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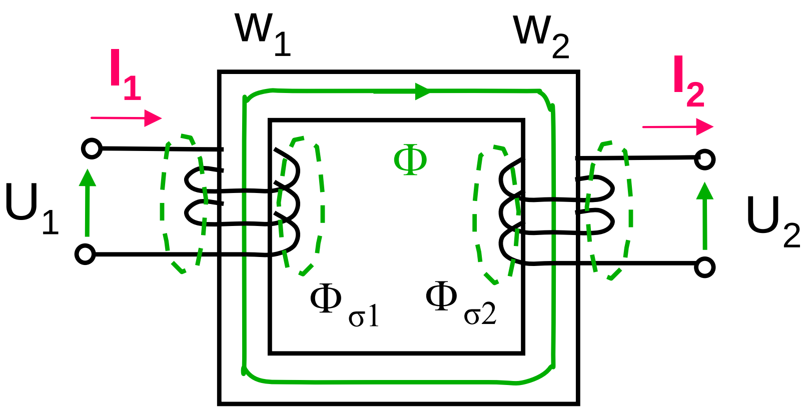
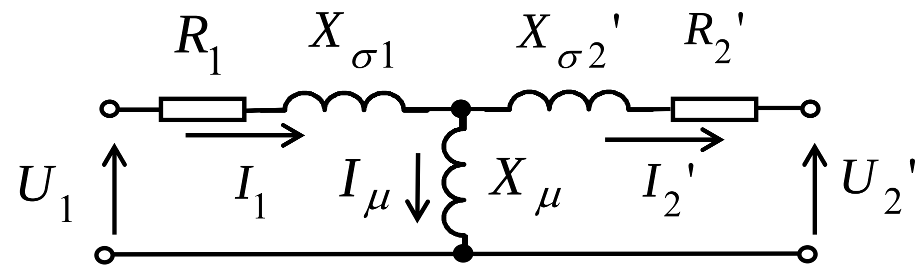
Transformer Protection

Transformer: Function principle and equivalent circuits



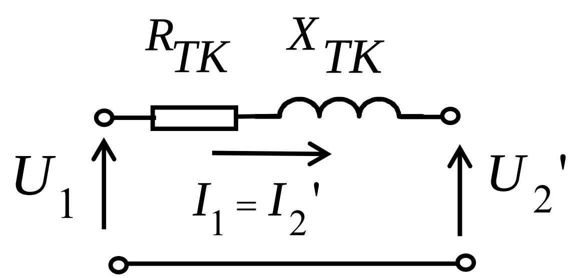
Equivalent electromagnetic circuit



Equivalent electric circuit

$$I_1 \cdot w_1 + I_2 \cdot w_2 = I_\mu \cdot w_1$$

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



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

$$X_{TK} = X_{\sigma 1} + X_{\sigma 2}'$$

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

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

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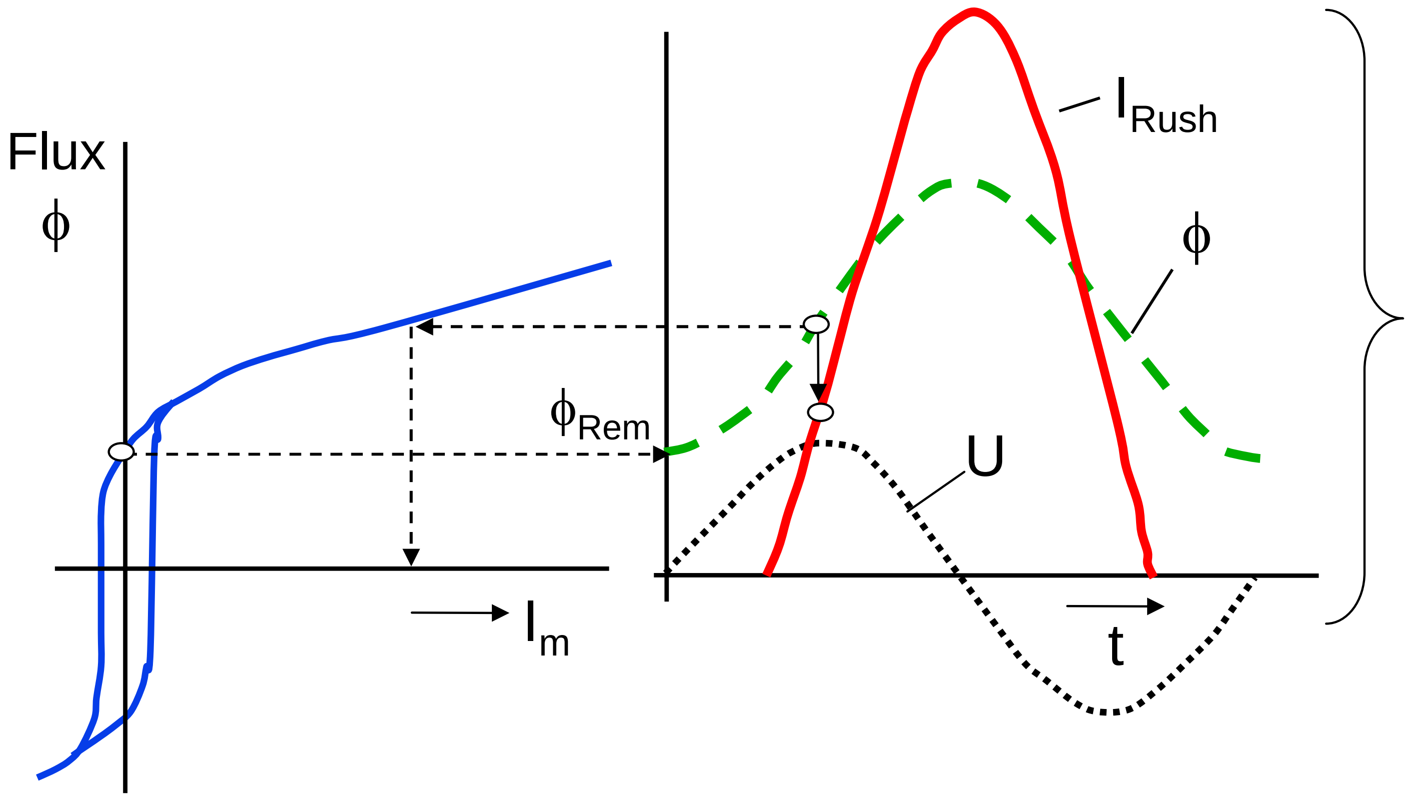
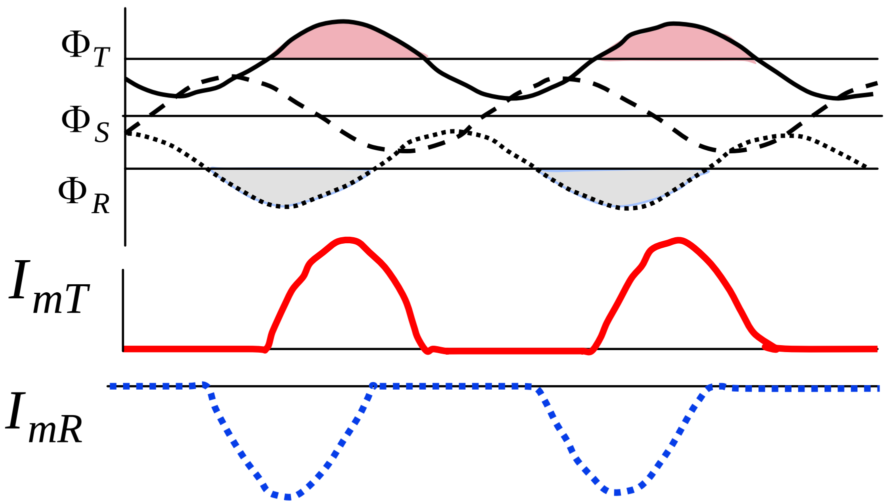


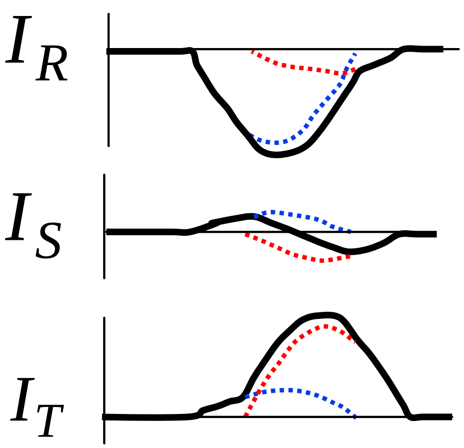
Inrush-current of a single phase transformer

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

Inrush currents of a Y-Δ-transformer

Neutral of Y-winding earthed

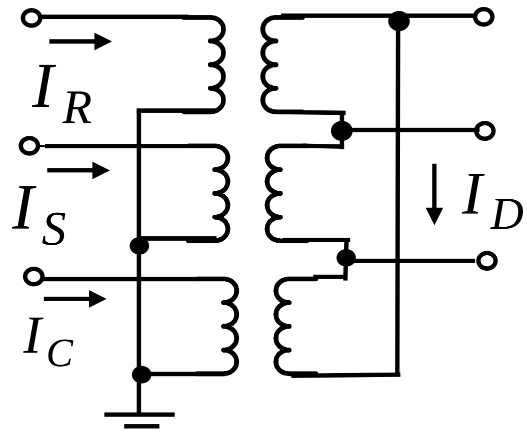




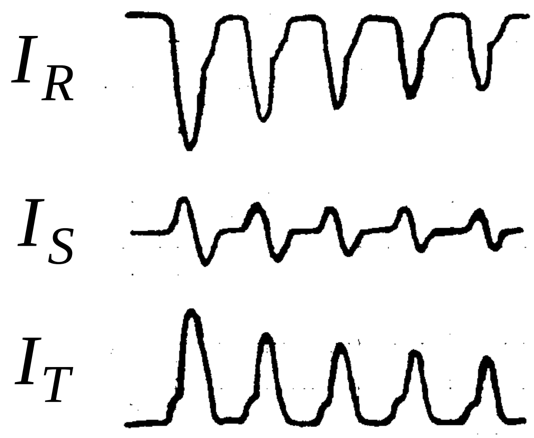
$$I_R = \frac{5}{6}\cdot I_{mR} - \frac{1}{6}\cdot I_{mC}$$

$$I_S = -\frac{1}{6}\cdot I_{mR} - \frac{1}{6}\cdot I_{mT}$$

$$I_T = \frac{5}{6}\cdot I_{mT} - \frac{1}{6}\cdot I_{mR}$$



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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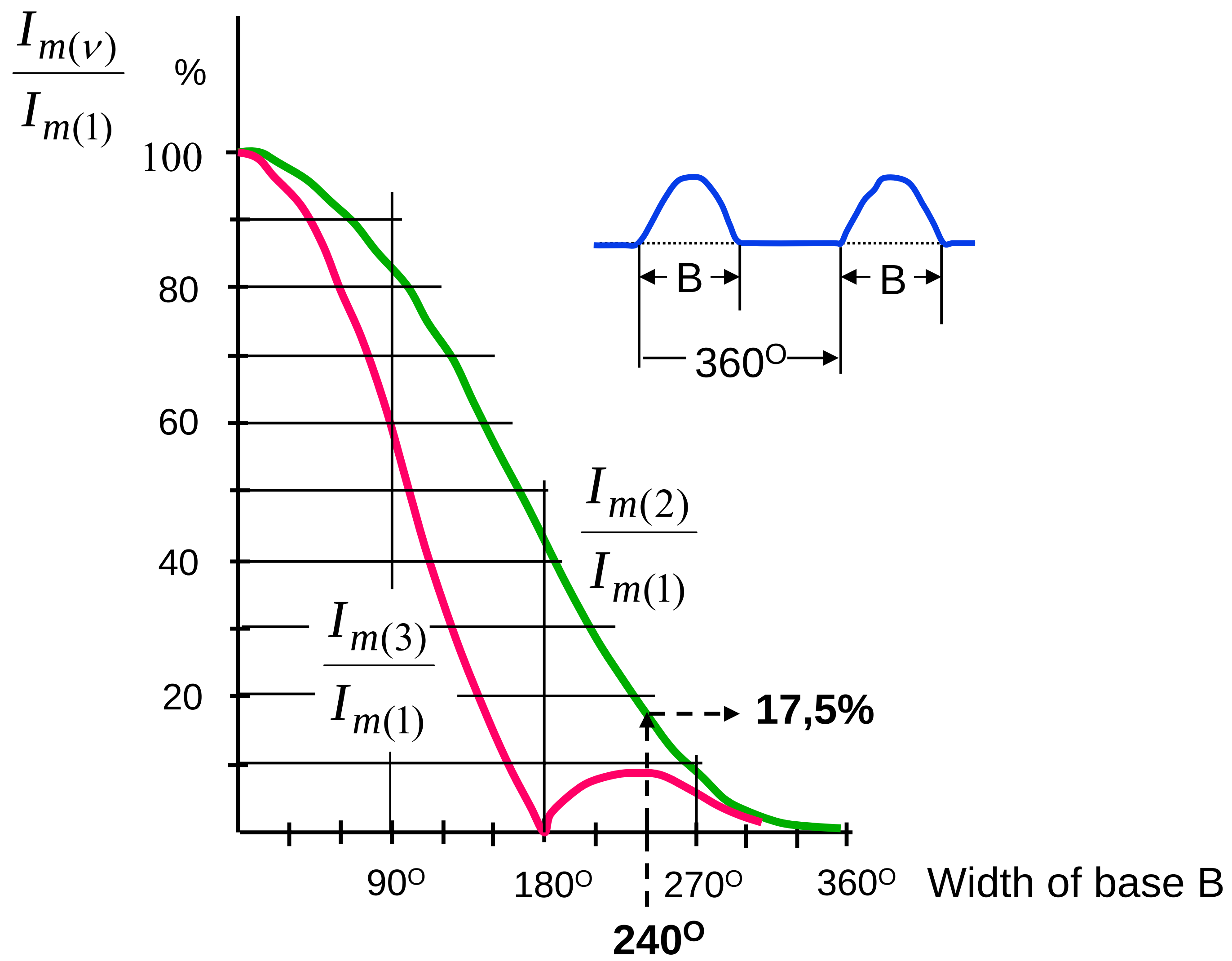
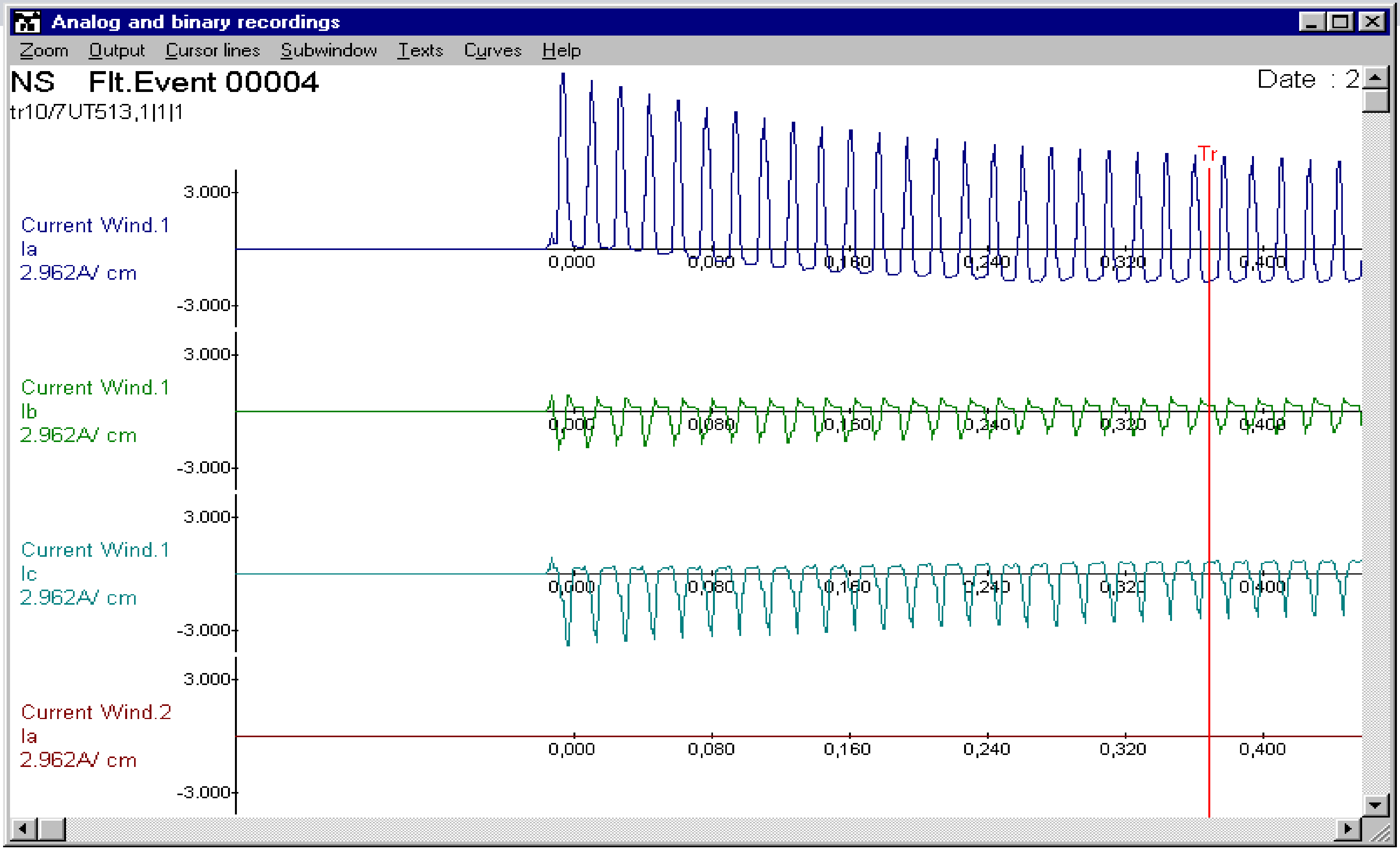
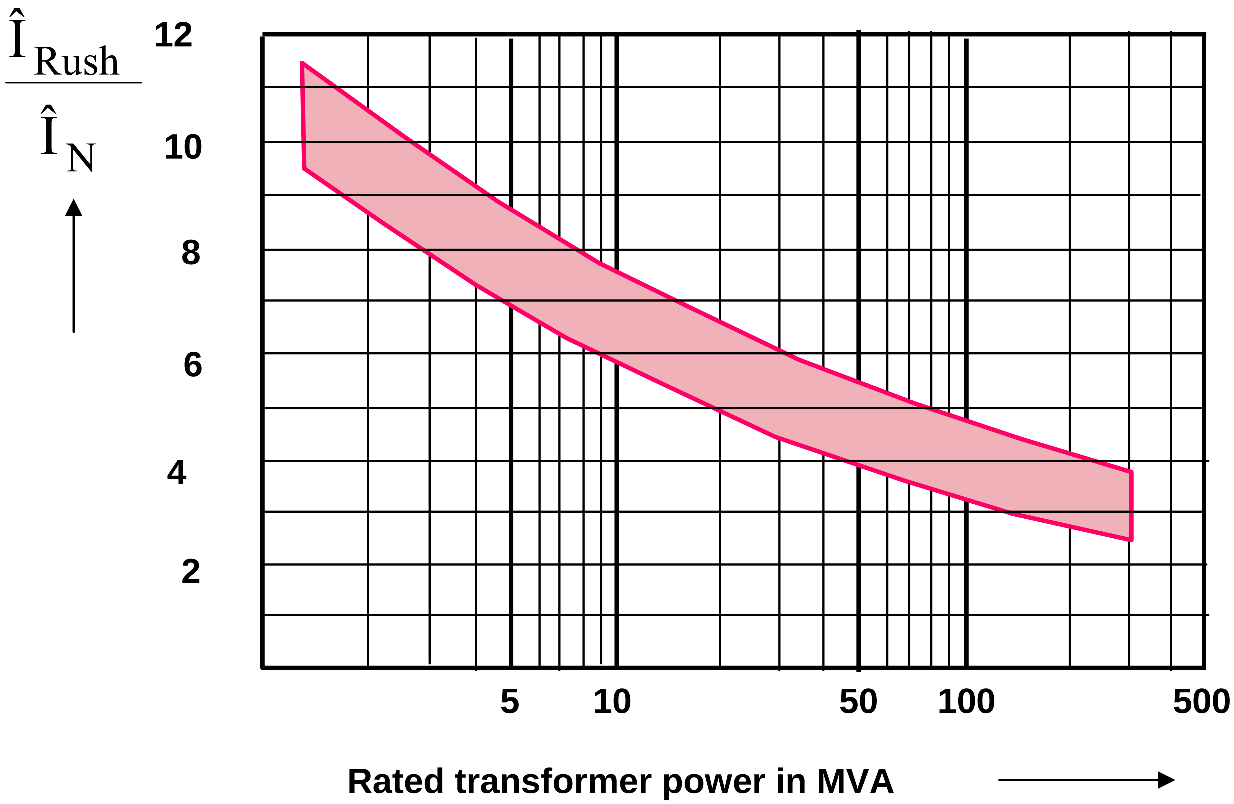


Inrush currents of a three-phase transformer recorded with relay 7UT51



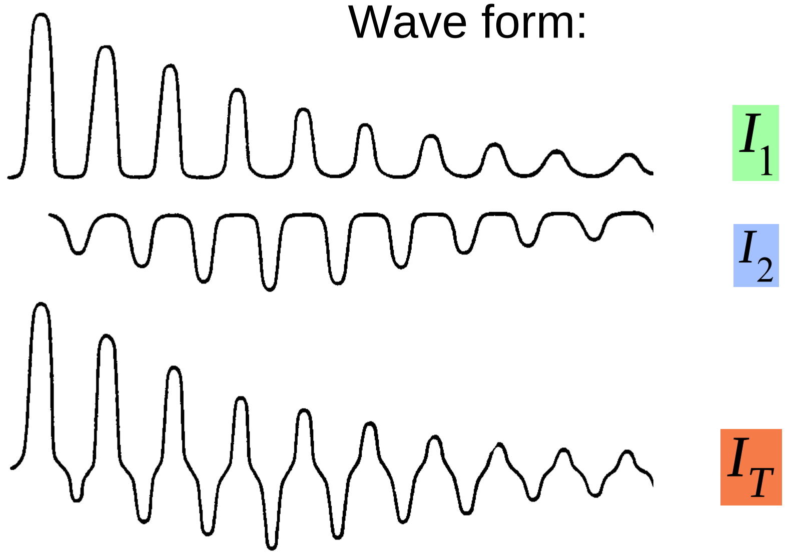
Transformer Inrush current:
Amplitude and time constant

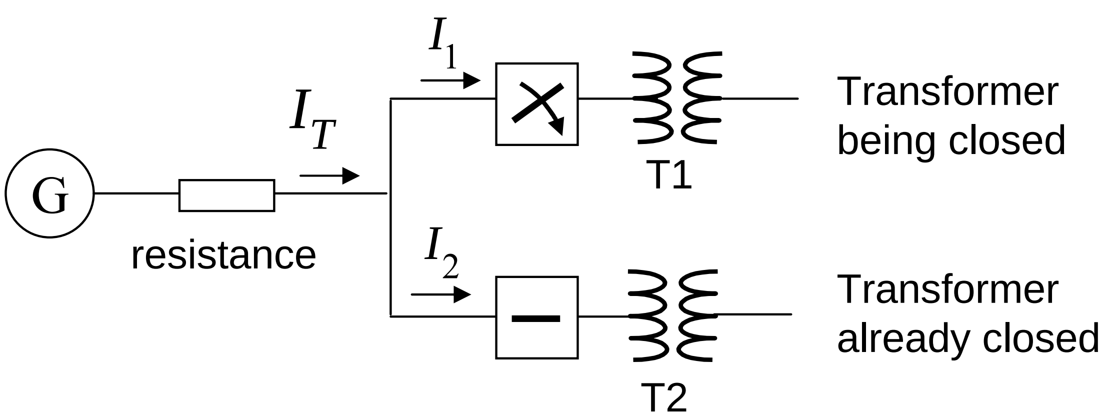


Rated power in MVA	time constant in seconds
0,5....1,0	0,16....0,2
1,0 10	0,2 1,2
>10	1,2 720

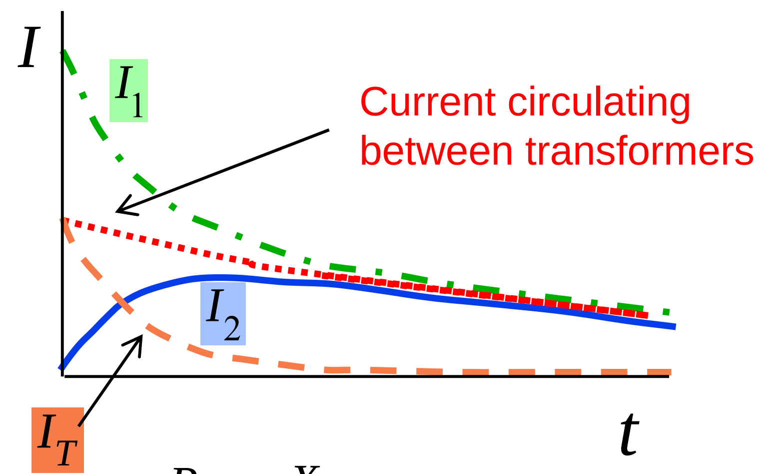
Sympathetic Inrush

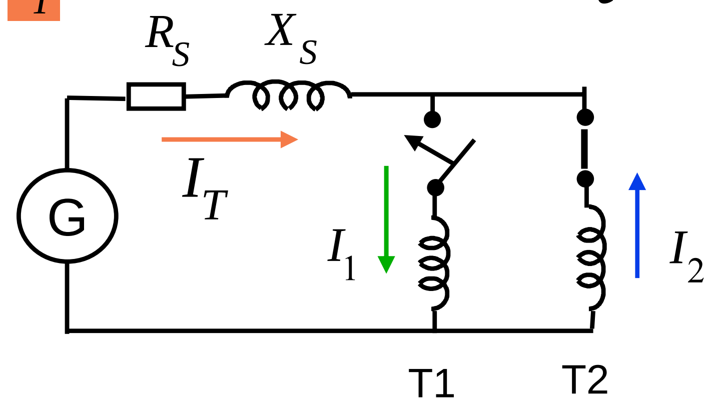
Wave form:





Transient currents:





Transformer overfluxing

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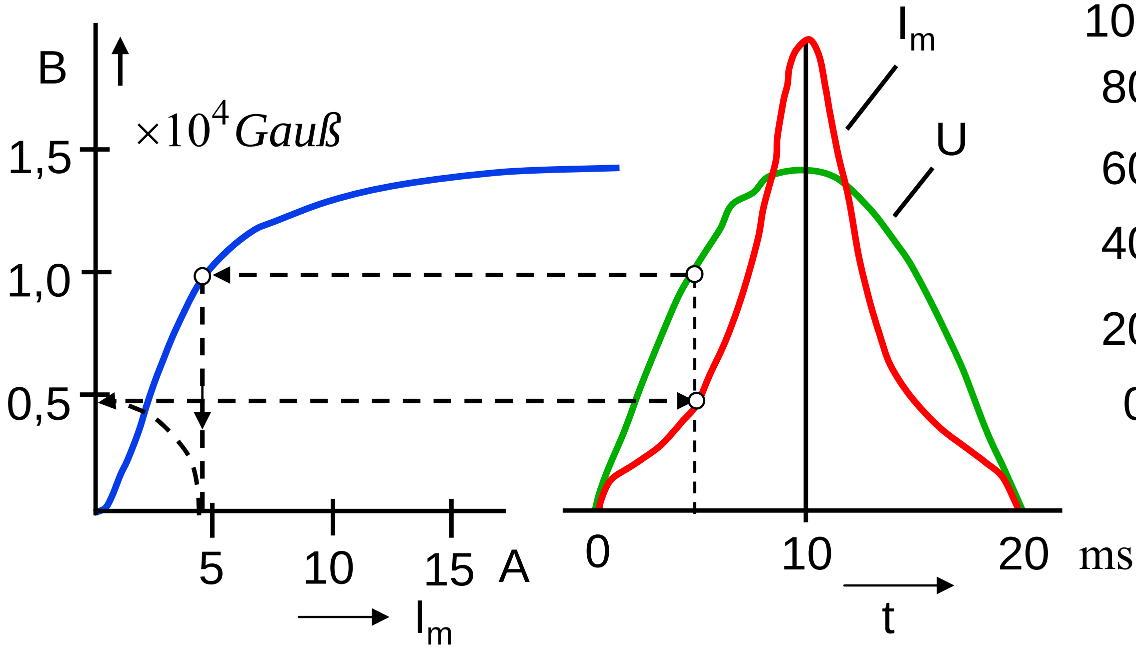
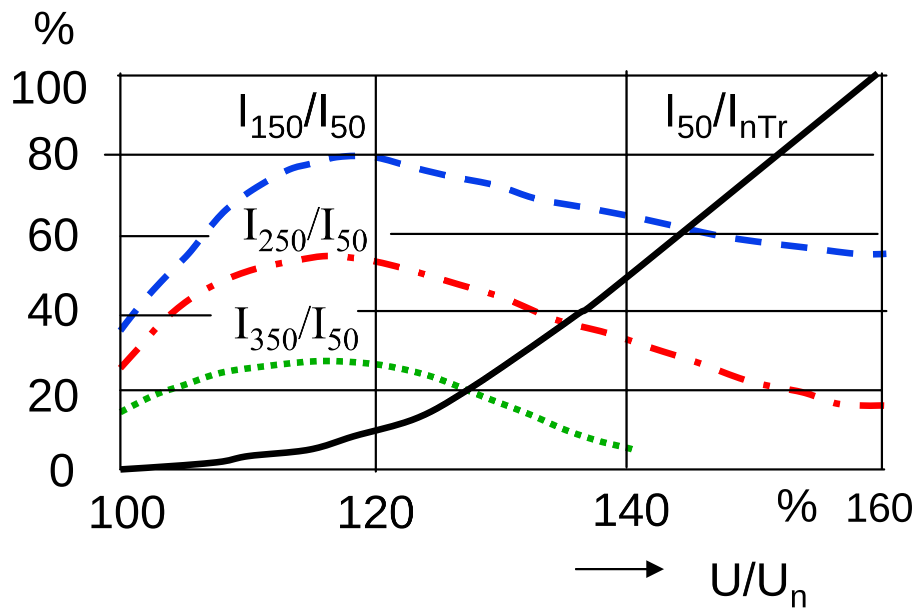
Deduction of wave form



Harmonic content



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

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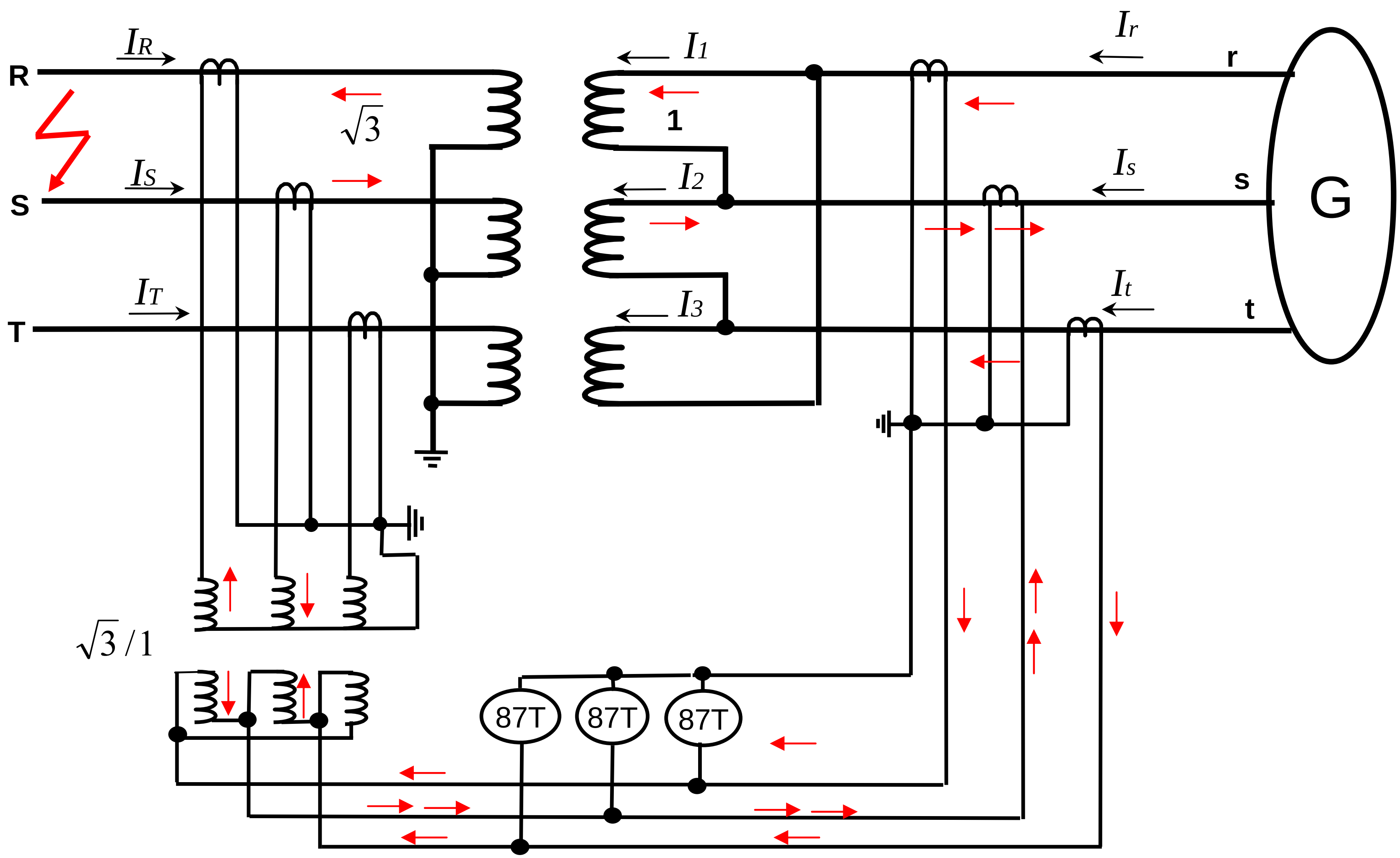
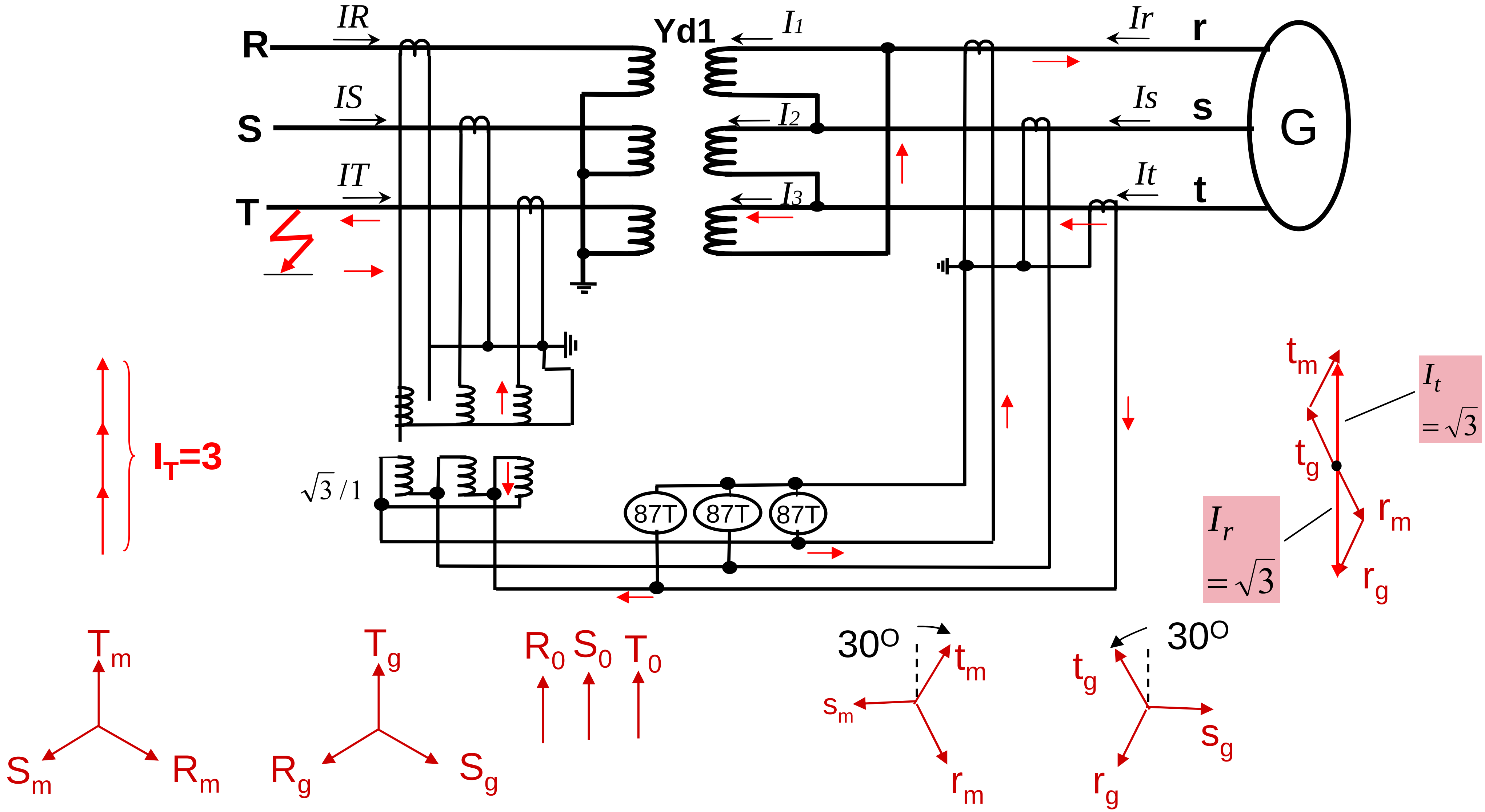


Vector group adaptation with matching CTs
Current distribution with external ph-E fault

SIEMENS



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

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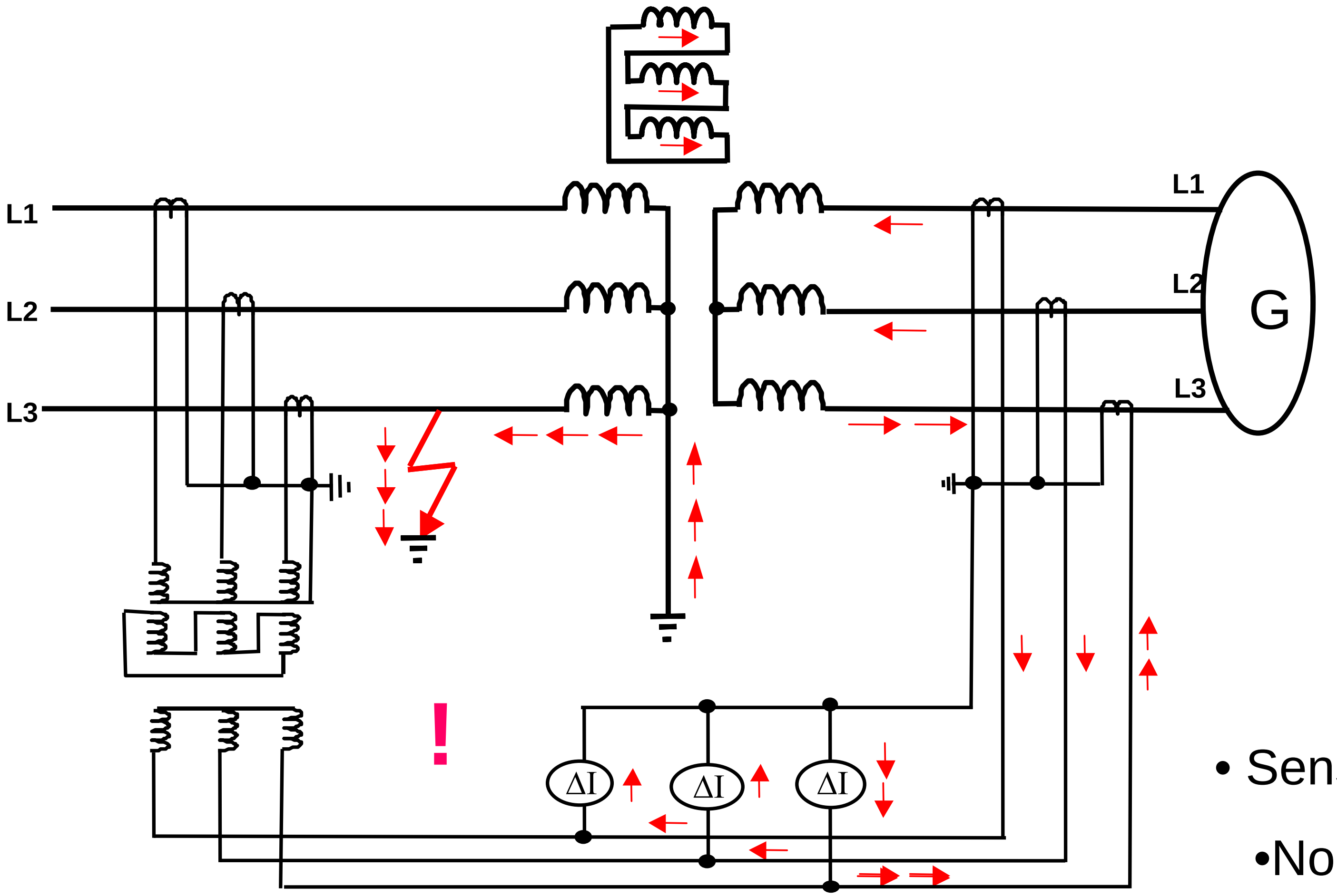

- Sensitivity only 2/3 I_F!
- Non-selective fault indication!

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

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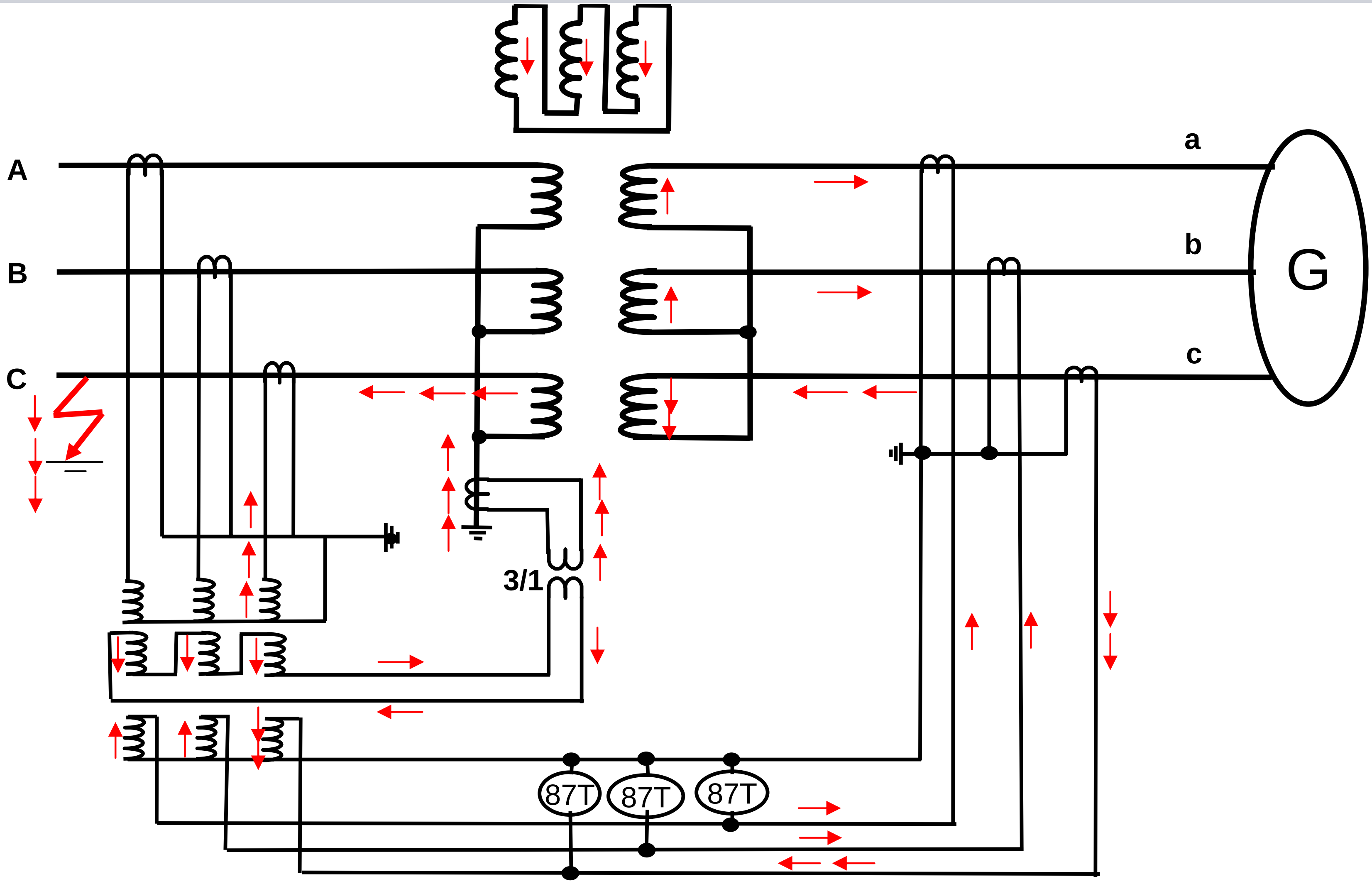

Traditional I_0-correction with matching CTs
Current distribution with internal ph-E fault

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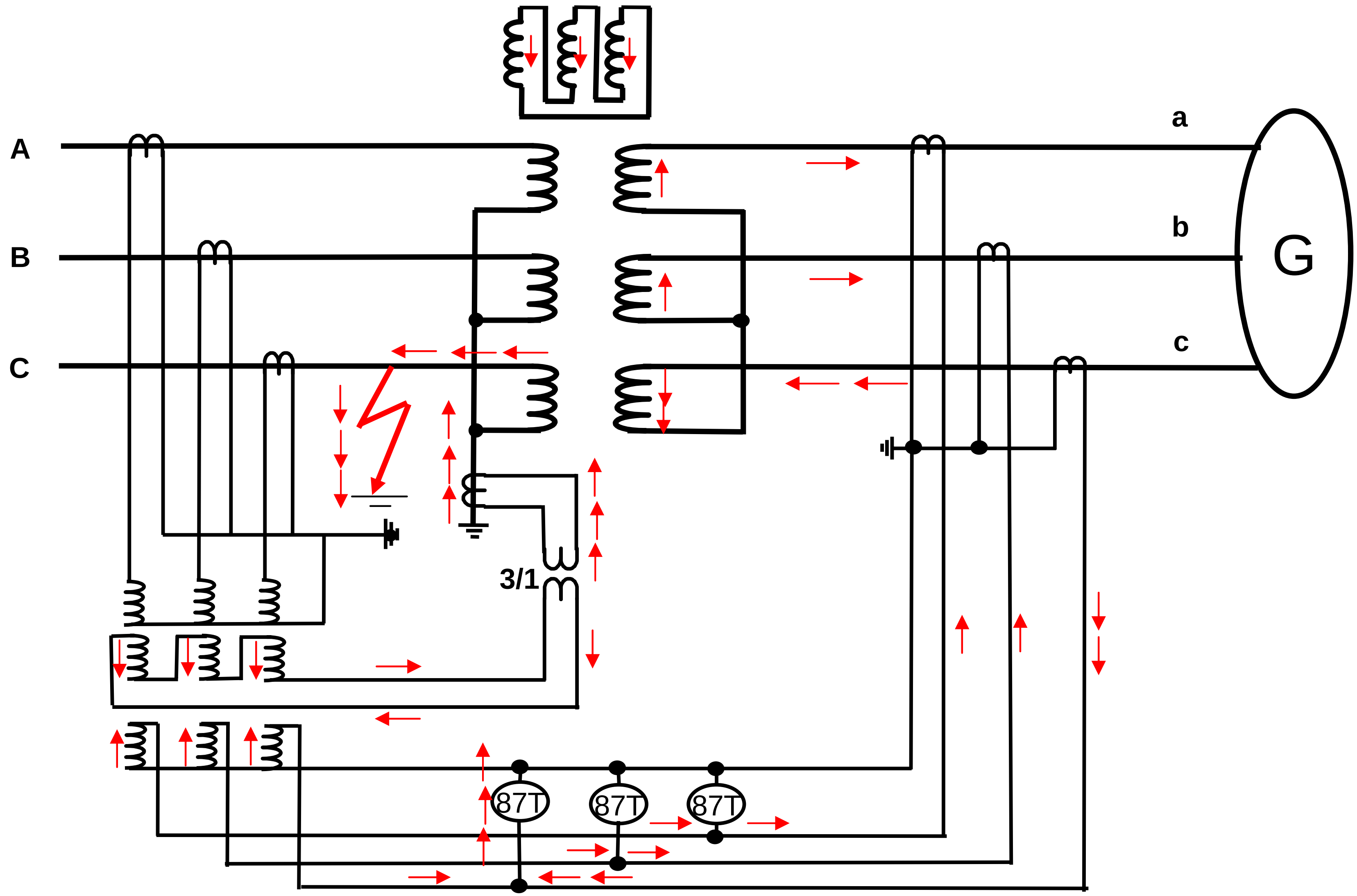

Transformer differential protection, connection

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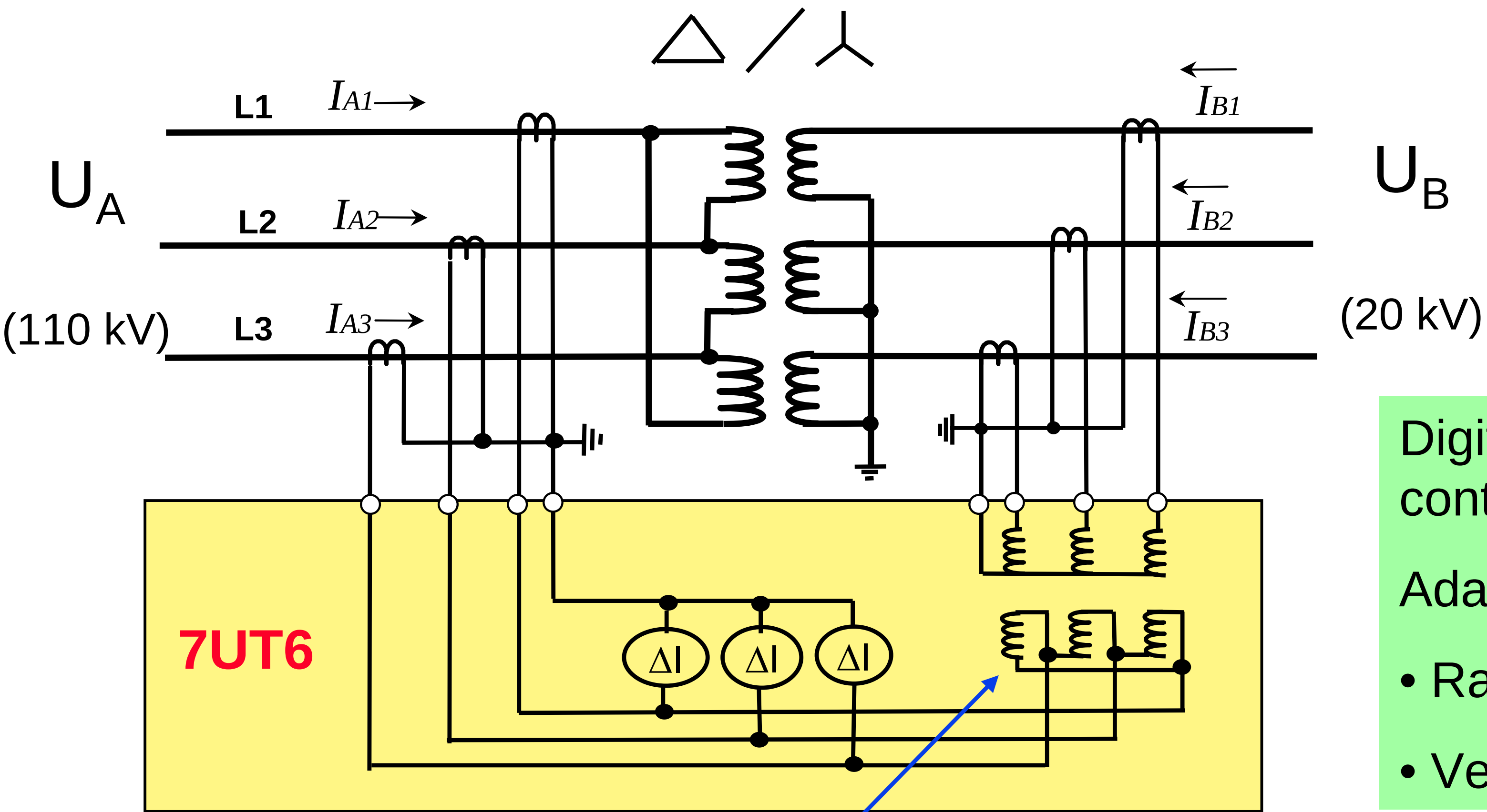

Software replica of matching transformers

Digital protection contains:

Adaptation to

- Ratio U_A / U_B
- Vector group

Digital transformer protection
Adaptation of currents for comparison (1)

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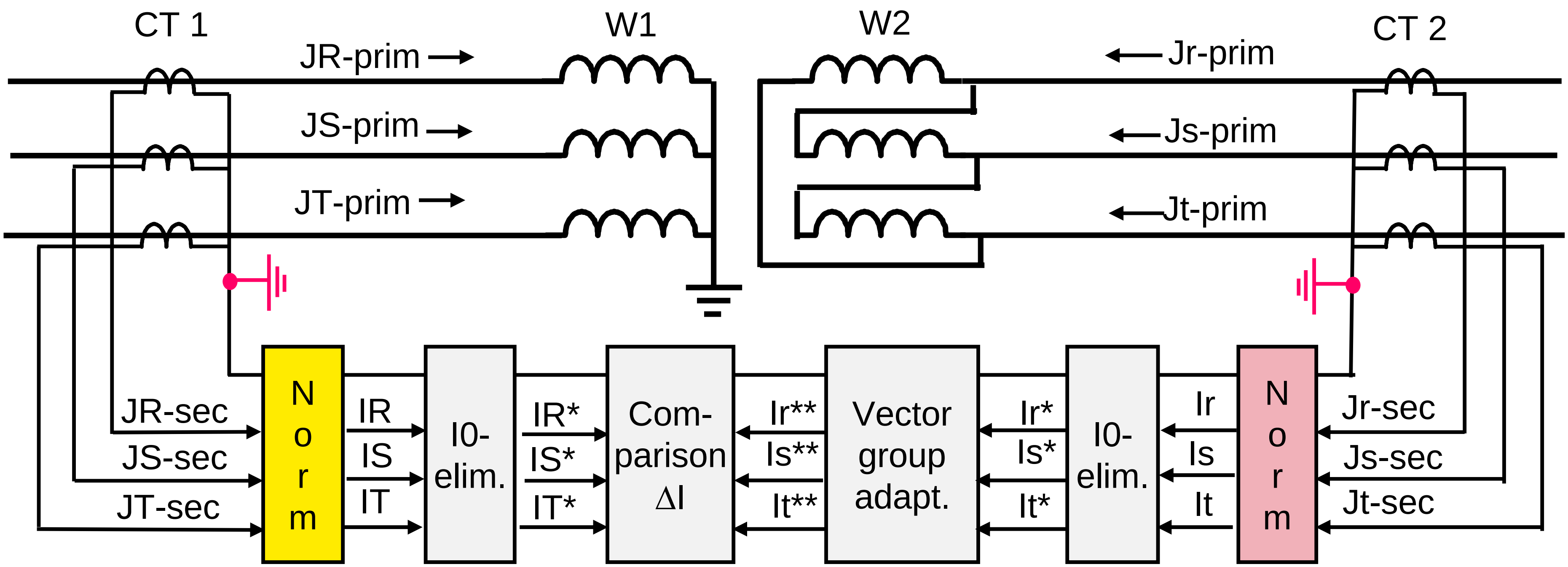


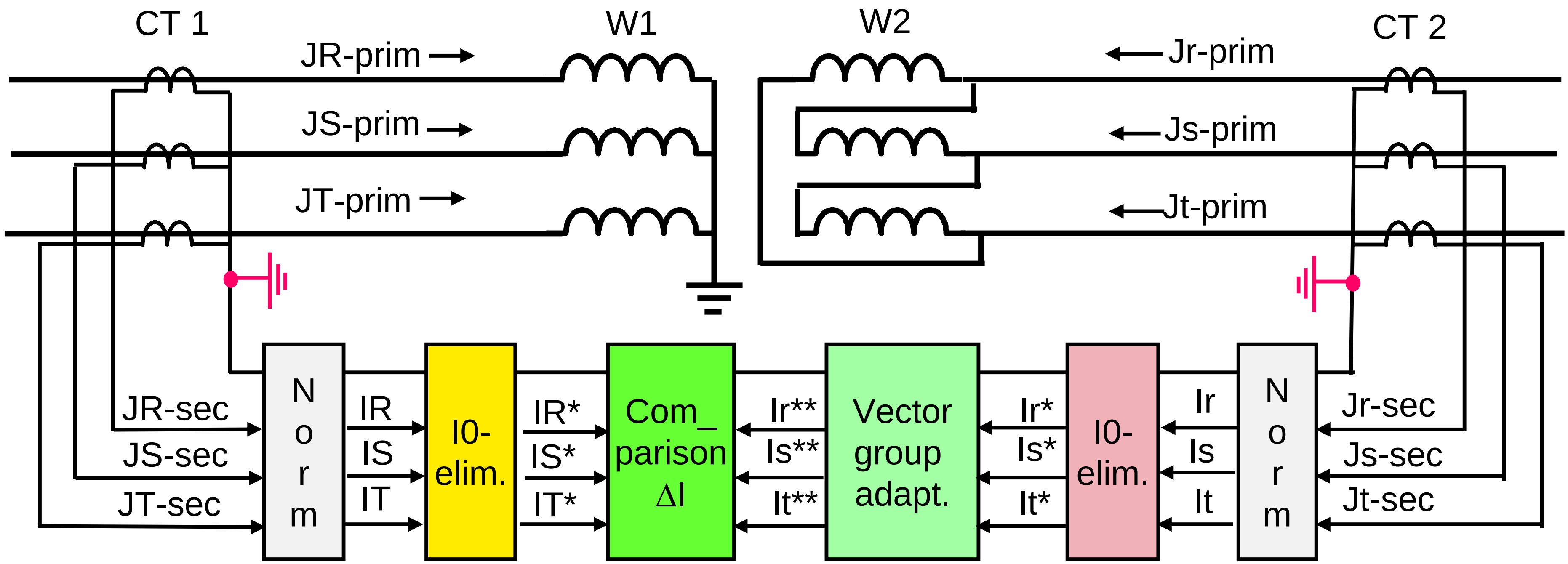
$$I_{N-Transf-W1} = \frac{S_N}{\sqrt{3} \cdot U_{N\text{-}1}}$$

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

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

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

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:

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

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

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

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

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

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:

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

Digital transformer protection
Current adaptation, Example (1)

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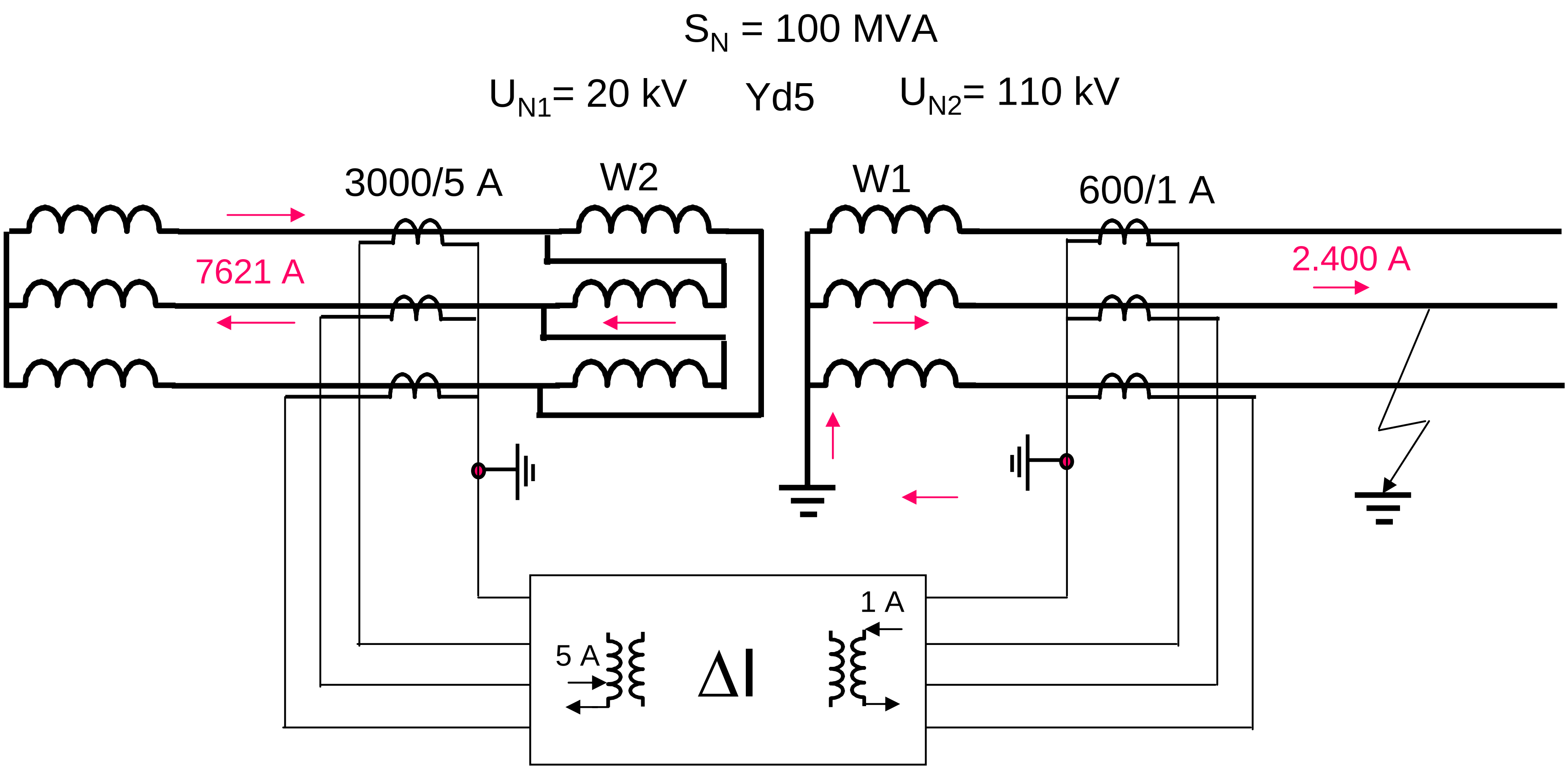

Digital transformer protection
Current adaptation, Example (2)

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20-kV-side

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

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

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

110-kV-side

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

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

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

I0-elimination:

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

Vector group adaptation: Yd5

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

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

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

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

7UT6
Operating characteristic

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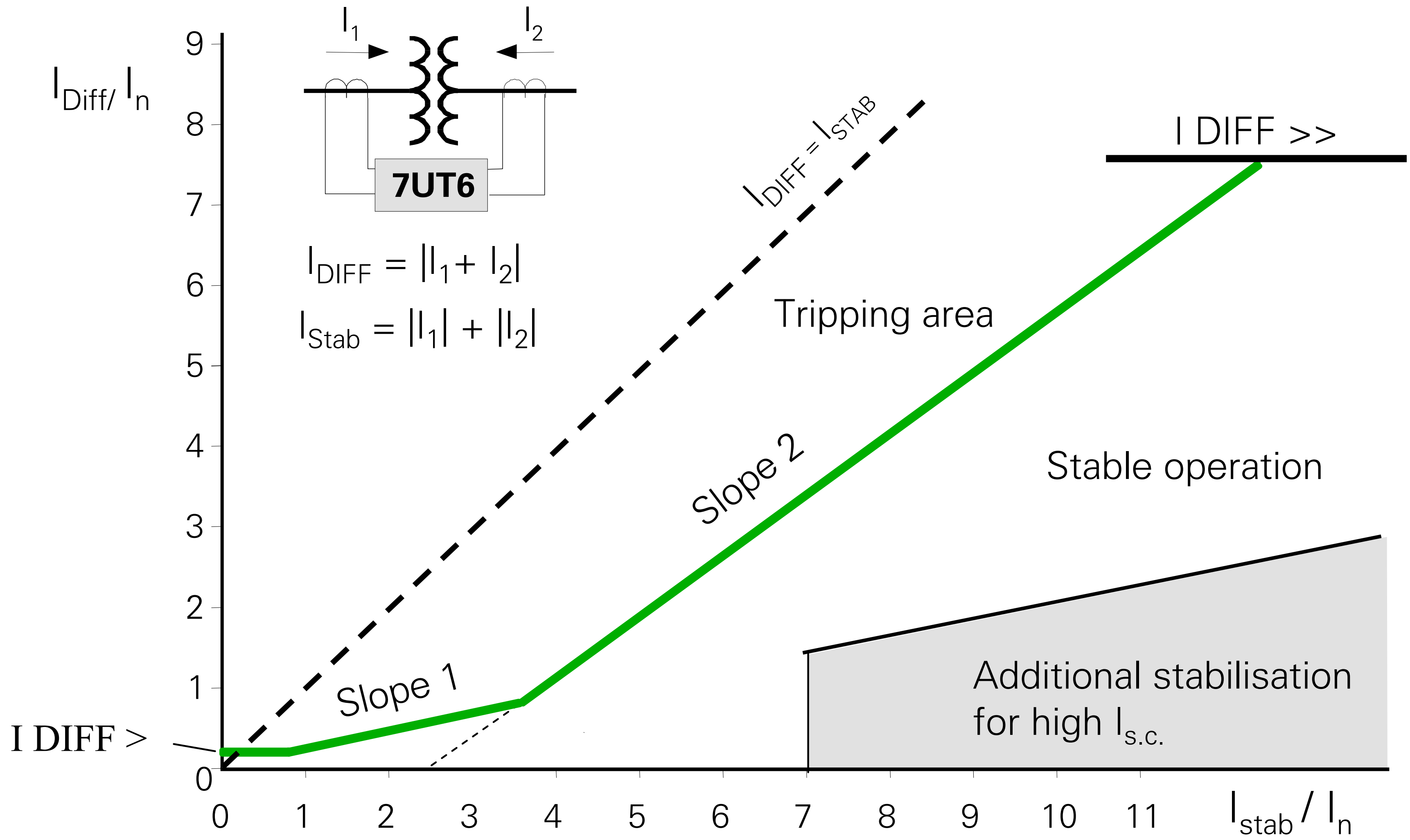

I_0-elimination / correction: Summary

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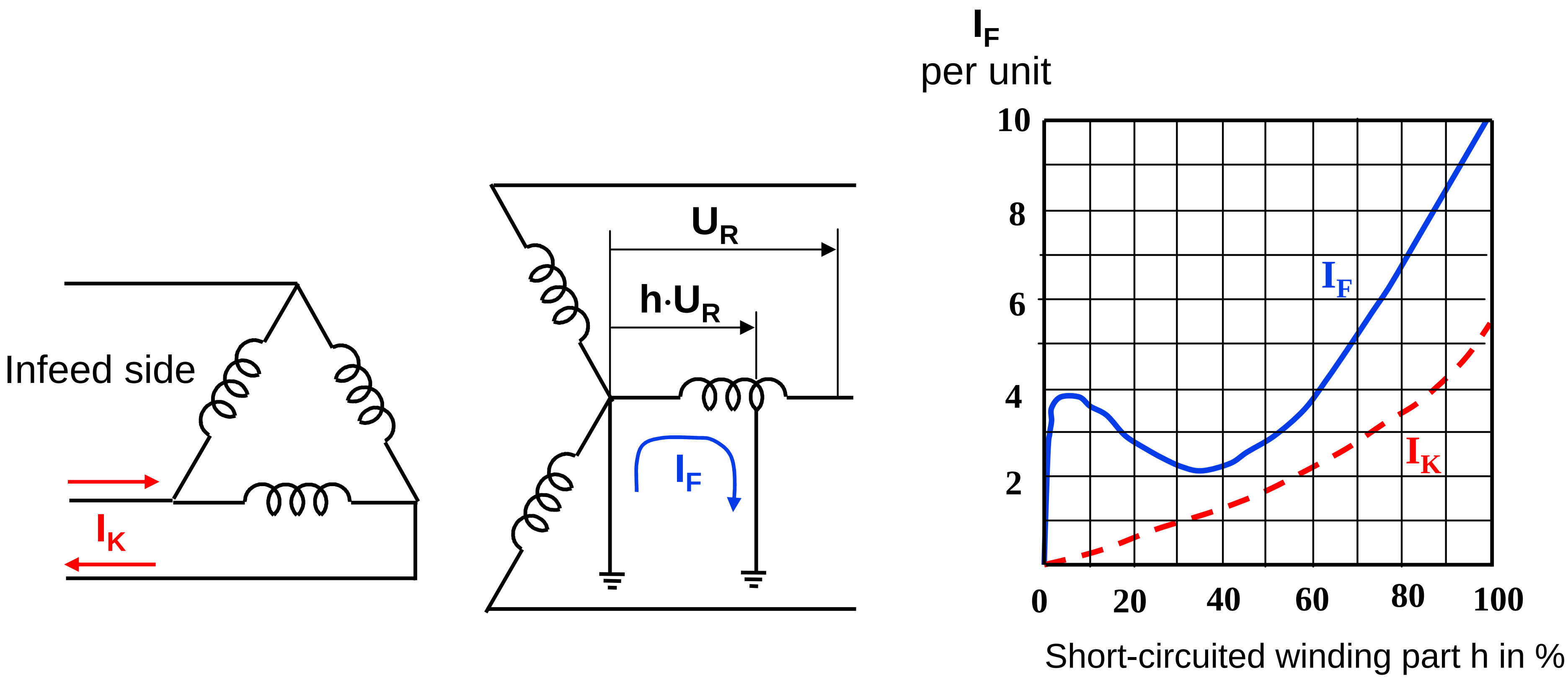
➔ **I_0- elimination** necessary at all windings with earthed neutral or with grounding transformer in the protection range
Earth fault sensitivity reduced to 2/3 !
Incorrect fault type indication!

➔ **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

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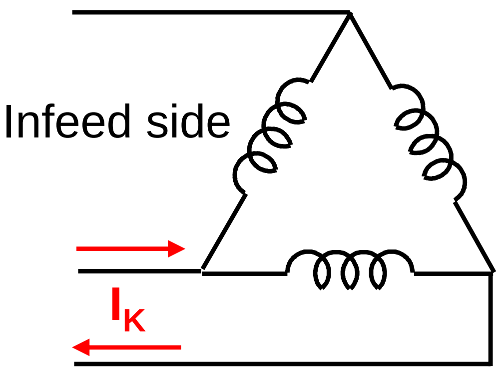
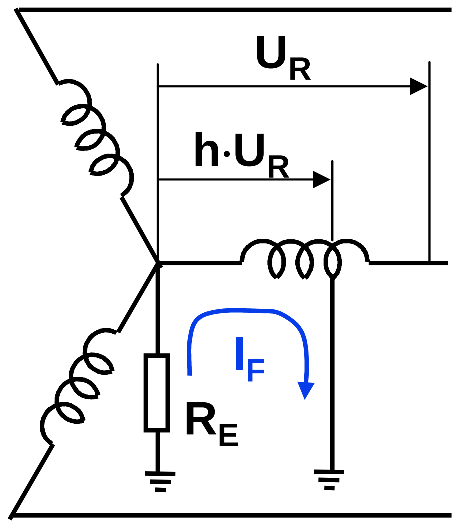
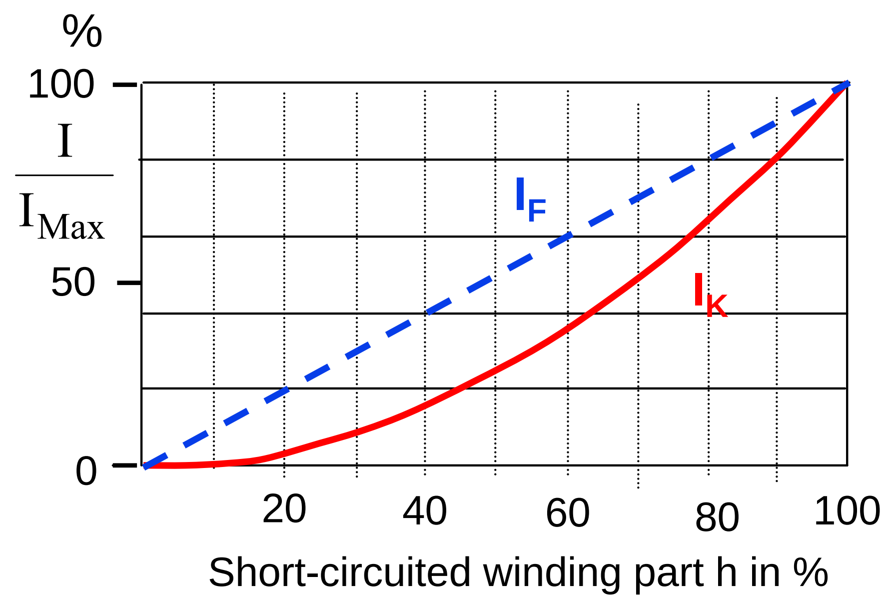






$$I_F = \frac{h \cdot U_R}{R_E}$$

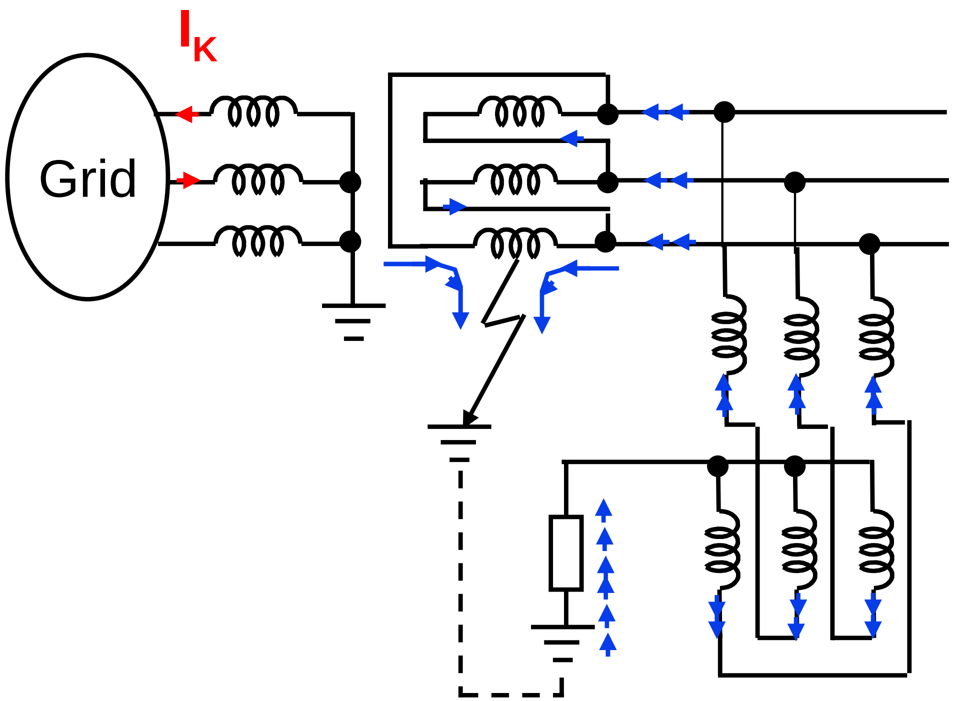
$$I_K = \frac{h \cdot w_2}{w_1} \cdot I_F = h \cdot \frac{U_{2n}}{U_{1n} \cdot \sqrt{3}} \cdot I_F$$

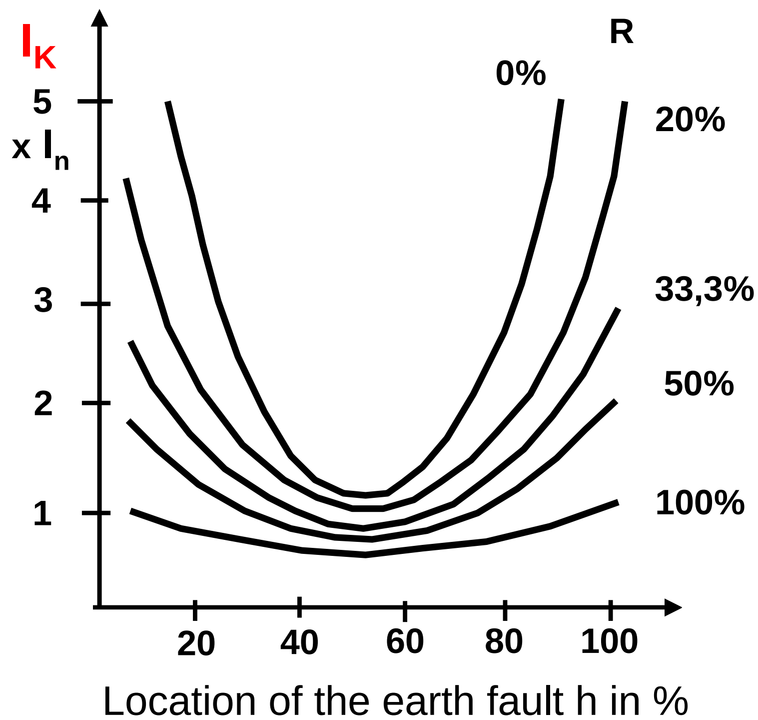
$$I_K = h^2 \cdot \frac{1}{\sqrt{3}} \cdot \frac{U_{2n}}{U_{1n}} \cdot \frac{U_R}{R_E}$$

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

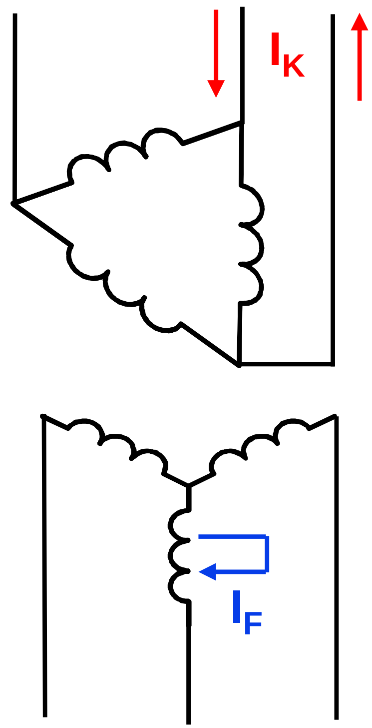
Transformer winding to earth fault

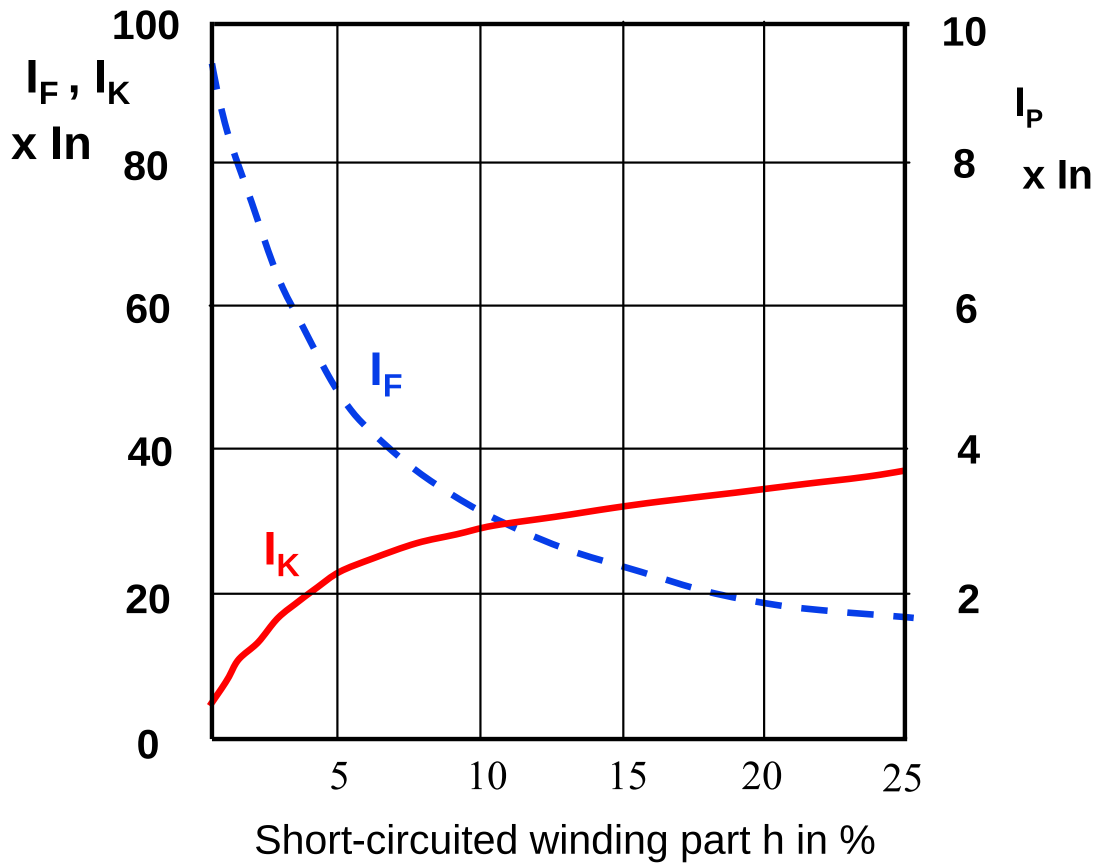
Earth fault in the delta winding





Transformer winding short-circuit





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

Restricted earth fault protection of relay 7UT6

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$$I_0^{*} = I_N$$

$$I_0^{**} = I_R + I_S + I_T = 3I_0$$

$$I_{restr} = \left|I_0^{*} - I_0^{**}\right| - \left|I_0^{*} + I_0^{**}\right|$$

Basic operating area:

$$I_{Op} = I_0^{*}$$

$$\text{for } -90^0 \le \varphi\left(I_0^{*} / I_0^{**}\right) \le +90^0$$

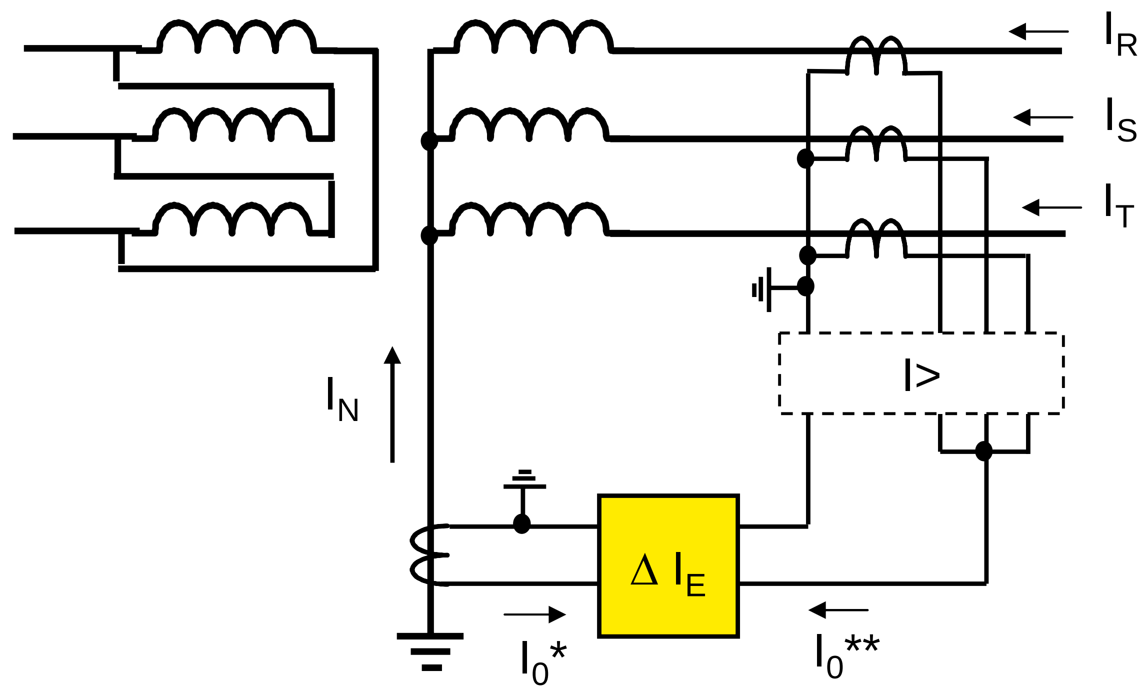
$$\text{if } I_{Op} \ge I_{set}$$

Extended operating area:

$$I_{Op} = I_0^{*} - k_0 \cdot I_{restr}$$

$$\text{for } +90^0 \le \varphi\left(I_0^{*} / I_0^{**}\right) \le +270^0$$

$$\text{if } I_{OP} \ge I_{restr}$$



Restricted earth fault protection of 7UT6
Operating characteristic (2)

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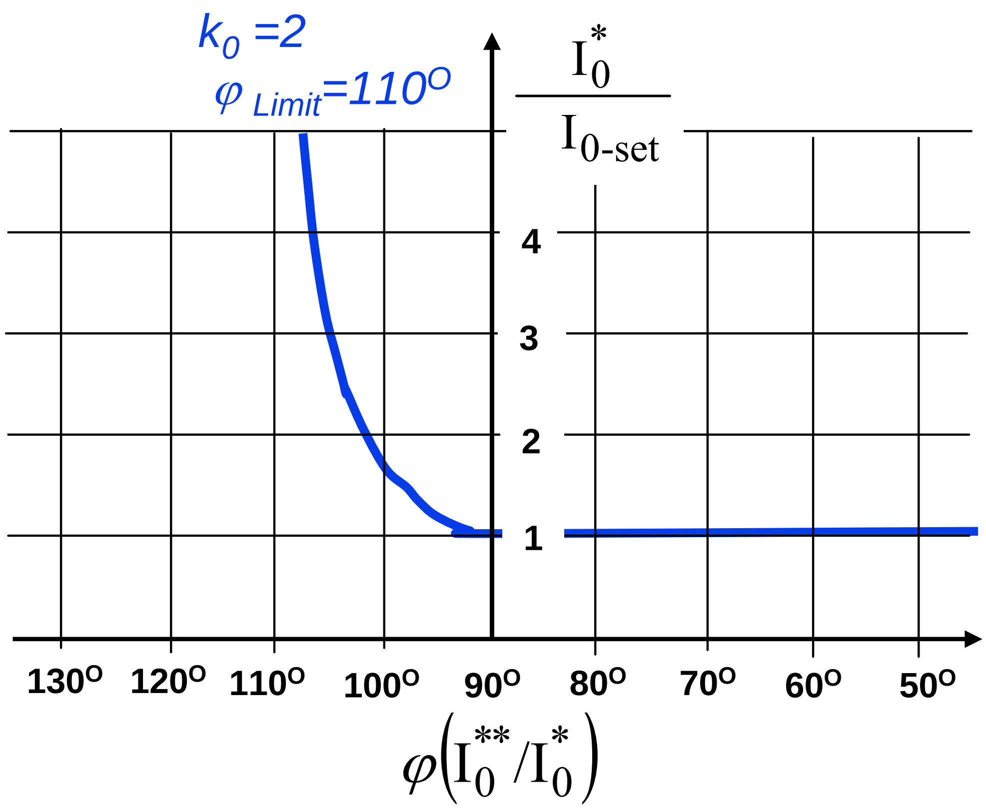
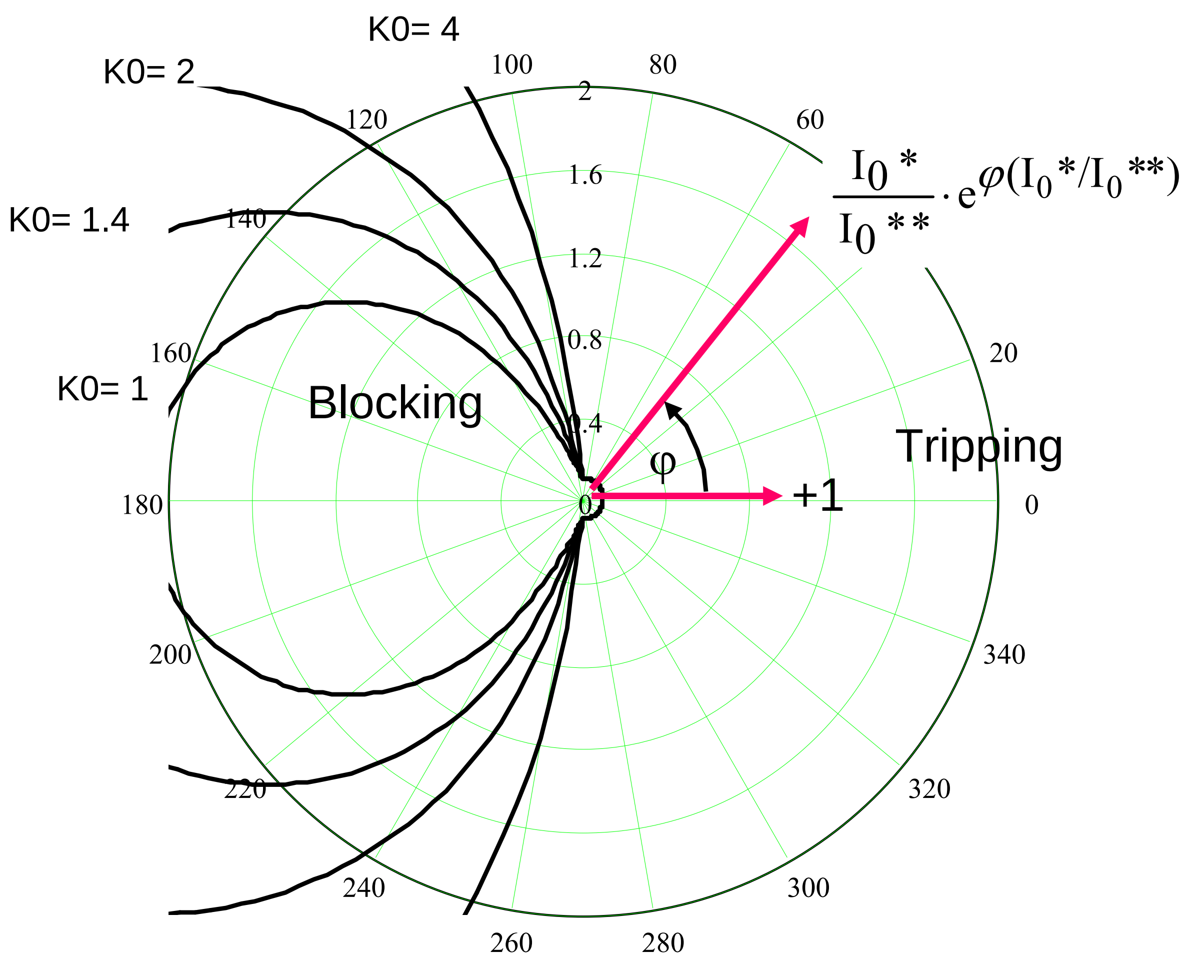
K_0	φ_{Limit}
1.0	130
1.4	120
2.0	110
4.0	100
∞	90



$$\frac{I_0^{**}}{I_0^*} = \frac{\Sigma I_{Ph}}{I_N} = 1$$

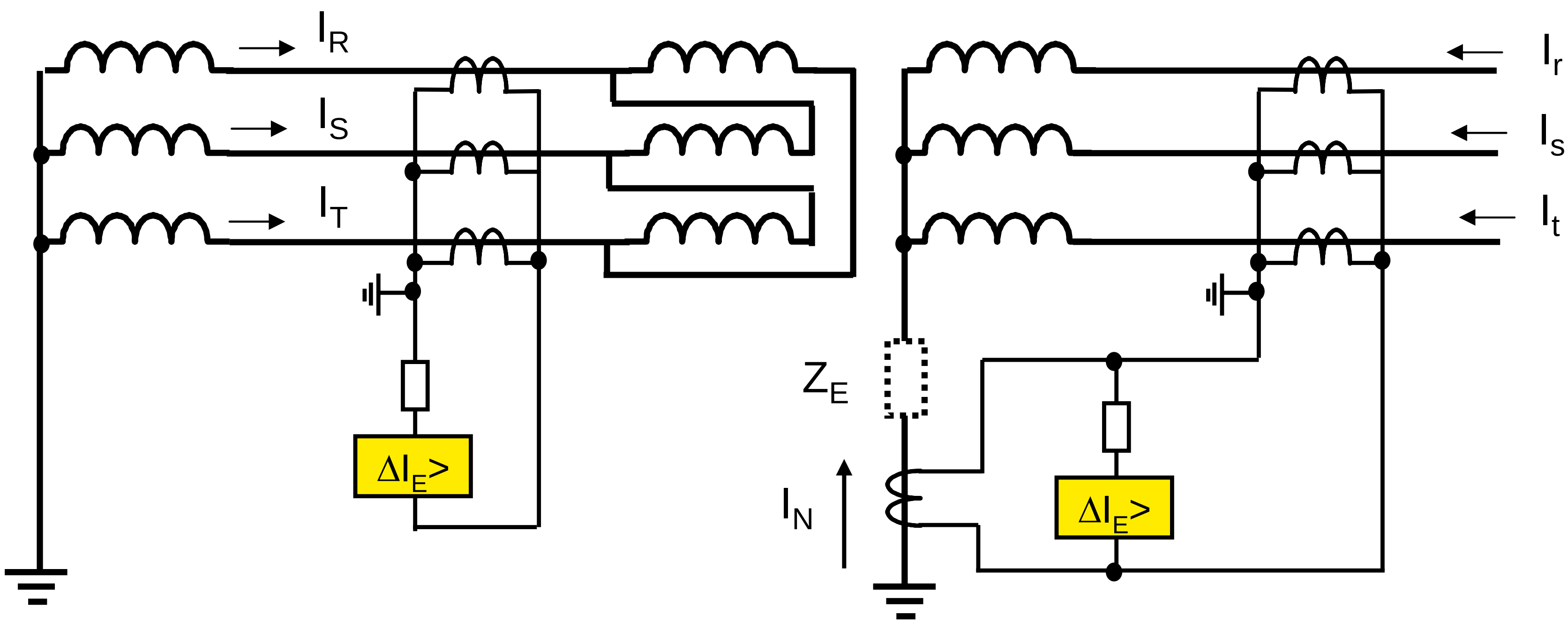
Restricted earth fault protection of 7UT6
Polar characteristic



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.

Transformer HI-earth fault protection



HI differential protection of an autotransformer

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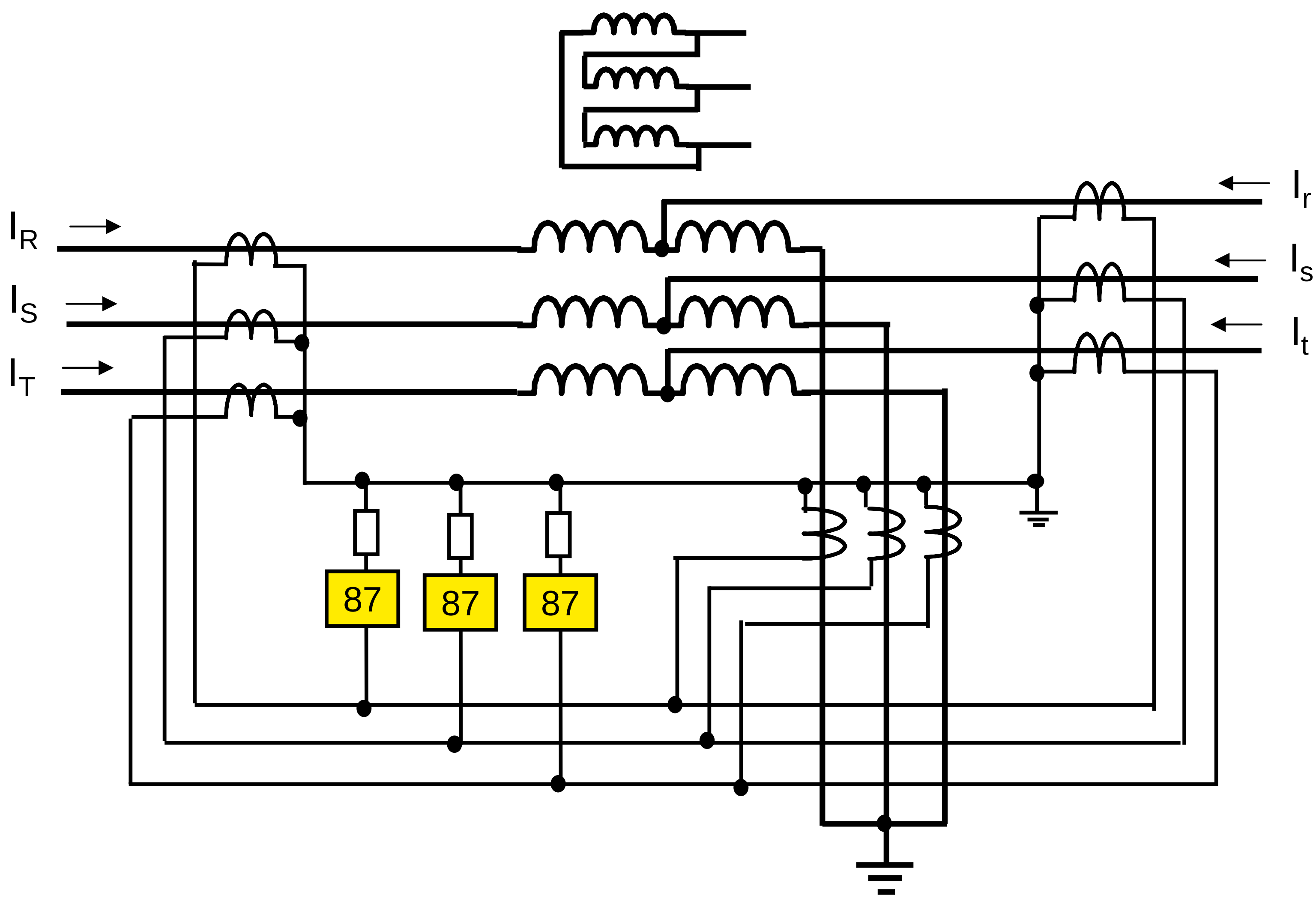

HI earth fault protection of an autotransformer

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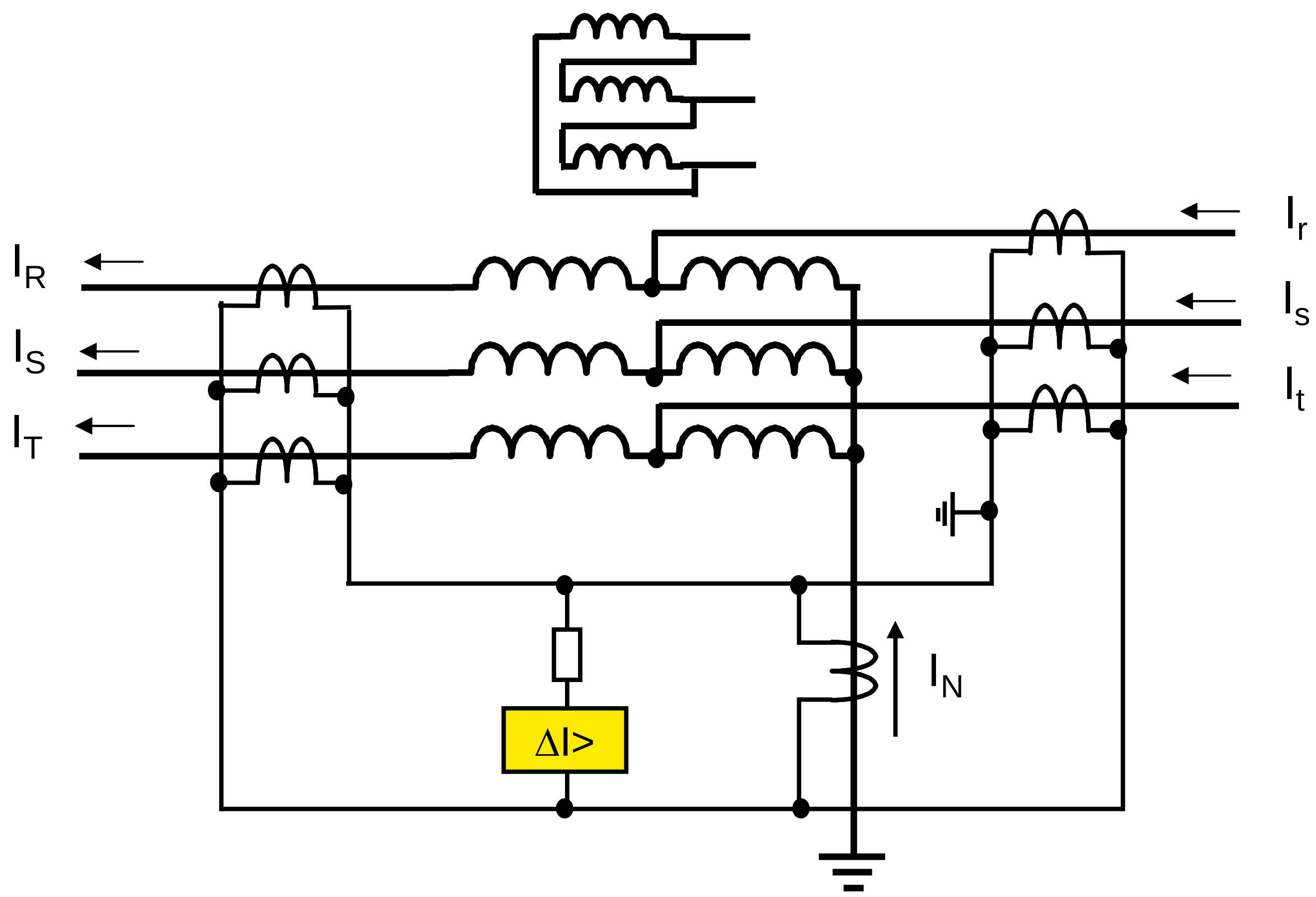
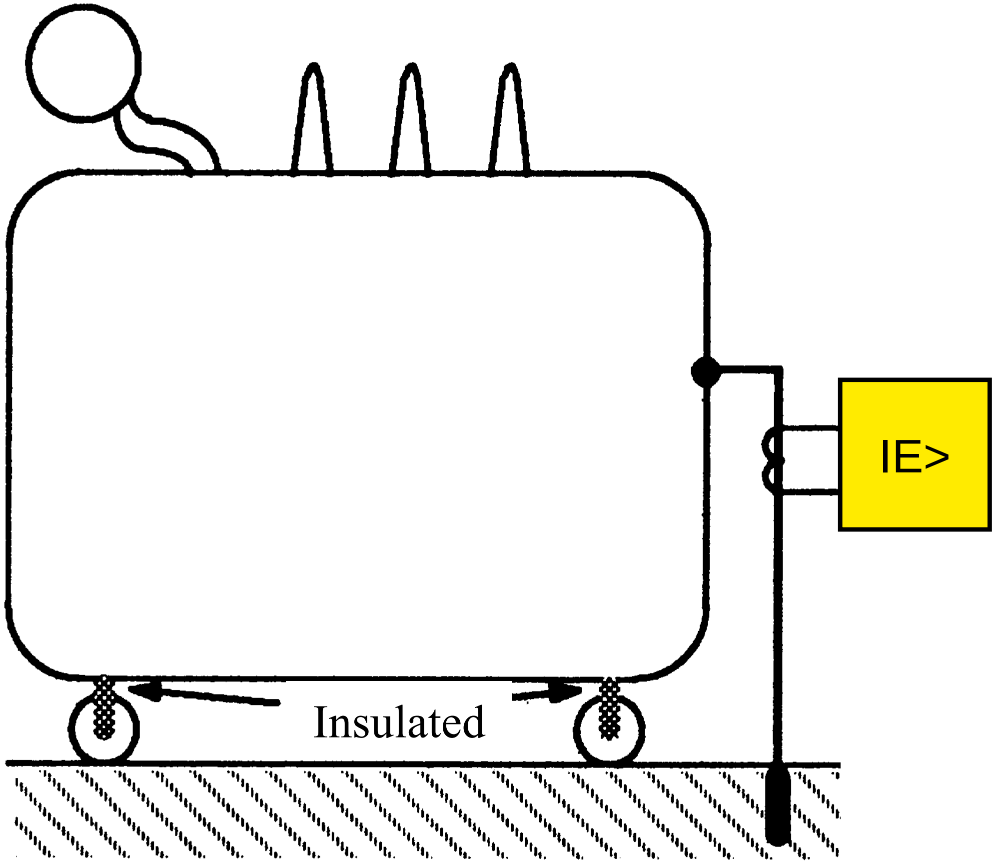


Transformer tank protection 64T: Principle



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Transformer Protection
with
Siemens SIPROTEC
7UT6

7UT612

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

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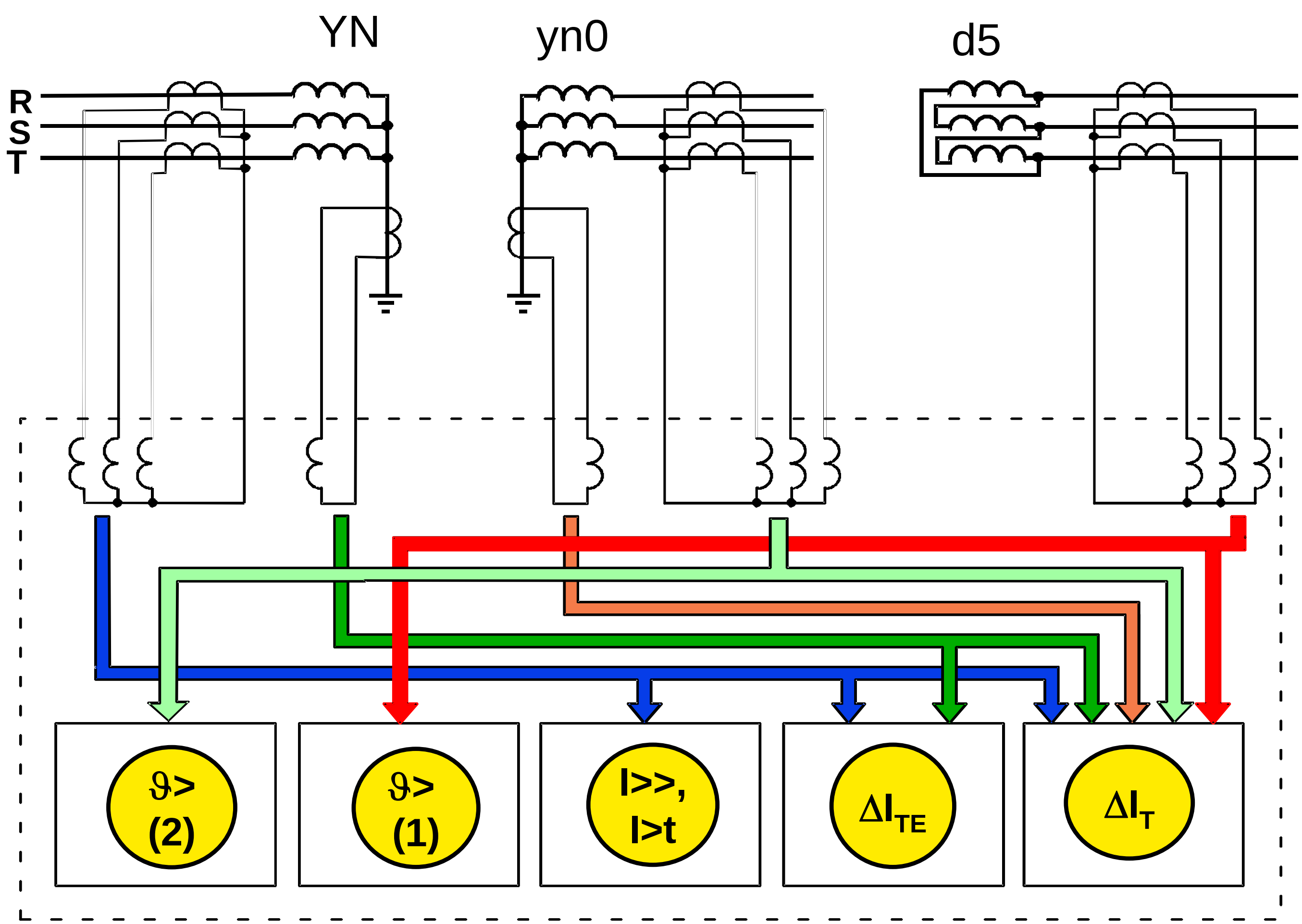

Relay 7UT6: Application examples

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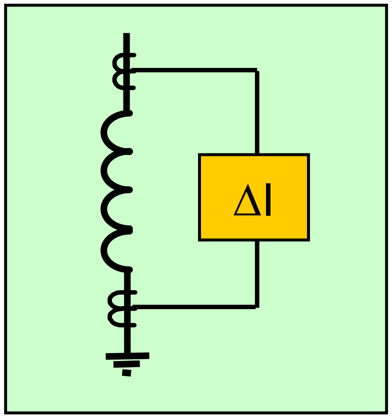
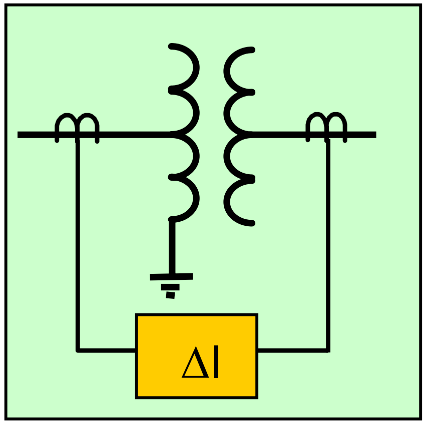
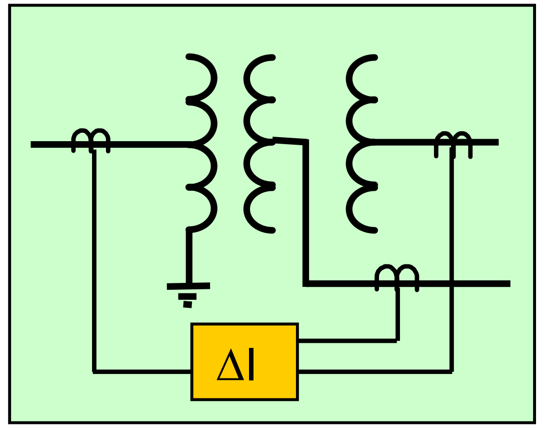


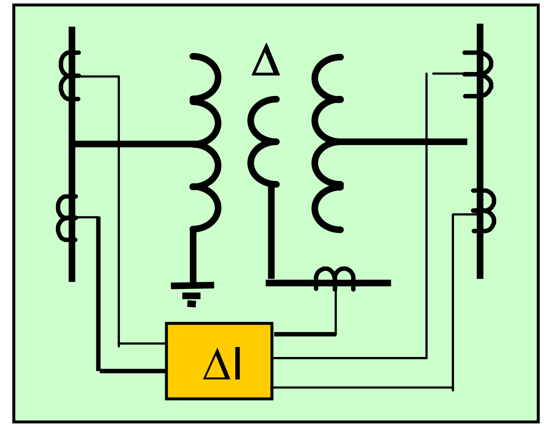
Shunt Reactor



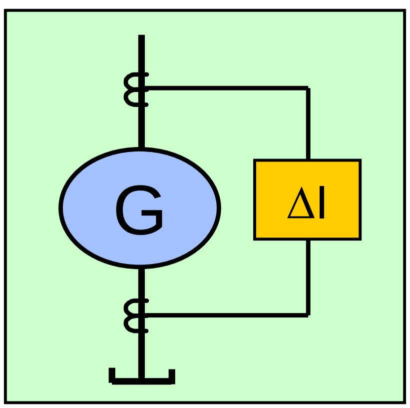
Two winding transformer



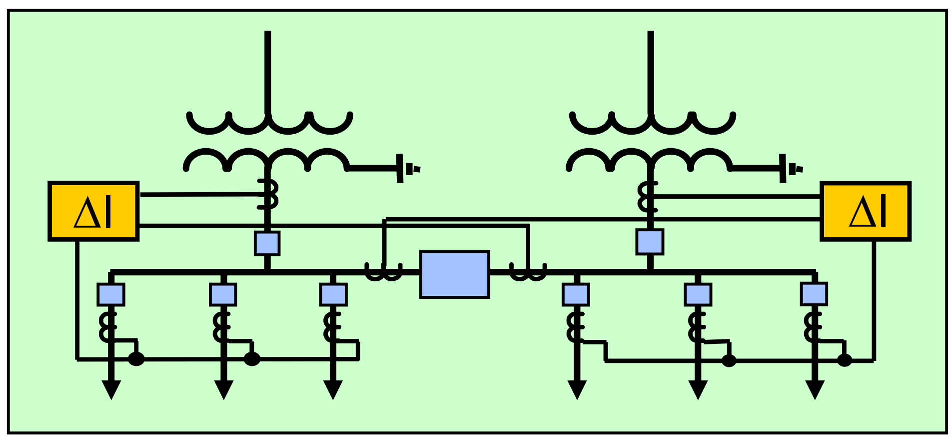
Three winding transformer



Transformer bank (1-1/2-LS)



Generator / Motor



Busbars

Operating characteristic

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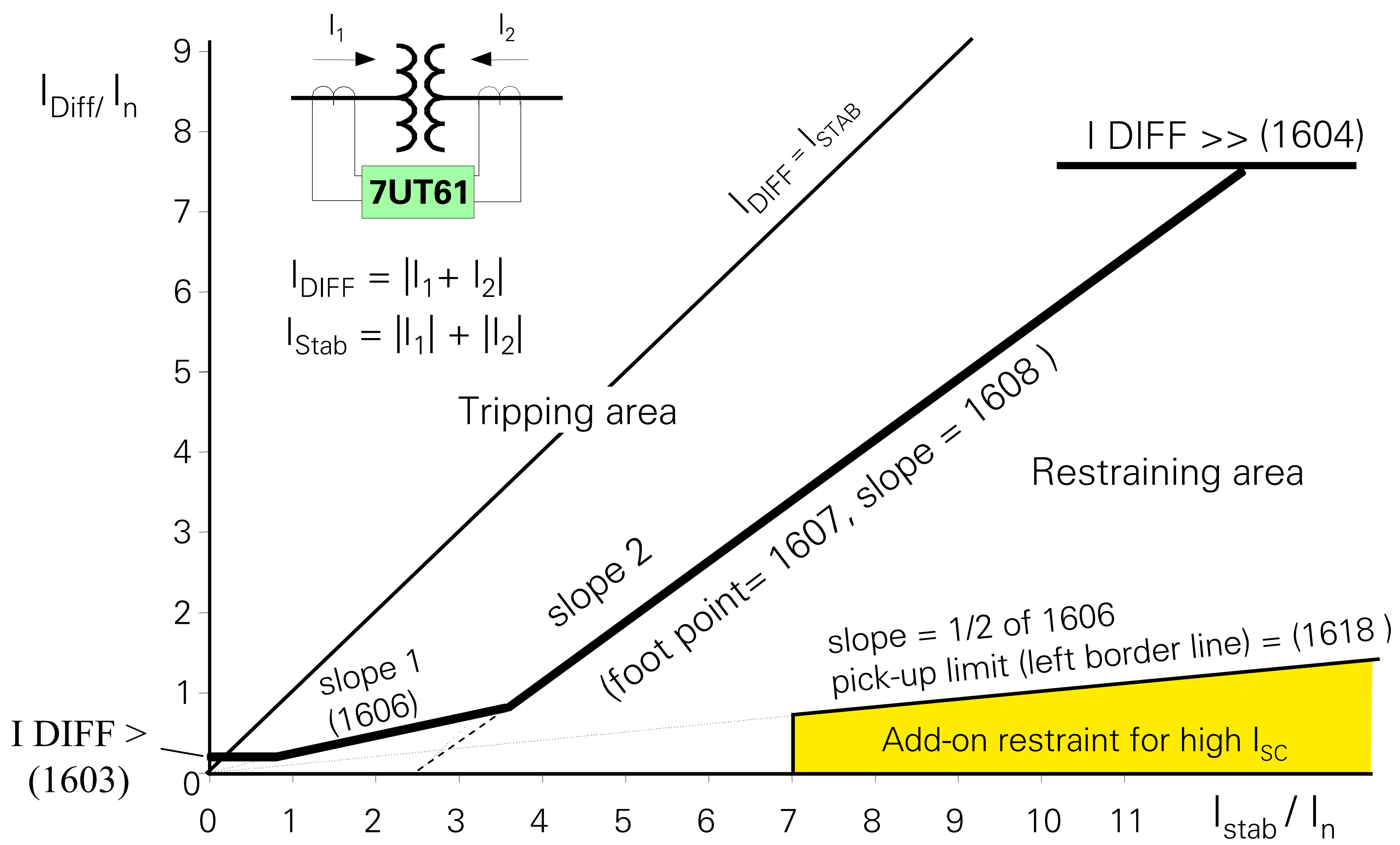

Advantages of digital transformer differential protection

SIEMENS

- High stability against c.t. saturation provided by integrated saturation detector and add-on stabilisation
- High stabile against inrush currents due to advanced filter technology (Fourier analysis) and optional cross-blocking function
- High stability against over-excitation (5th harmonic blocking)
- Short tripping time - typically 1.5 cycles
- High set ΔI fast tripping < 1 cycle
- Sensitive earth differential protection against interturn faults and earth faults near winding neutral
- Integral ratio and vector group adaptation (no external auxiliary CTs required)
- Integral thermal overload protection
- External start of fault recording (e.g. by gas pressure relays)

7UT6
Integrated protection functions

87T

Transformer differential protection

- ΔI>
- Rush-stabilised (2nd harmonic)
- Stabilised against overfluxing (5th harmonic)
- ΔI>> high set element, non-stabilised

49-1
49-2

Thermal overload protection

50/51
50HS

Time overcurrent protection (IT or DT)

87N

Earth current differential protection (7UT613)

64T

Tank protection (7UT613**)**

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Application examples

Protection of a two winding transformer

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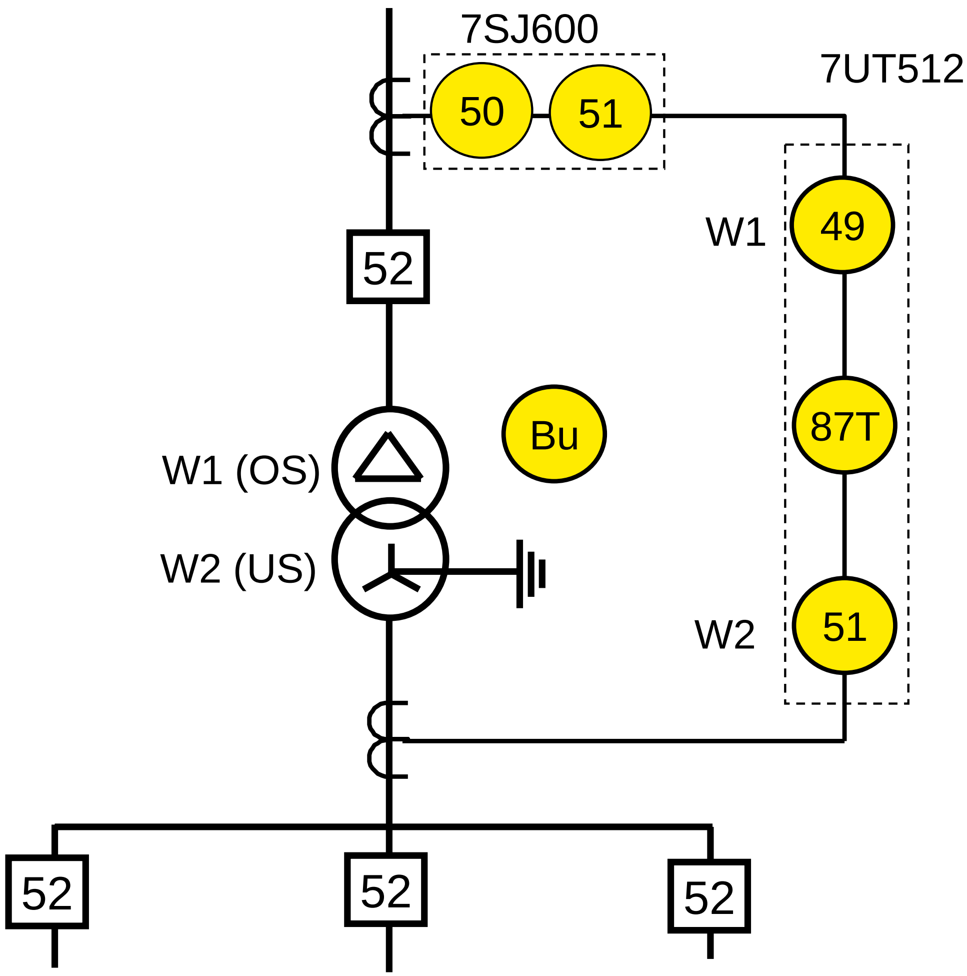
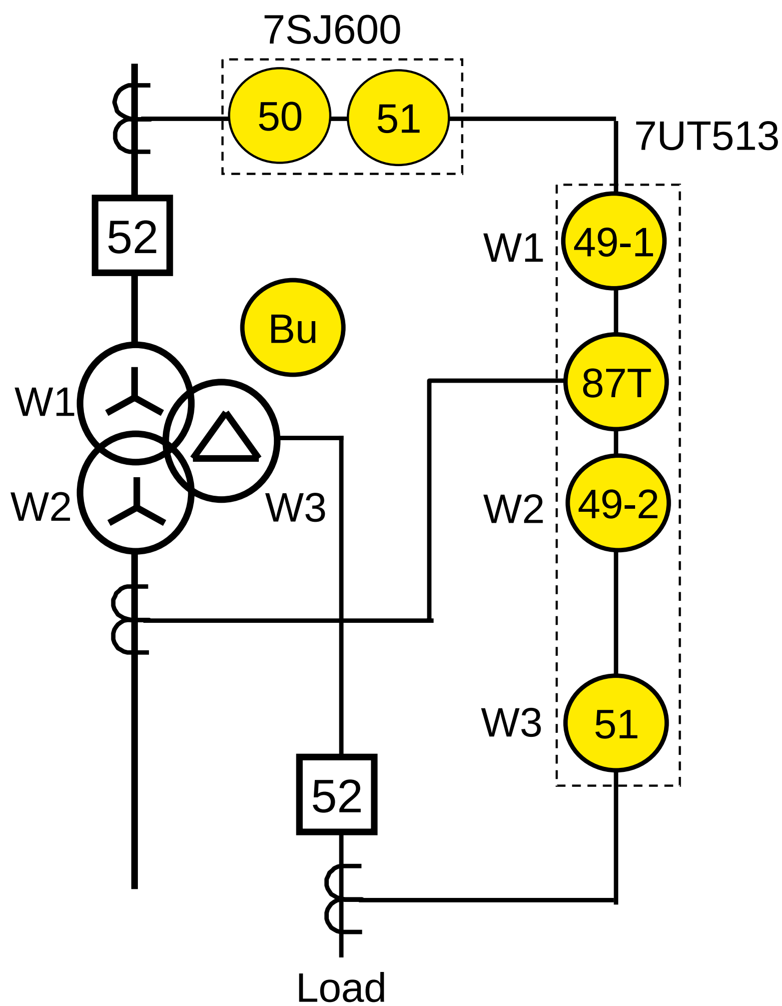


Protection of a three winding transformer



Restricted earth fault protection for a two winding transformer

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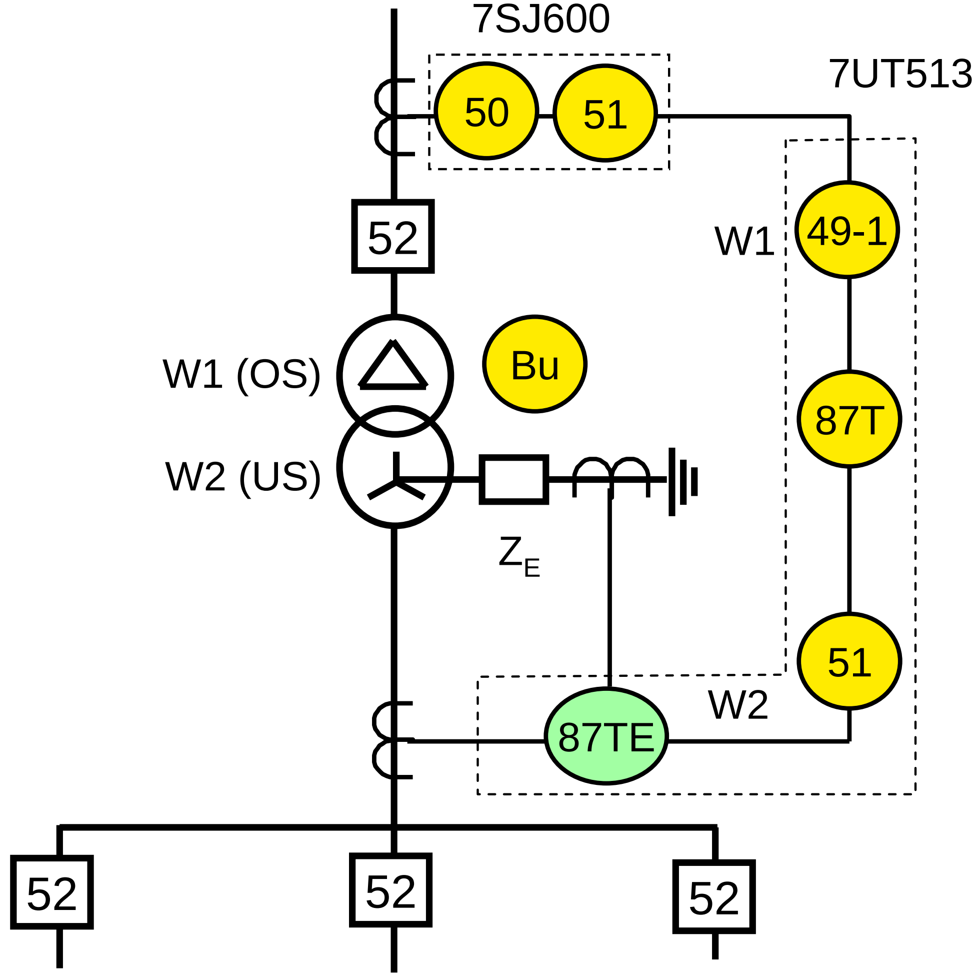
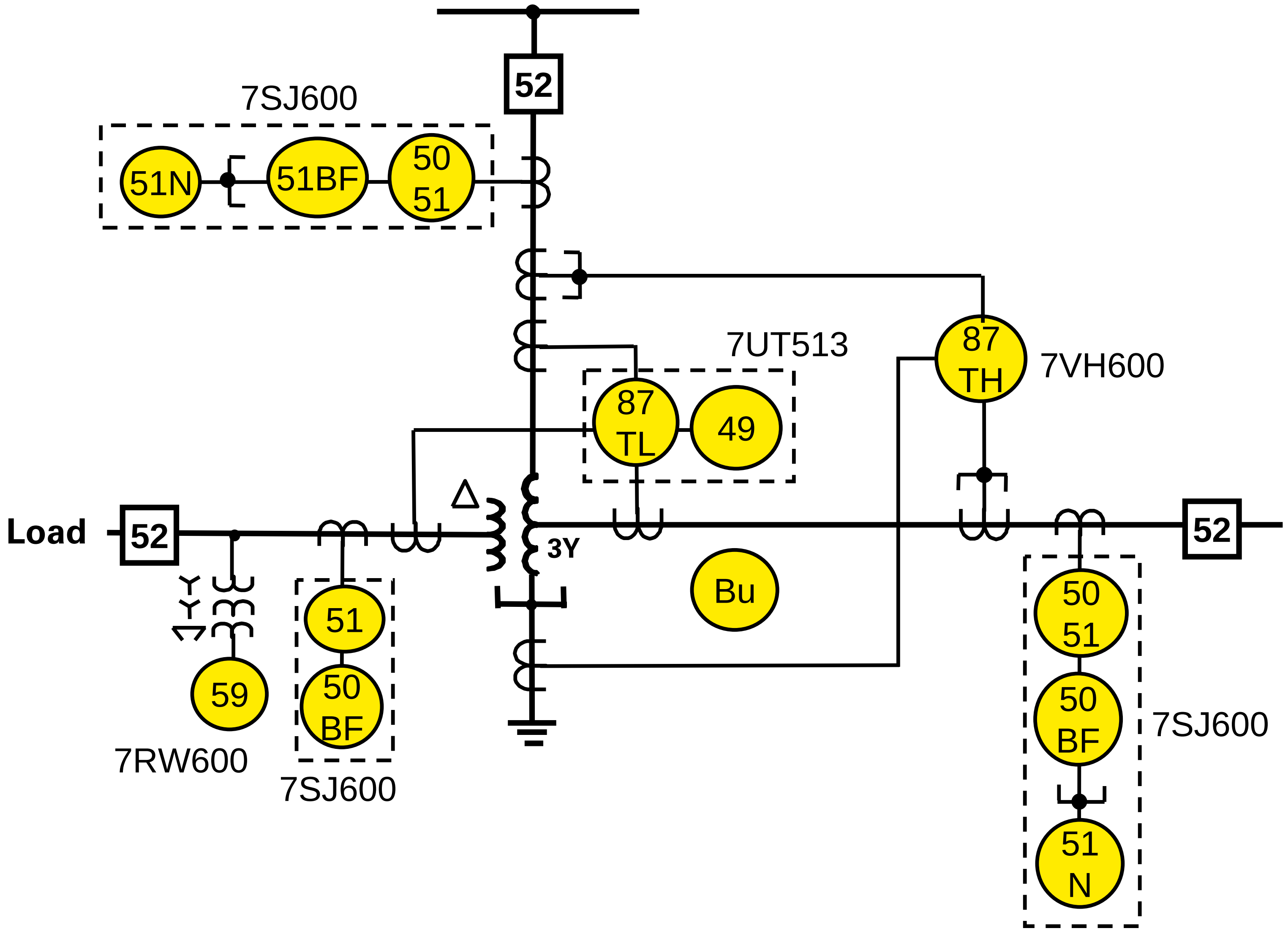
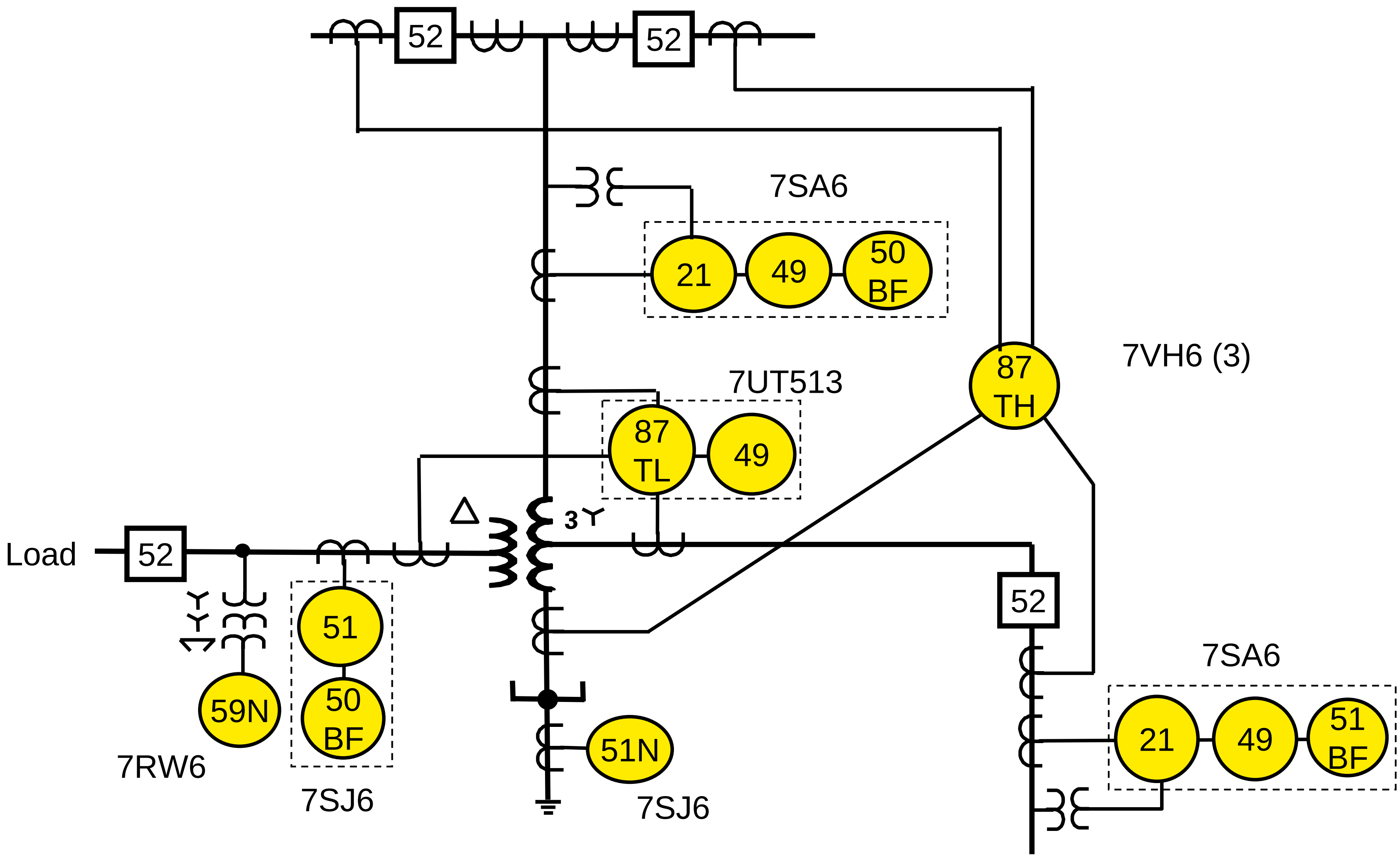


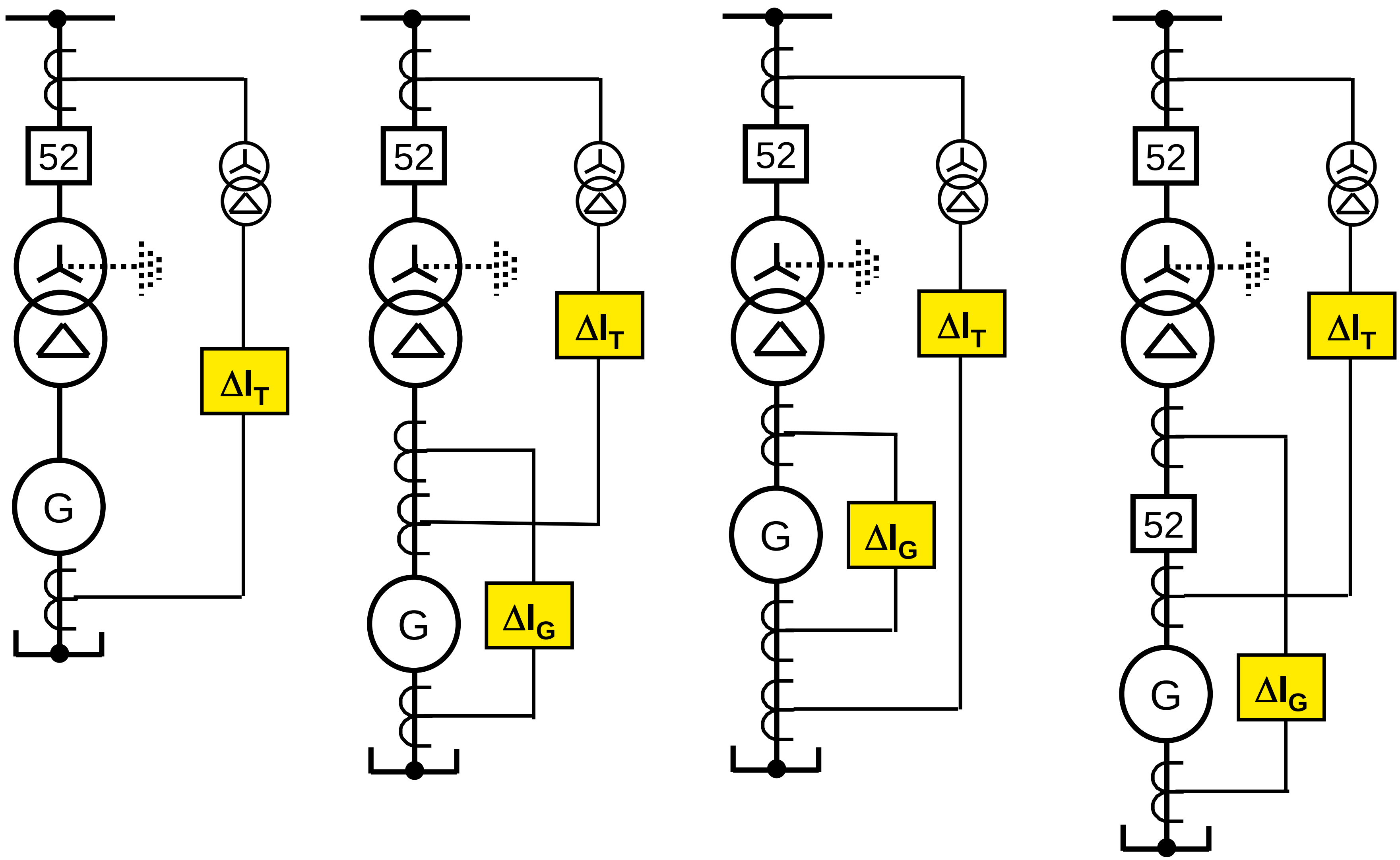
Protection of an autotransformer



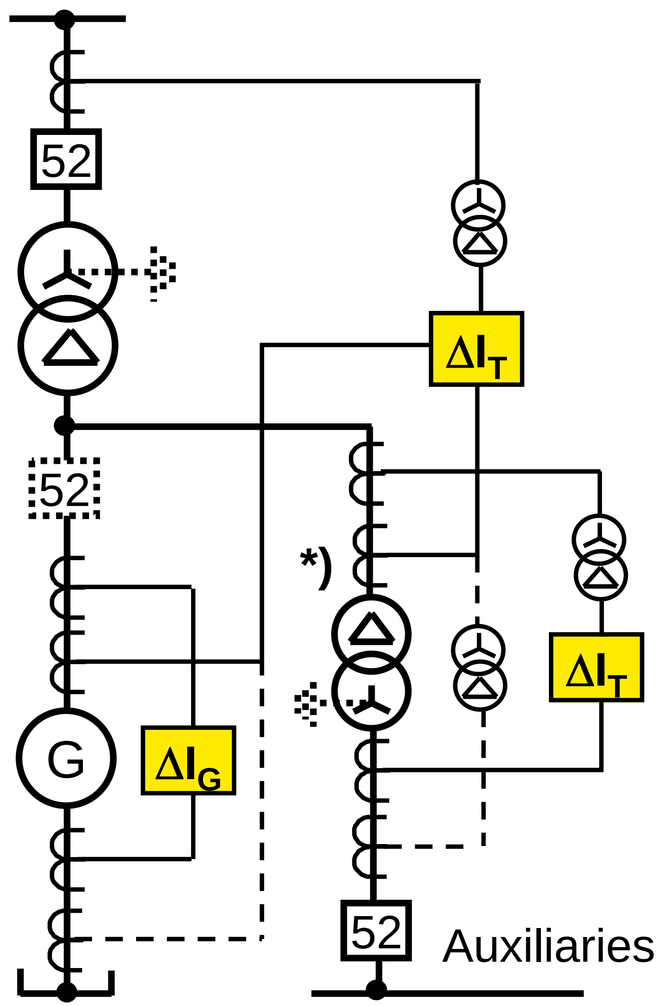
Protection of a large transformer bank



Differential protection of generation units



Differential protection of generation units (2)



*) same ratio as generator CTs

Thermal protection of transformers

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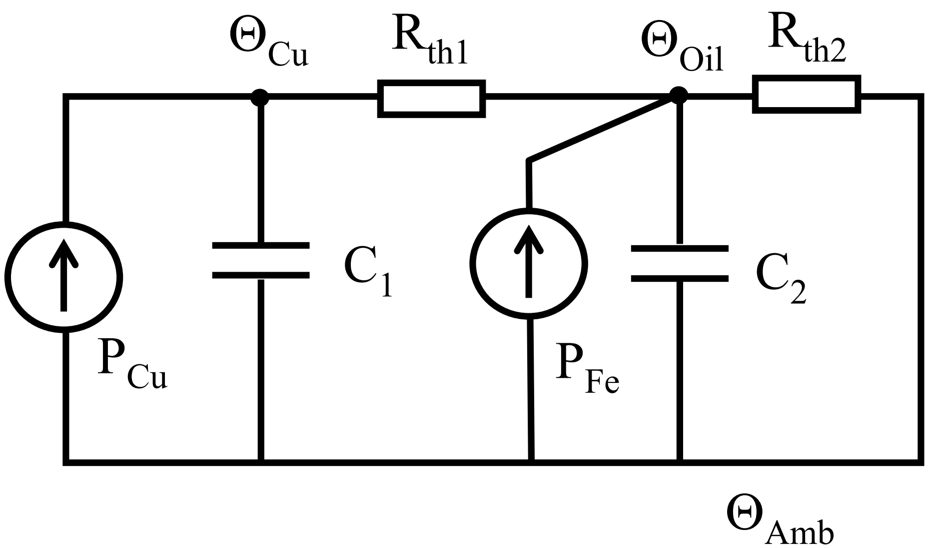


Legend:

P_{Cu}: Winding losses ($I^2 \cdot R$)

P_{Fe}: Core and tank losses

R_{th1}: Thermal resistance Copper-Oil

R_{th2}: Thermal resistance Oil-Air (cooling medium)

C_1: Winding thermal capacity

C_2: Thermal capacity of Oil, Core and tank

Θ_{Cu}: Winding copper temperature

Θ_{Oil}: Oil temperature

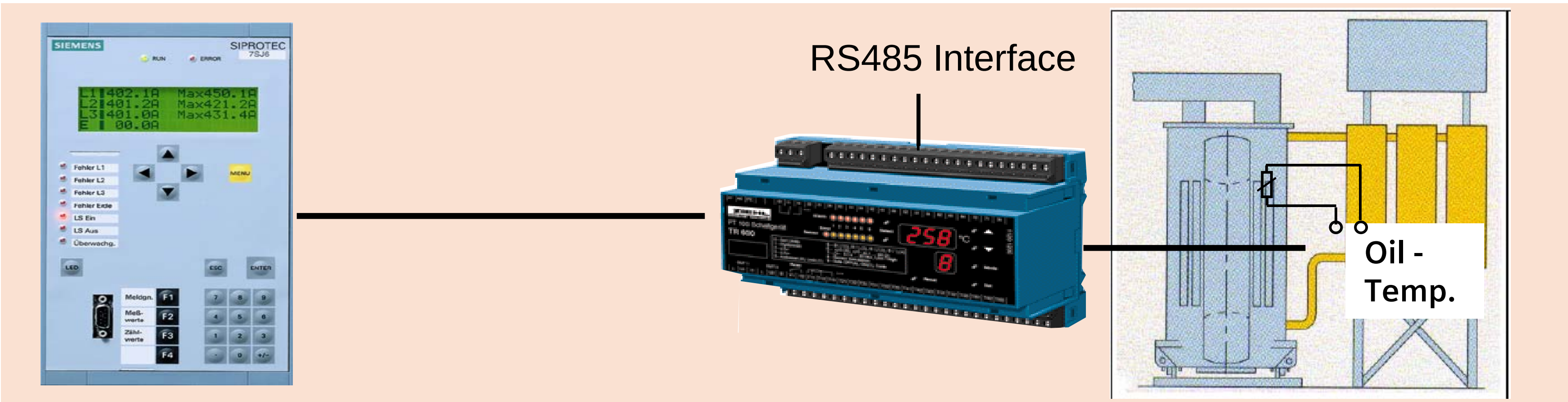
$\Theta_{Amb.}$: Ambient temperature

Lifetime of insulation depends on the winding Hot-spot temperature.

6 °C higher temperature increases the aging of the insulation by the factor 2!

7SA6: Temperature monitoring

SIEMENS



- Two thermo-devices can be connected to the serial service interface
- Monitoring of up to 12 measuring points (6 per thermo-device)
- One input is reserved for hot spot monitoring (measurement of oil temperature)
- Thermistors: Pt100, Ni100 or Ni120

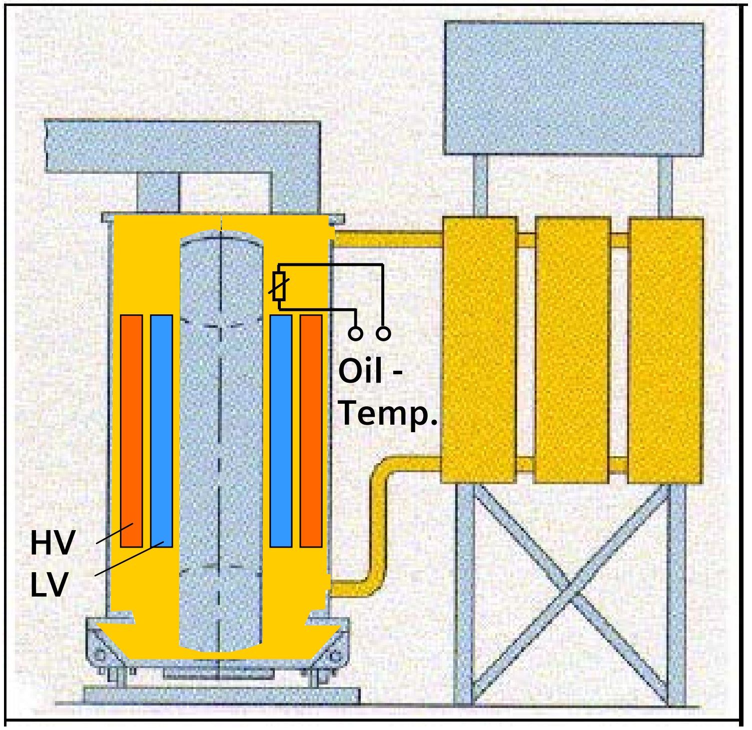
The the upper oil temperature is directly measured by the use of thermoelement.
The hot spot temperature is calculated by the relay using the thermal model Cu-Oil:

$$\frac{d\Theta_{Cu}}{dt} = \frac{1}{\tau_{Th}} \cdot \left(\frac{I}{Ir}\right)^2 - \frac{1}{\tau_{Th}} \cdot \left(\Theta_{Cu} - \Theta_{Oil}\right)$$

I = actual transformer current
Ir = rated transformer current
τ_{th} =time constant of the winding

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

SIEMENS



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

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° 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 (2)
Example: Natural cooling

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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

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

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