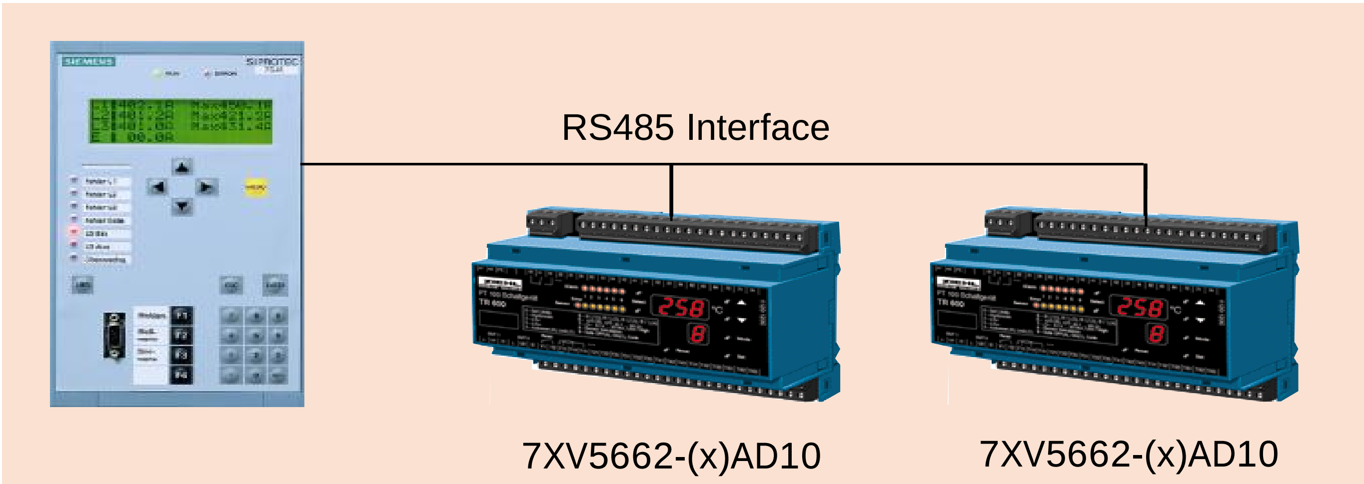


Differential protection functions $I_{Diff}>$ and $I_{Diff}>>$



Fast tripping using sampled momentary values
ensures dependable operation in case of extreme CT saturation!

7SA6: Temperature monitoring



- Two thermo-devices can be connected to the serial service interface (RS485)
- Monitoring of up to 12 measuring points (6 per thermo-device)
  - each with two pick-up levels
- Display of the measured temperatures
  - directly at the thermo-device (which can also be used stand alone)
  - at the relay
- One input is reserved for hot spot monitoring (measurement of oil temperature)
- Thermistors: Pt100, Ni100 or Ni120

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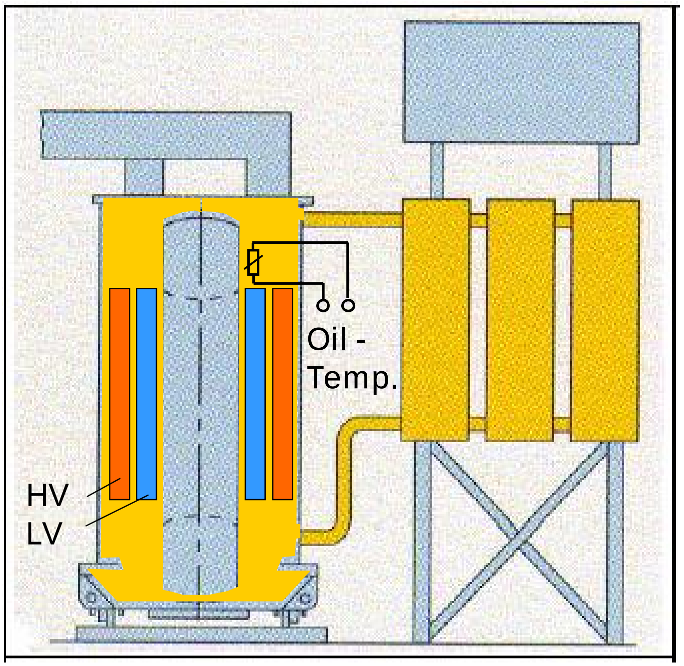
7UT6: Temperature monitoring with hot spot calculation (1)

Example: Natural cooling



$$\Theta_h = \Theta_O + H_{gr} \cdot k^Y$$

Θh= hot spot temperature

Θh= oil temperature

H_{gr}=hot-spot-to-oil temperature gradient

k= load factor I/In

Y= winding exponent

Aging rate:

$$V = \frac{\text{Aging at } \Theta_h}{\text{Aging at } 98°C} = 2^{(\Theta_h - 98)/6}$$

98^O is reference for the aging of Cellulose insulation

Mean value of aging during a fixed time interval:

$$L = \frac{1}{T_2 - T_1} \cdot \int_{T_1}^{T_2} V \cdot dt$$

7UT6: Temperature monitoring with hot spot calculation (1)

Example: Natural cooling

Thermal Meter - 22.09.2003 - Differential 7UT61 / 7UT612 / 7UT...

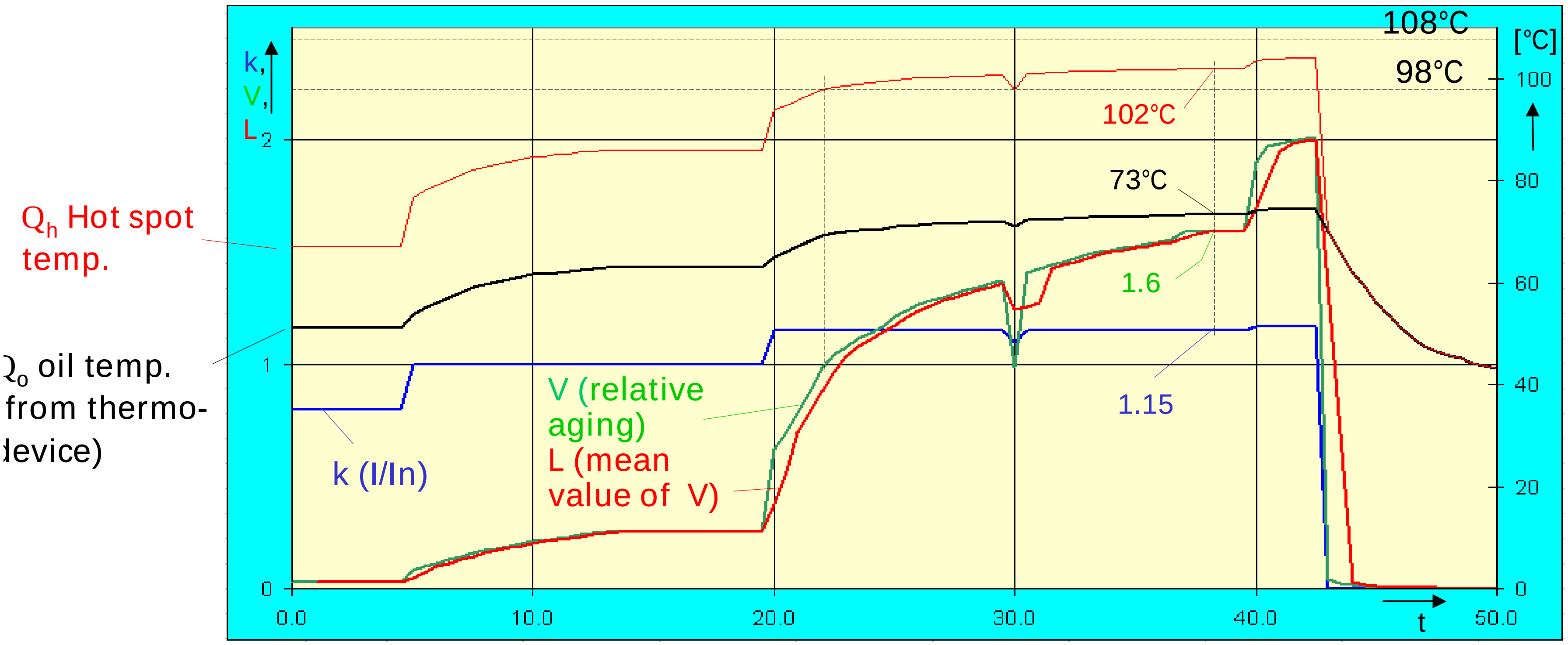
Number	Measured value	Value
01060	Hot spot temperature of leg 1	102 °C
01061	Hot spot temperature of leg 2	102 °C
01062	Hot spot temperature of leg 3	102 °C
01063	Aging Rate (L)	1.6
01066	Load Reserve to warning level	-10 %
01067	Load Reserve to alarm level	5 %

RTD-Box Measuring Values - 22.09.2003 - Differential 7UT61 / 7UT...

Number	Measured value	Value
01068	Temperature of RTD 1	73 °C

$$\Theta_h = \Theta_o + H_{gr} \cdot k^Y \approx 73 + 23 \cdot 1.15^{1.6} = 102°C$$

$$V = 2^{(\Theta_h - 98)/6} = 2^{(102-98)/6} \approx 1.6$$



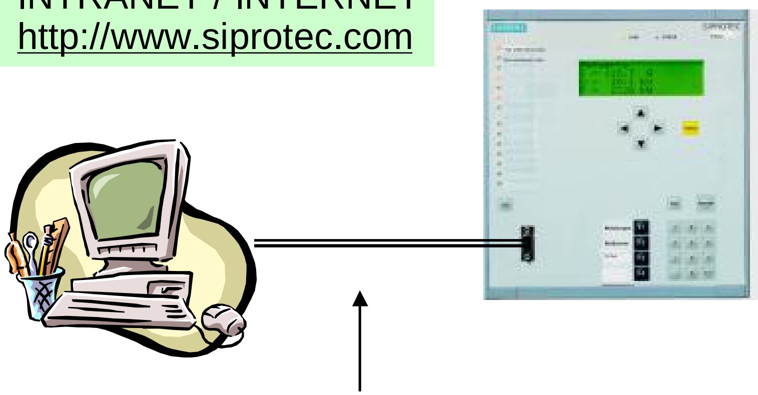
7UT6: Commissioning und service tool (1)

WEB-Technology

IBS-Tool

Help system in the
INTRANET / INTERNET
http://www.siprotec.com

Access to WEB Browser



Relay homepage address of :
http://141.141.255.160
IP-address can be set with program DIGSI 4 at the front or service interface of the relay

WEB server
in relay firmware

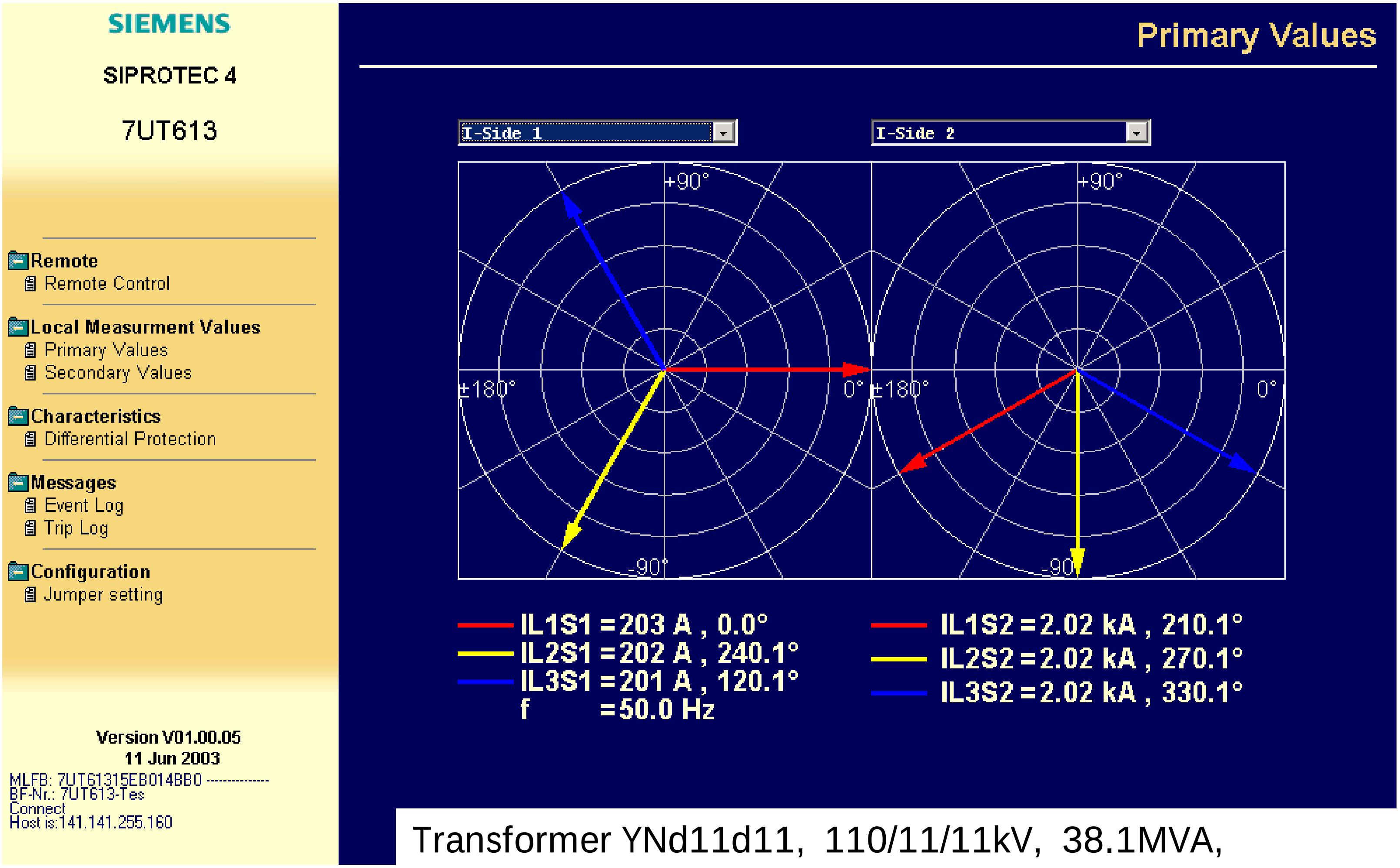
Server sends HTML pages and JAVA code to WEB Browser via DIAL-UP connection

1. Serial connection
Directy or with modem to standard DIAL-UP network

2. HTM L page view
at IP-address of the relay
http://141.141.255.160

7UT6: Commissioning and service tool (2)

Current phasors of all terminals can be displayed

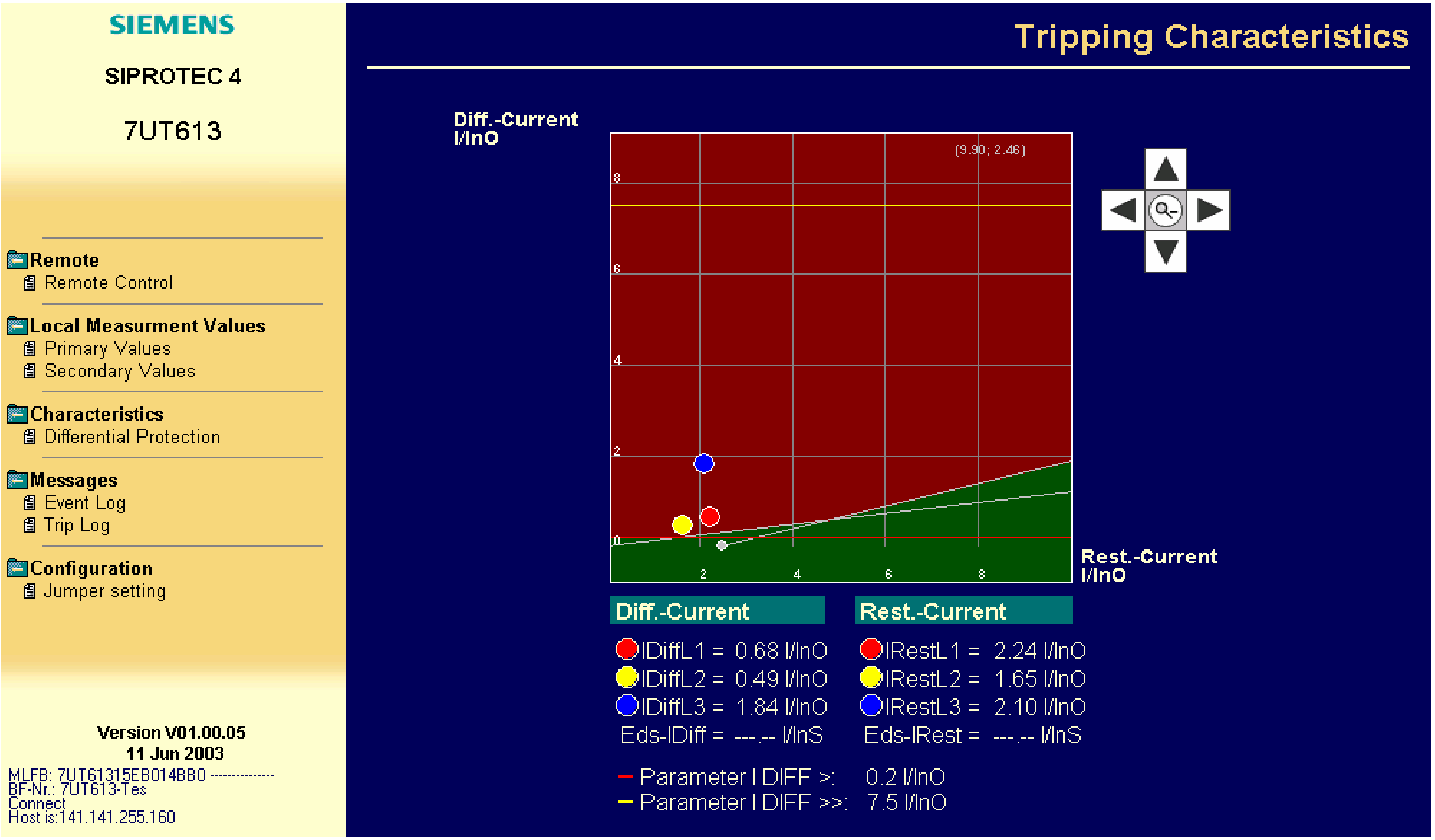


Transformer YNd11d11, 110/11/11kV, 38.1MVA,

IL2S2 à wrong polarity

7UT6: Commissioning and service tool (3)

Operating/restraint position can be displayed



Transformer YNd11d11, 110/11/11kV, 38.1MVA, IL2S2 à wrong Polarität

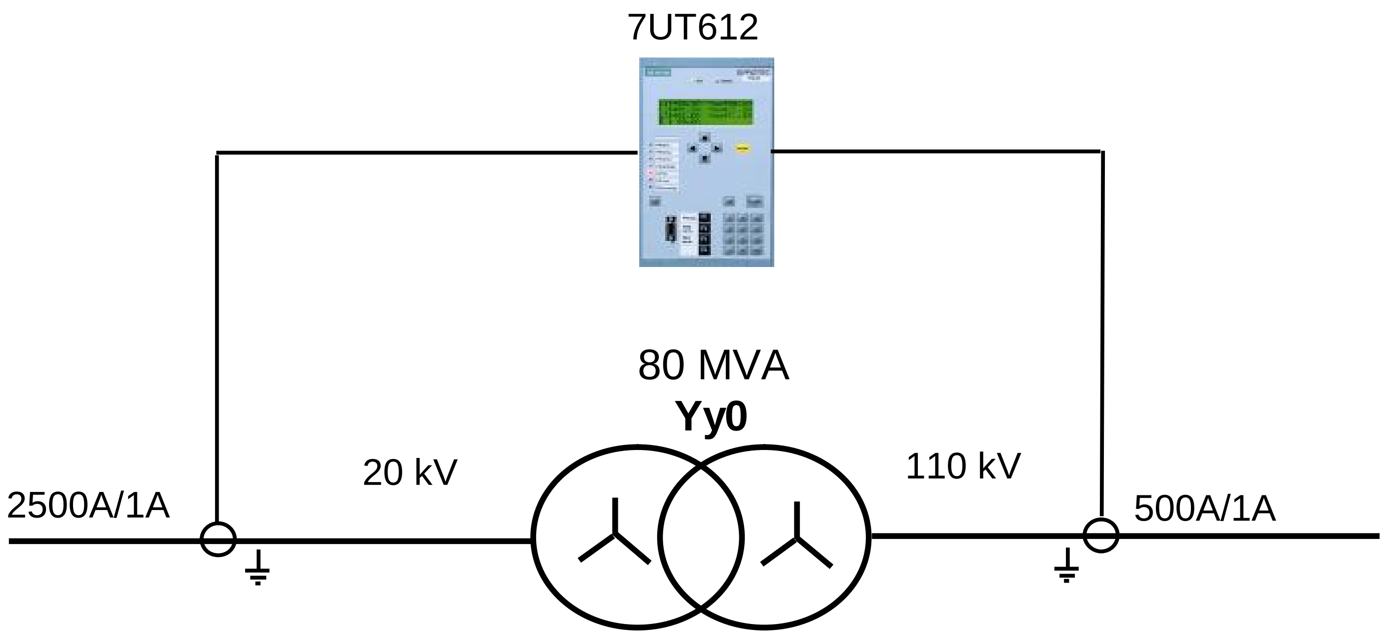
Power Transmission and Distribution

Differential Protection (7UT)

Determination of the Transformer Vector Group

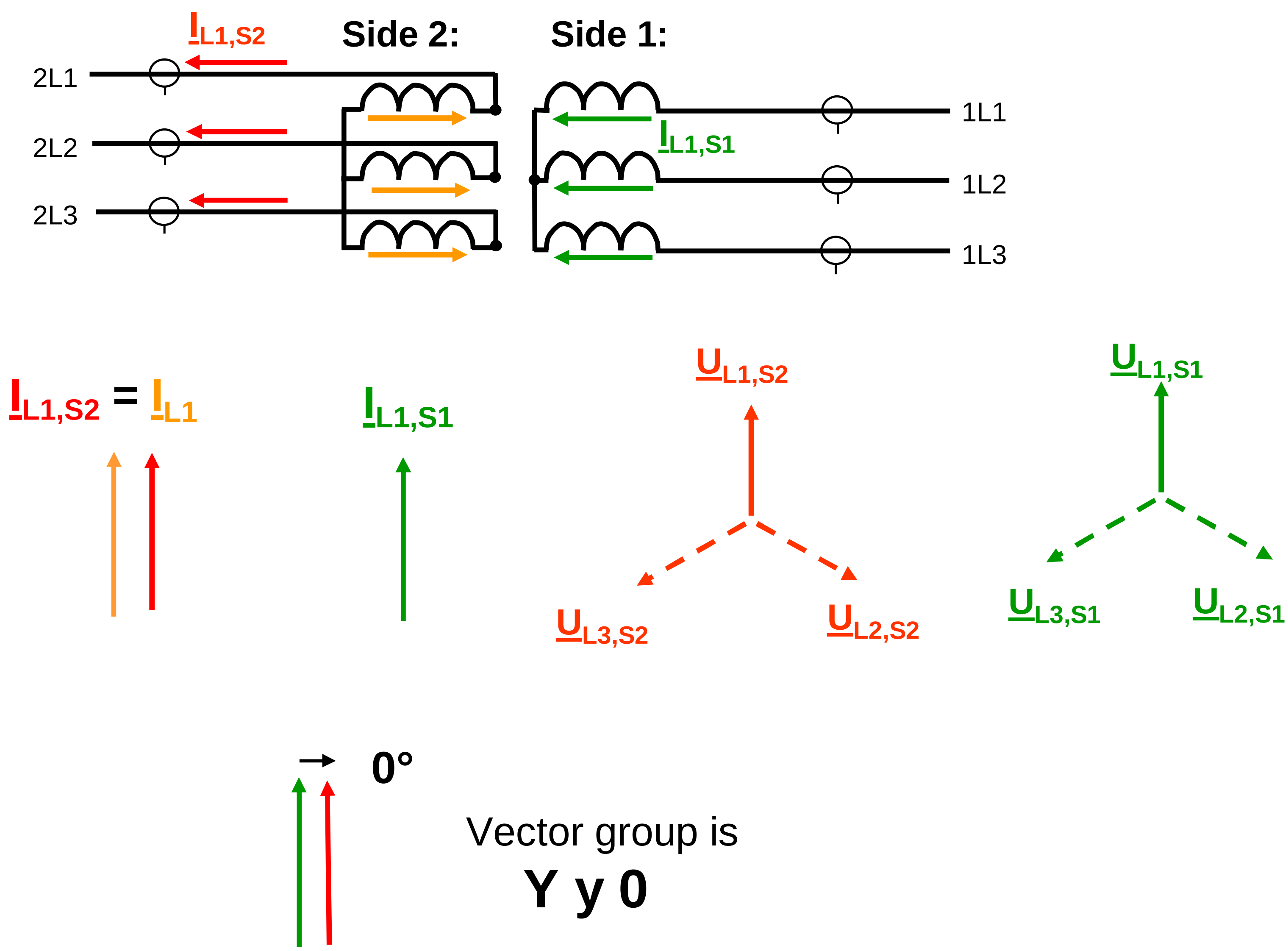
SIEMENS

Transformer with Vector Group Yy0



SIEMENS

Method of Vector Group Determination (ExampleYy0)

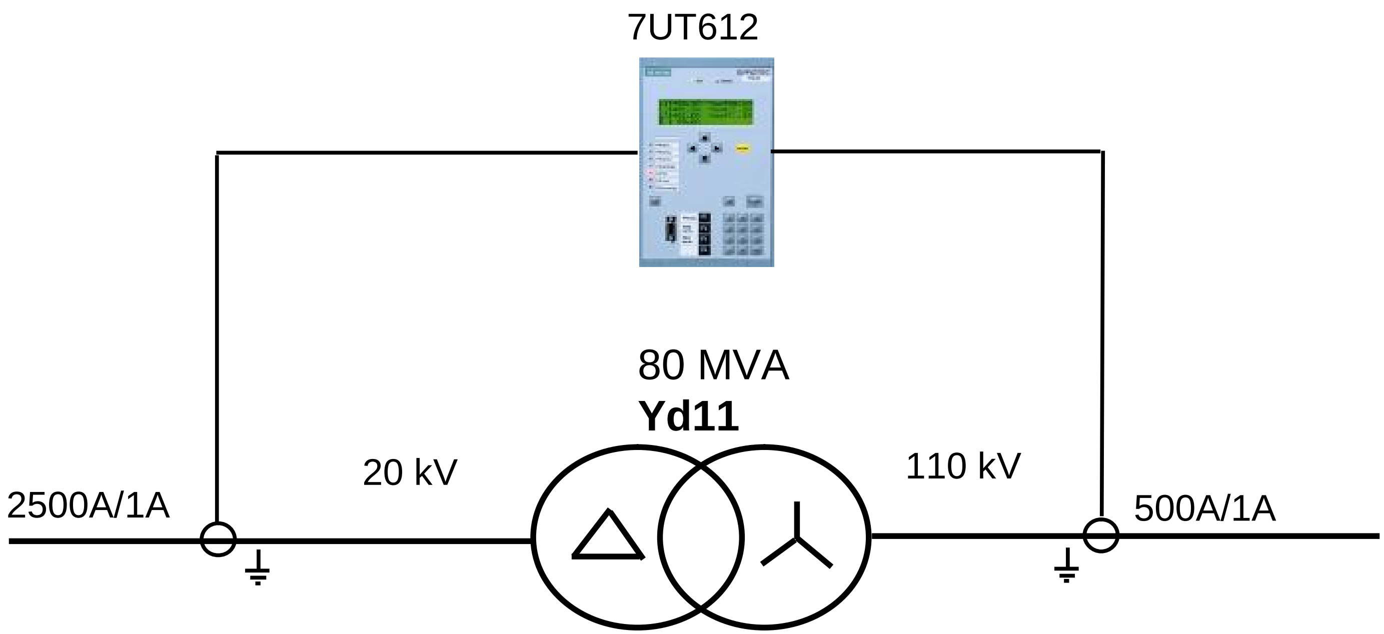


Vector group is

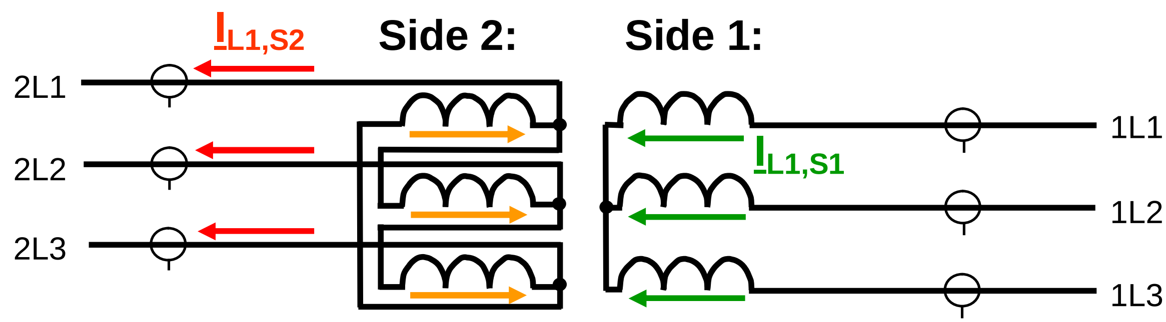
Y y 0

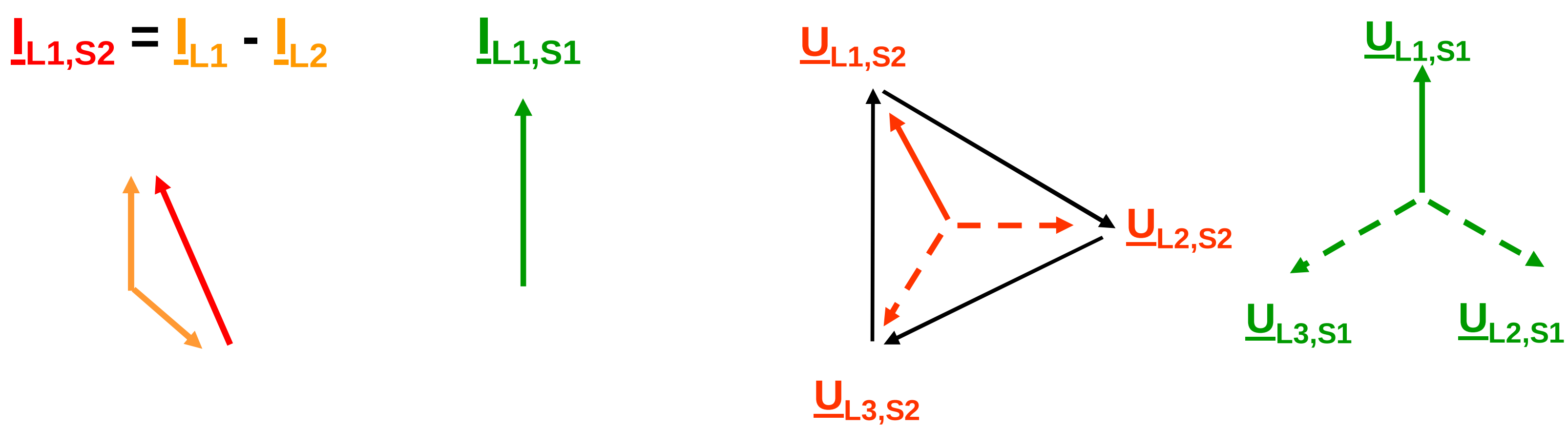
SIEMENS

Transformer Protection

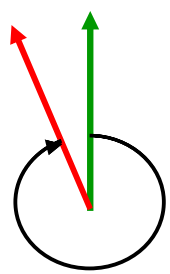


Method of Vector Group Determination (ExampleYd11)





Vector group is
Y d 11



330°
(n * 30°)

Definitions in SIPROTEC 4 Relays

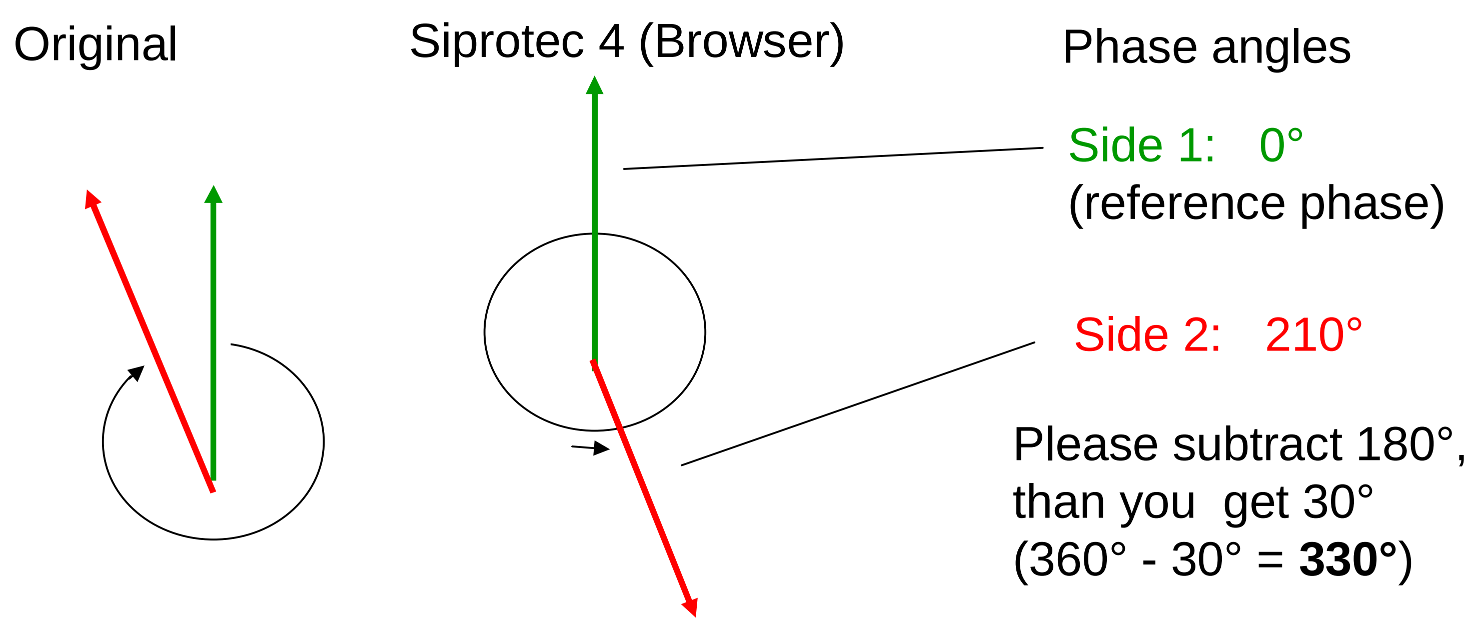
Vector definition to a node is positive

The shown vectors or phase angles are transformed in this positive definition

The phase angle is displayed mathematics positive.

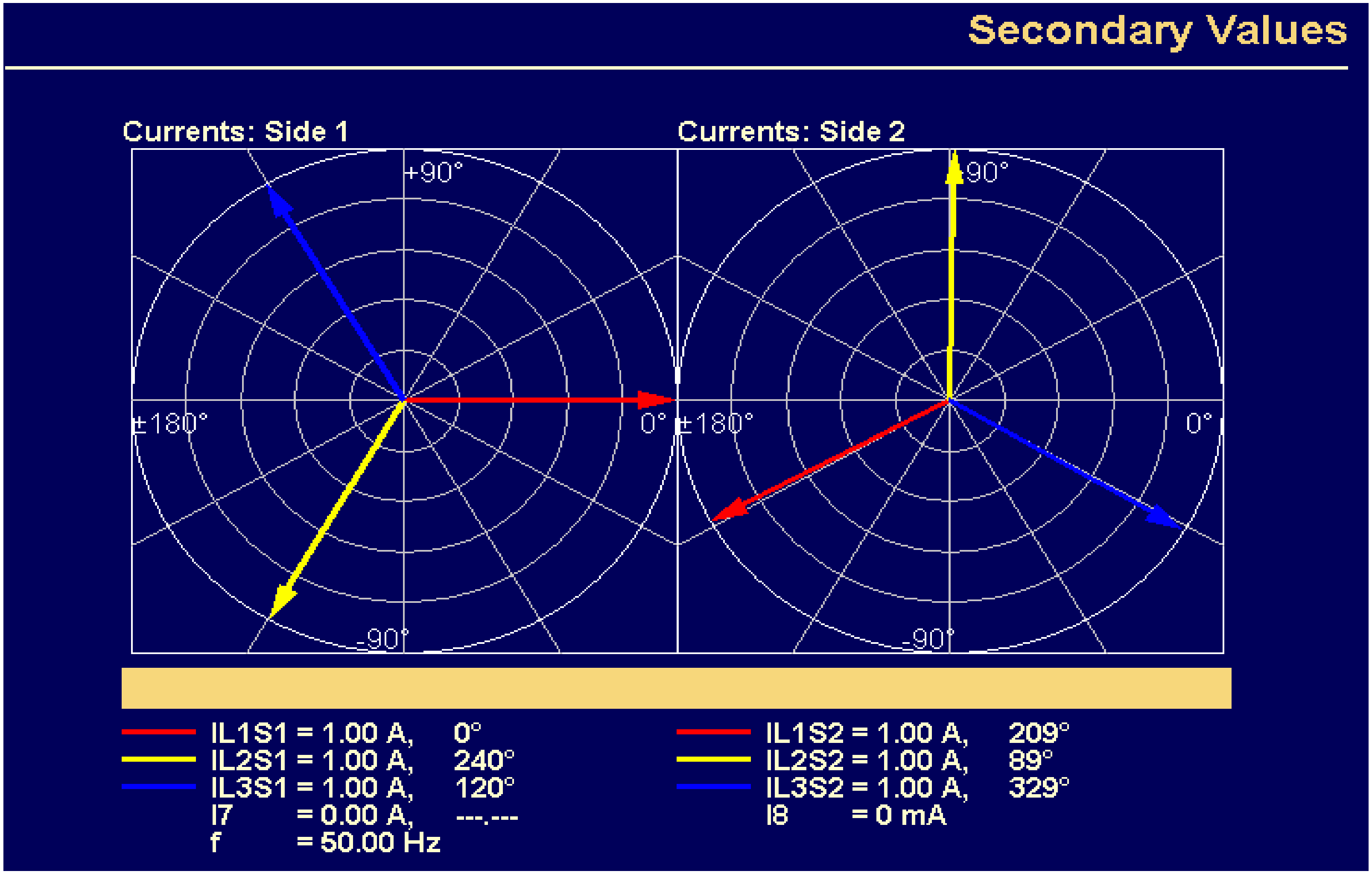
The reference phase is always phase L1 on side 1

How to see the vector group Yd11?



SIEMENS

Web Tool (Browser) Vector group YNd11



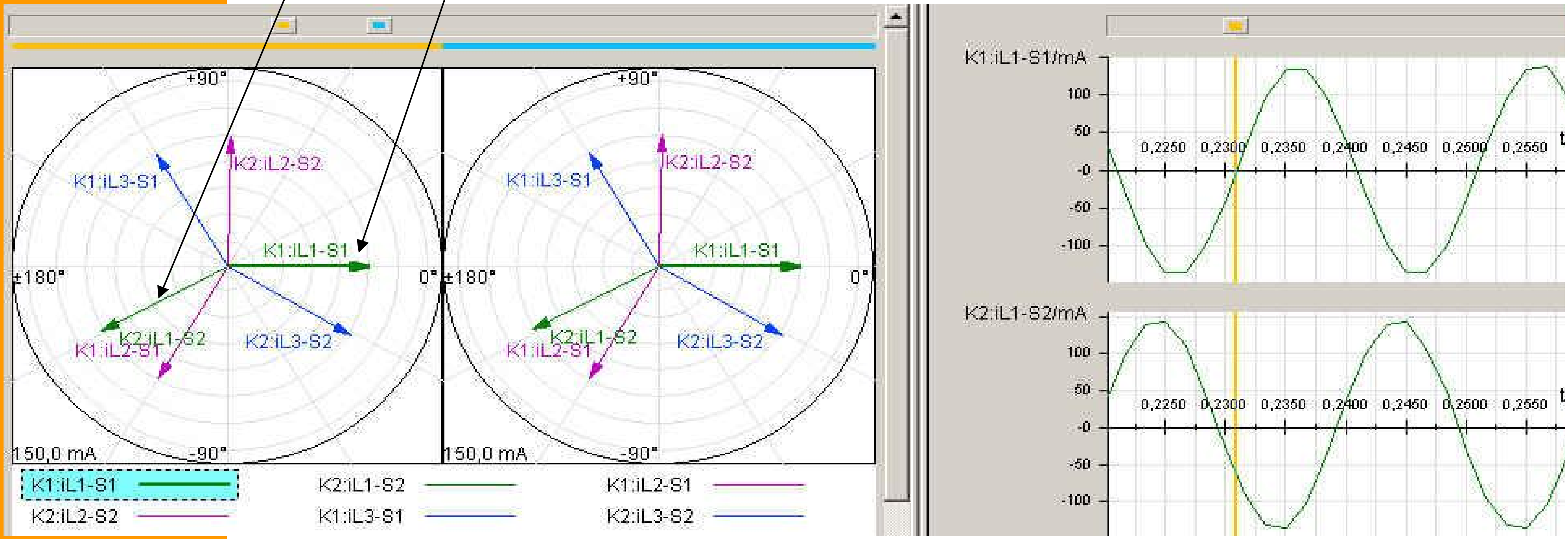
SIEMENS

Vector Group Determination via Fault Record

IL1;Side 2 lags 150° or leads 210°

Star point is towards the protected object

IL1;Side 1

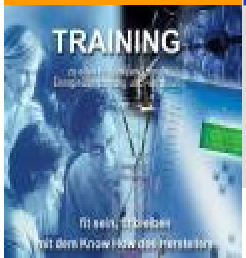


Way 1:
IL1 Side: 150° + 180° = **330°**

Way 2:
IL1 Side: 210° - 180° = 30°
leads 30° or lags **330°**

Phase shift is according the vector group definition 330° → **11** * 30°

SIEMENS

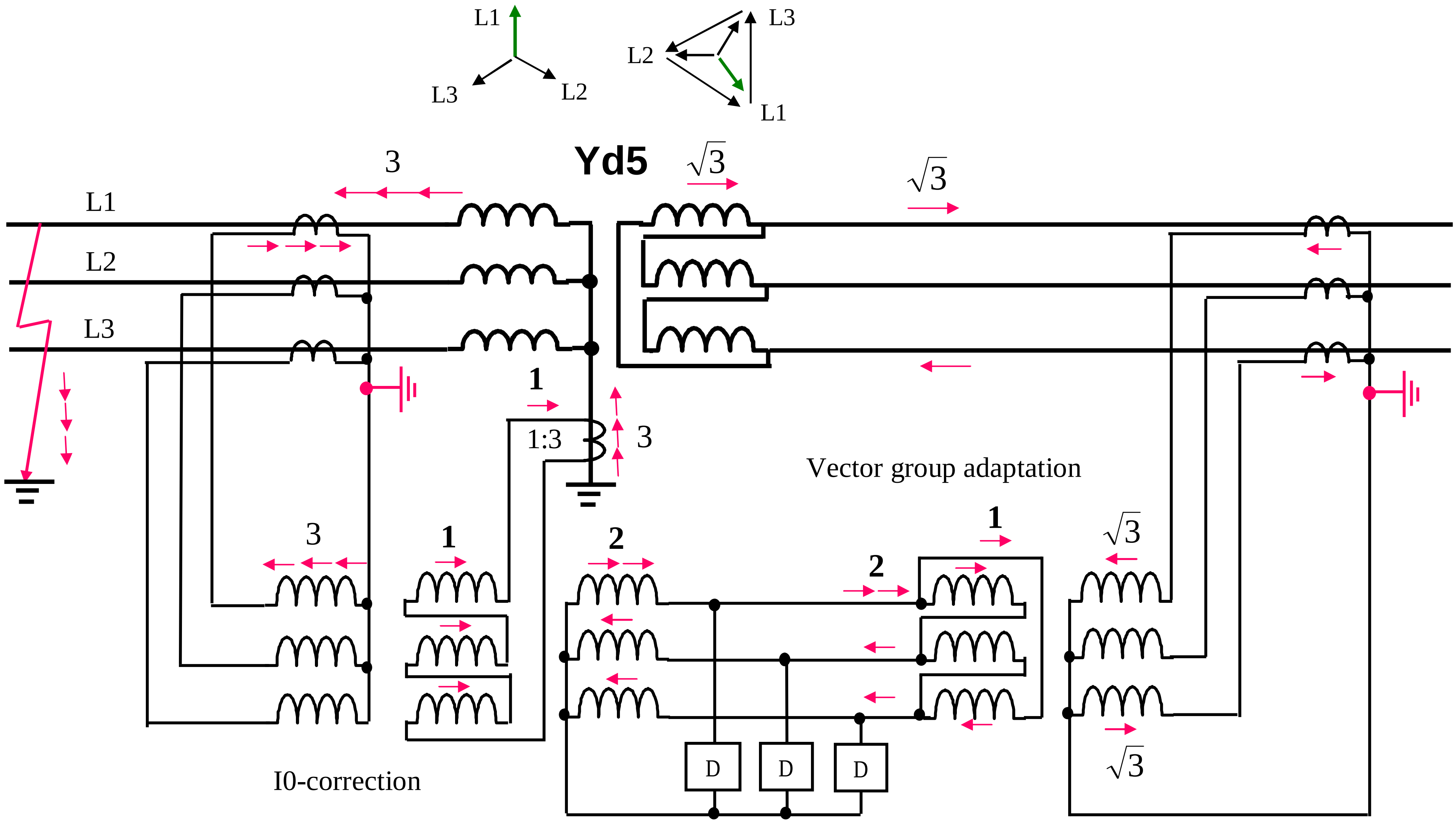


Digital Transformer Differential Protection

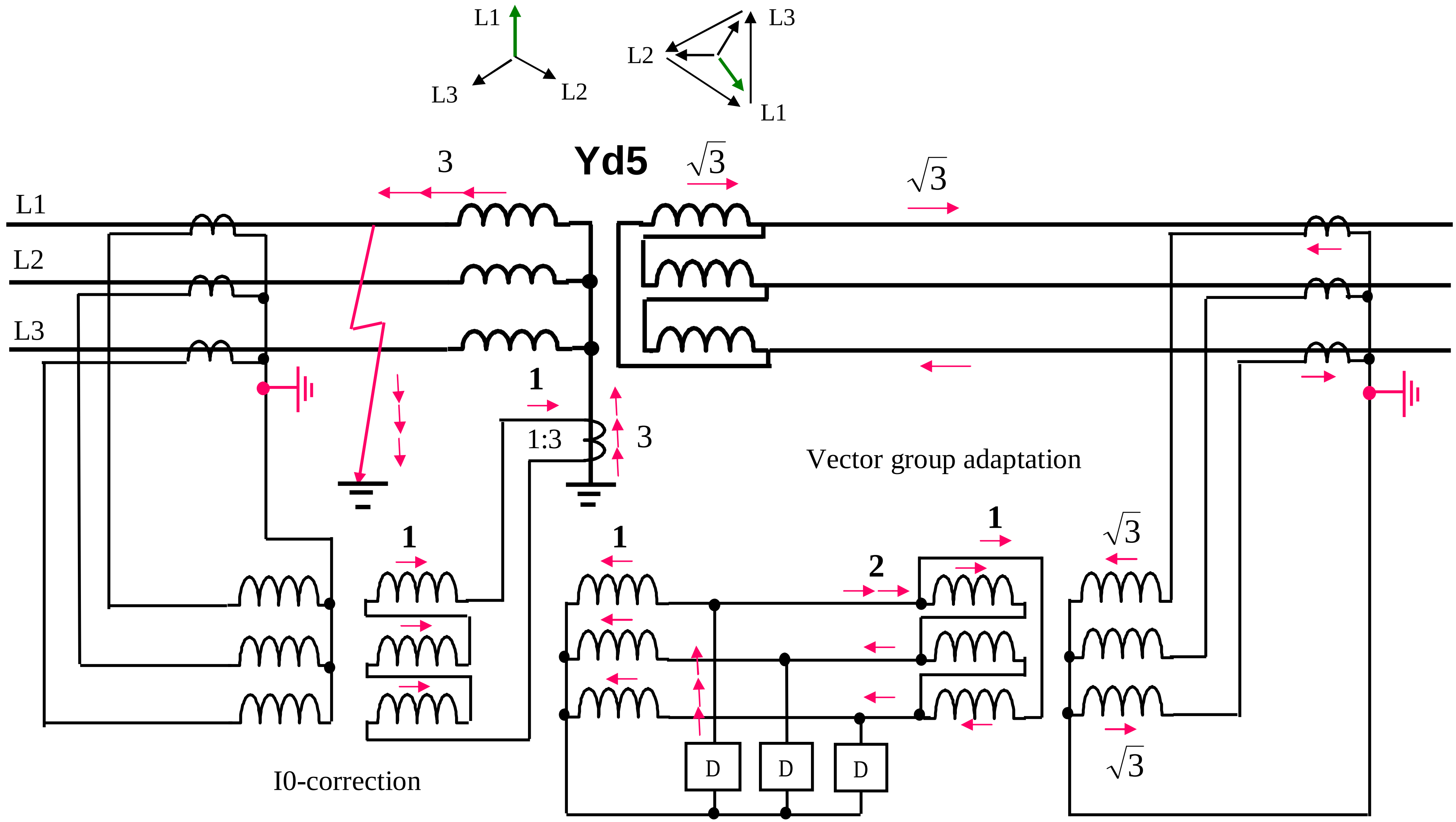
I0-correction
+ vector group adaptation

SIEMENS

Transformer differential protection with I0-correction External fault



Transformer differential protection with I0-correction
Internal fault



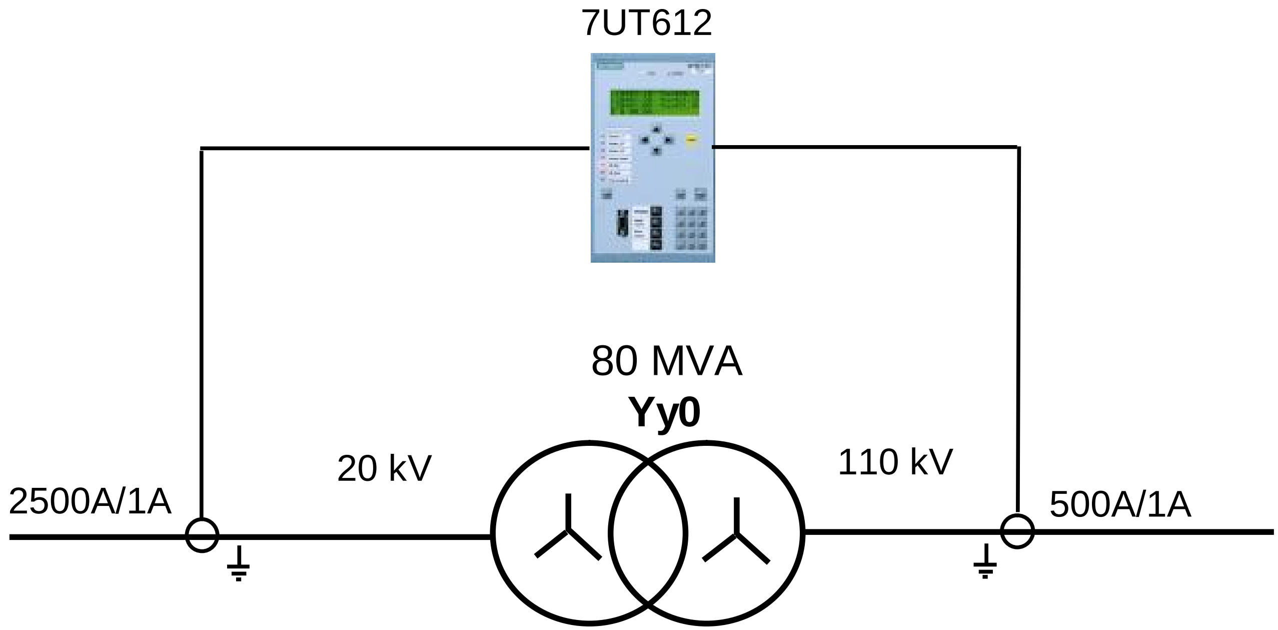
Power Transmission and Distribution

Differential Protection (7UT)

Determination of the Transformer Vector Group

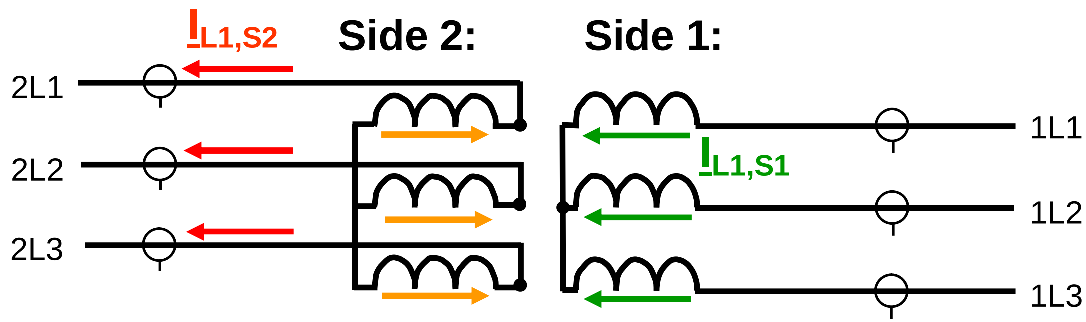
SIEMENS

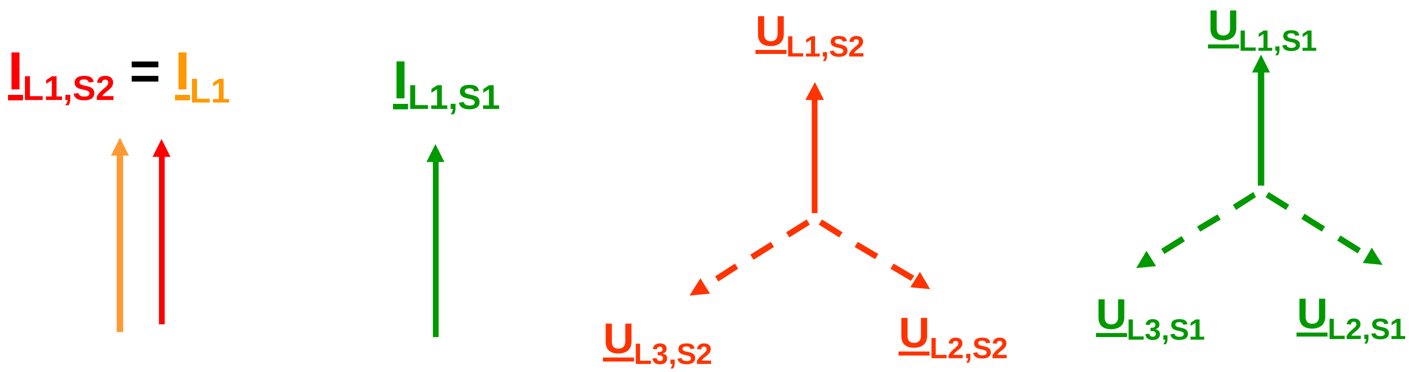
Transformer with Vector Group Yy0

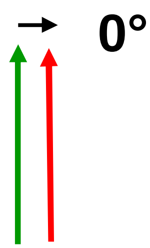


SIEMENS

Method of Vector Group Determination (ExampleYy0)



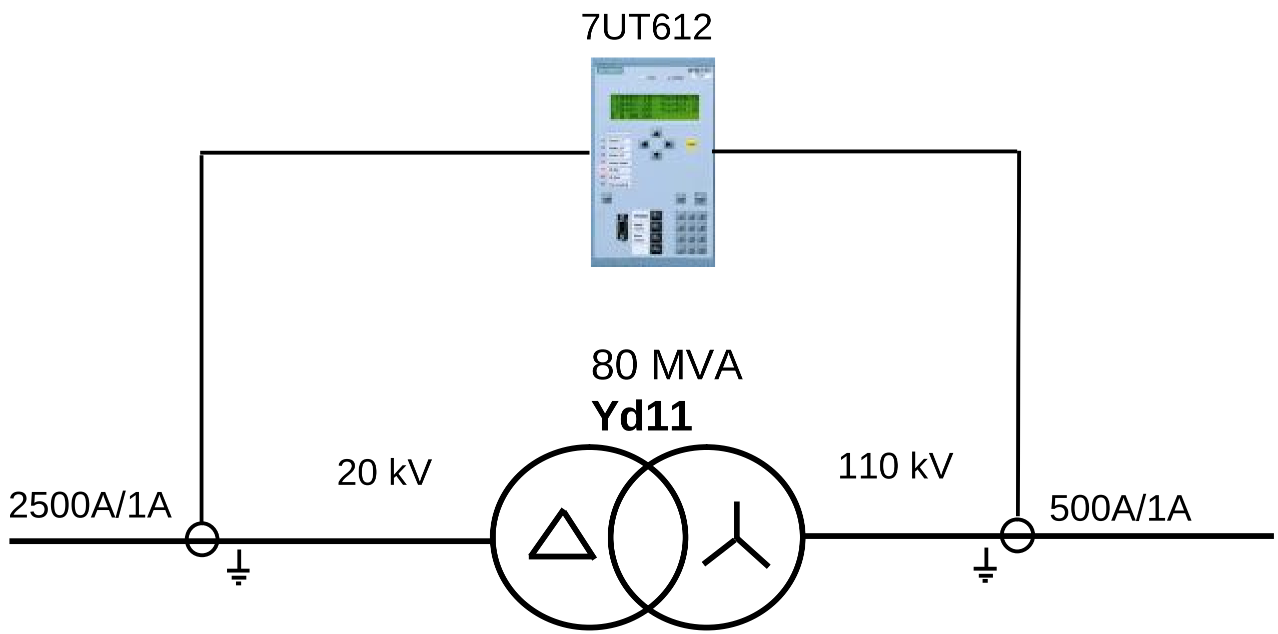




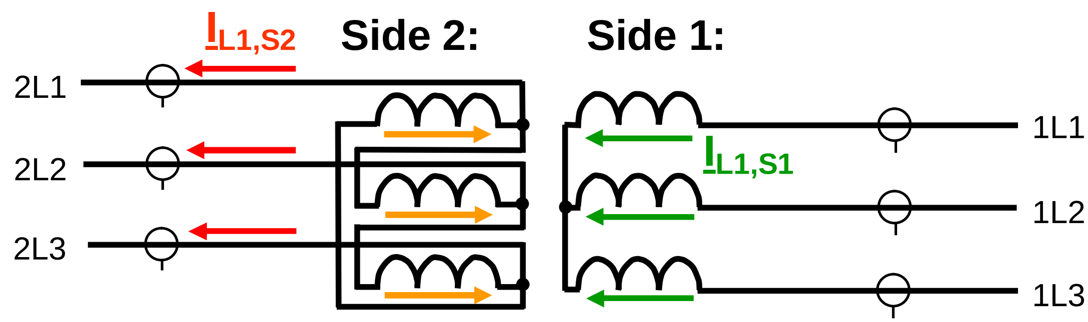
Vector group is

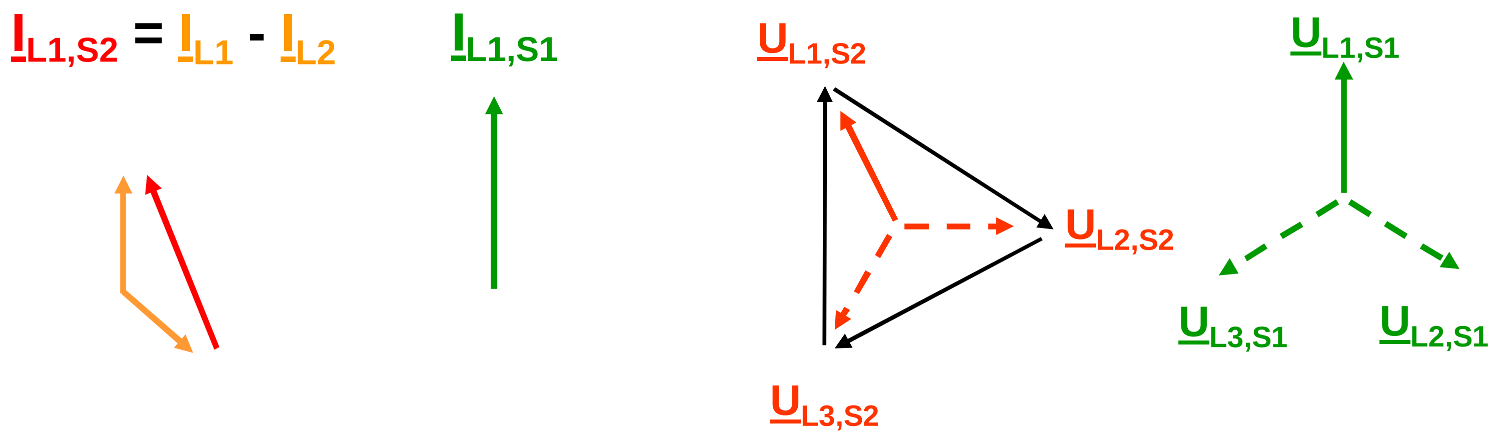
Y y 0

SIEMENS

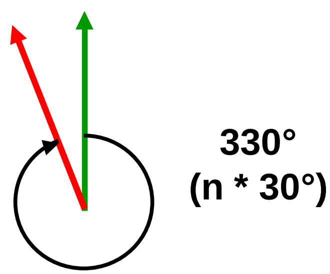

7UT612
80 MVA
Yd11
20 kV
110 kV
2500A/1A
500A/1A

Method of Vector Group Determination (ExampleYd11)





Vector group is
Y d 11



SIEMENS

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The shown vectors or phase angles are transformed in this positive definition

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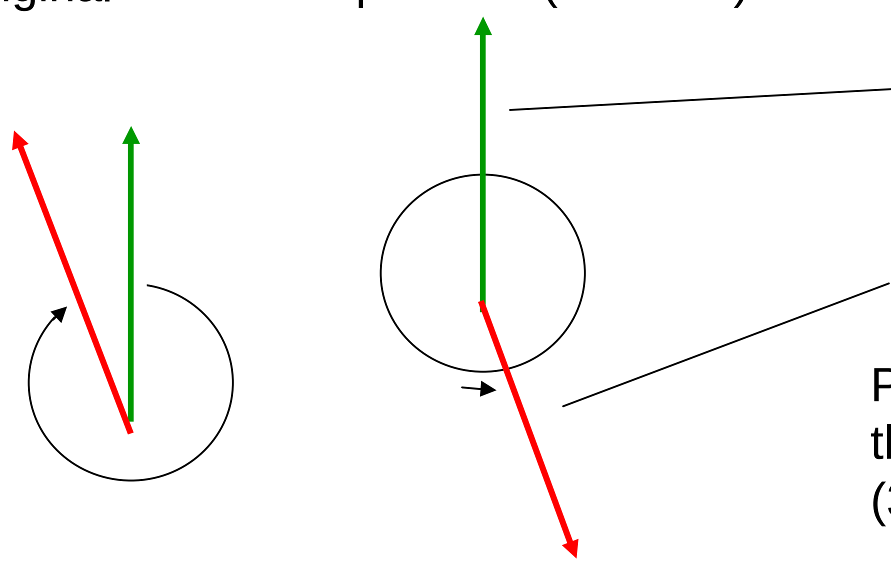
The reference phase is always phase L1 on side 1

How to see the vector group Yd11?

Original

Siprotec 4 (Browser)

Phase angles



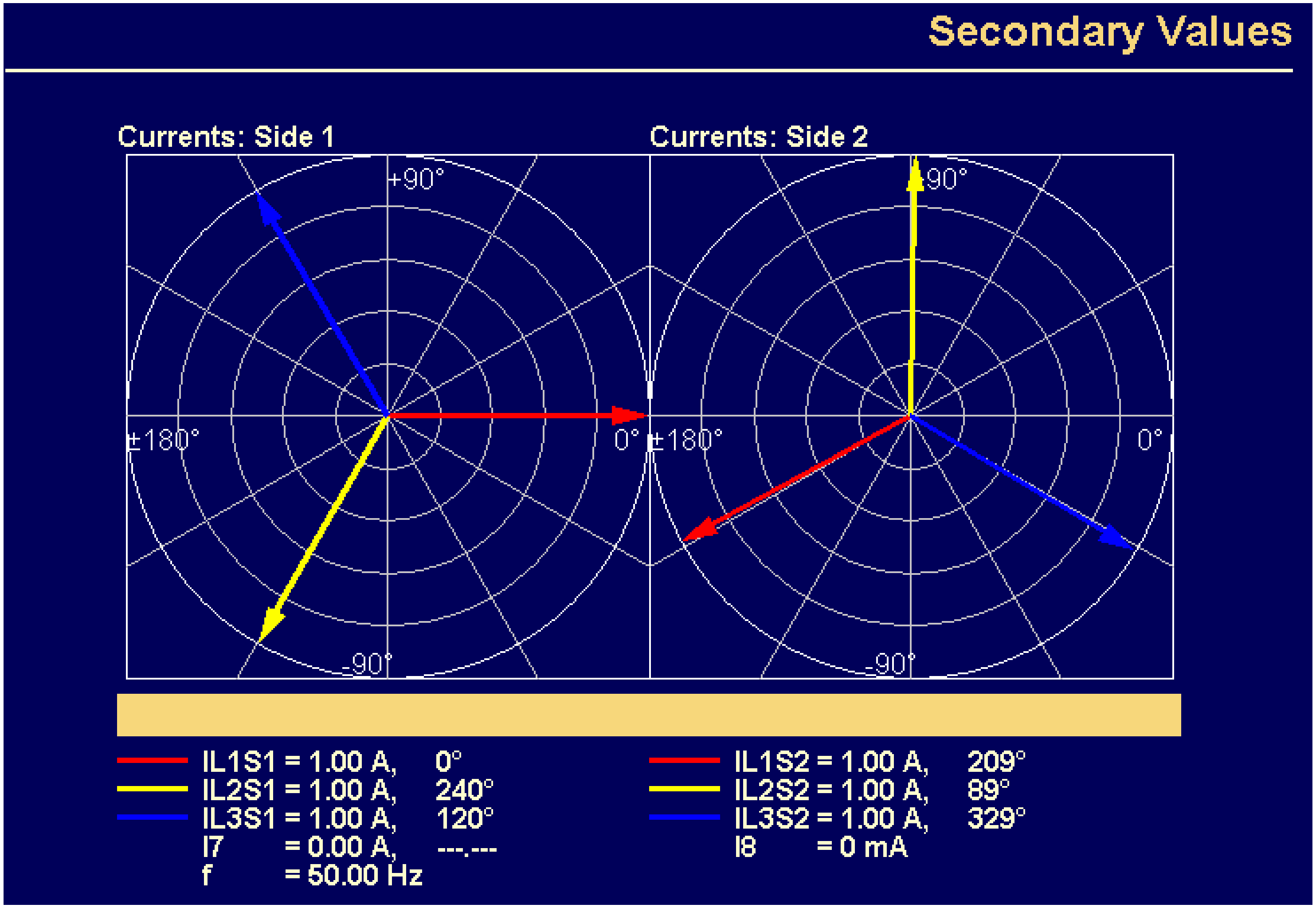
Side 1: 0°
(reference phase)

Side 2: 210°

Please subtract 180°, than you get 30°
(360° - 30° = **330°**)

SIEMENS

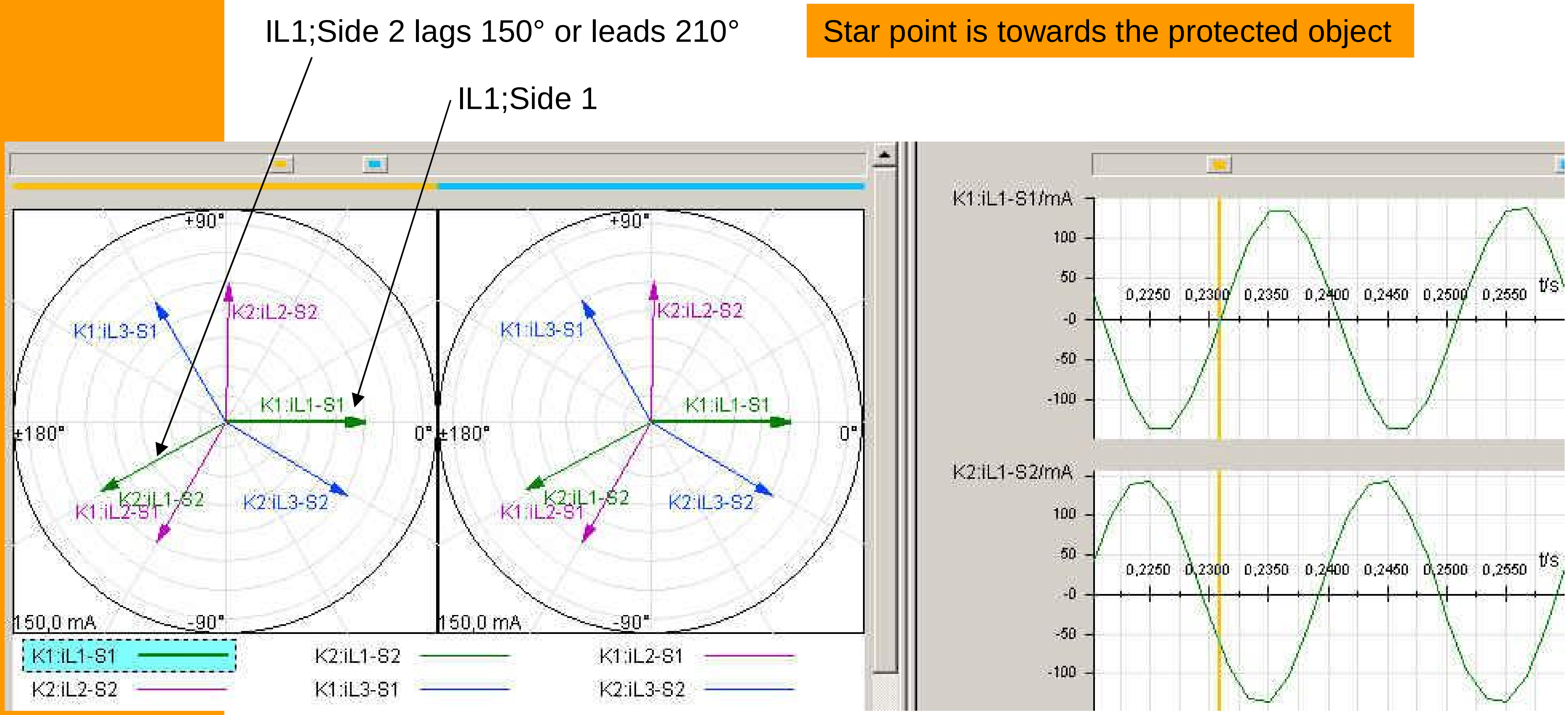
Web Tool (Browser) Vector group YNd11



SIEMENS

Vector Group Determination via Fault Record

Star point is towards the protected object



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IL1 Side: 150° + 180° = **330°**

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IL1 Side: 210° - 180° = 30°
leads 30° or lags **330°**

Phase shift is according the vector group definition 330° → **11** * 30°

SIEMENS