Short-circuits in ES

Short-circuit:

- cross fault, quick emergency change in ES
- the most often fault in ES
- transient events occur during short-circuits

Short-circuit formation:

- fault connection between phases or between phase(s) and the ground in the system with the grounded neutral point

Main causes:

- insulation defect caused by overvoltage
- direct lightning strike
- insulation aging
- direct damage of overhead lines or cables

Short-circuit impacts:

- total impedance of the network affected part decreases
- currents are increasing => so called short-circuit currents I_k
- the voltage decreases near the short-circuit
- I_k impacts causes device heating and power strain
- problems with I_k disconnecting, electrical arc and overvoltage occurred during the short-circuit
- synchronism disruption of ES working in parallel
- communication line disturbing => induced voltages

Note: In short-circuit places transient resistances arise.

- transient resistance is a sum of electrical arc resistance and resistance of other I_k way parts (determination of exact resistances is difficult)
- current and electrical arc length is changing during short-circuit => resistance of electrical arc is also changing

- transient resistances are neglected for I_k calculation (dimensioning of electrical devices) → *perfect short-circuits*

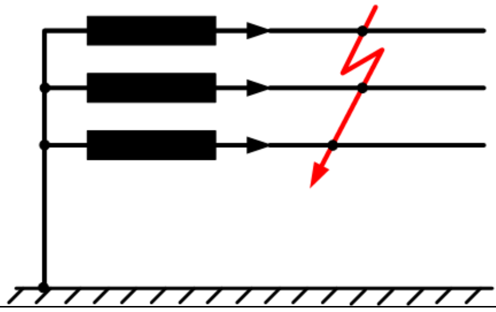
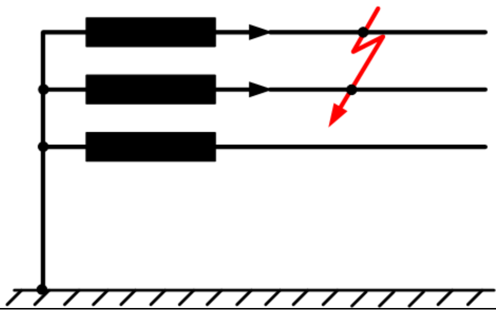
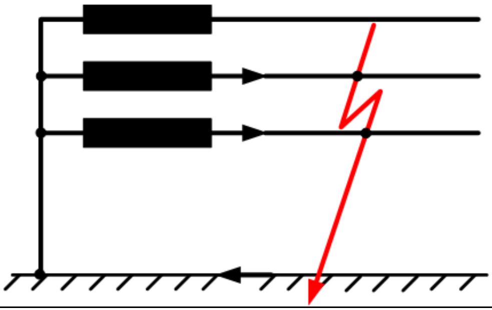
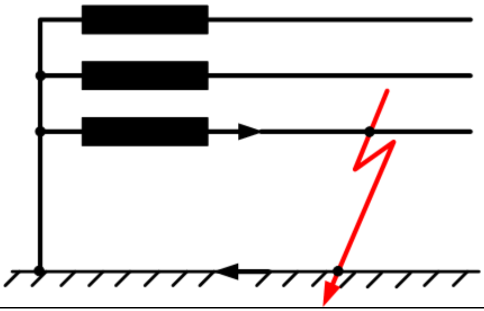
Short-circuits types

Symmetrical short-circuits:

- Three-phase short-circuit => all 3 phases are affected by short-circuit
  - little occurrence in the case of overhead lines
  - the most occurrences in the case of cable lines => other kinds of faults change to 3ph short-circuit due to electrical-arc impact

Unbalanced (asymmetrical) short-circuits:

- phase-to-phase short-circuit
- double-phase-to-ground short-circuit
- single-phase-to-ground short-circuit:
  - in MV a different kind of fault => so called *ground fault*
  - in case of ground fault in MV (insulated or indirectly grounded neutral point) => no change in LV (grounded neutral point)

Short-circuit type	Diagram	Occurrence probability (%)		
		MV	110 kV	220 kV
3ph		5	0,6	0,9
2ph		10	4,8	0,6
2ph to ground		20	3,8	5,4
1ph		*	91	93,1

Short-circuit current time behaviour

$$W_L = \frac{1}{2} L i^2$$

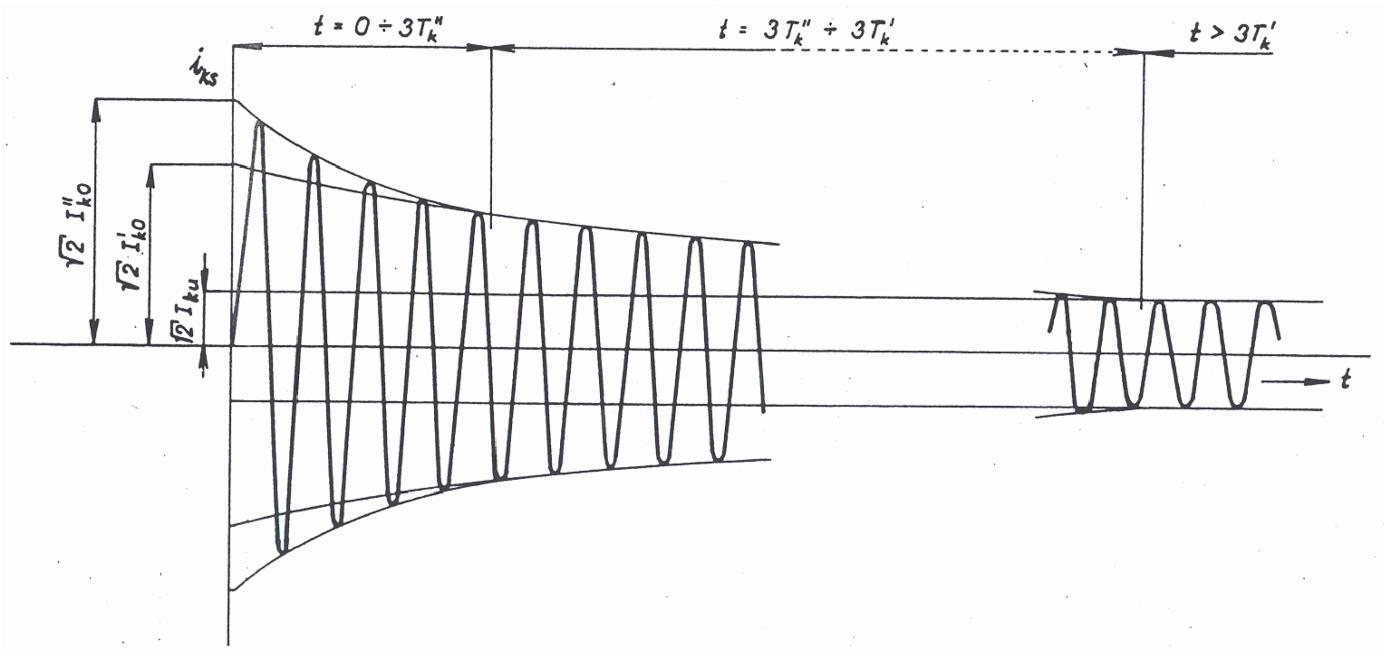
$$P = \frac{dW_L}{dt} < \infty$$ $\rightarrow$ transient event

Time behaviour: open-circuit, resistances neglected
$\rightarrow$ reactance, current of inductive character, higher I_k values

Impact of R on I_k attributes:

- finite R values decrease short-circuit impacts
- R neglecting results in time constants prolongation $\tau = L/R$

$U = U_{max}$ in the short-circuit moment → I_k starts from zero (min. value)

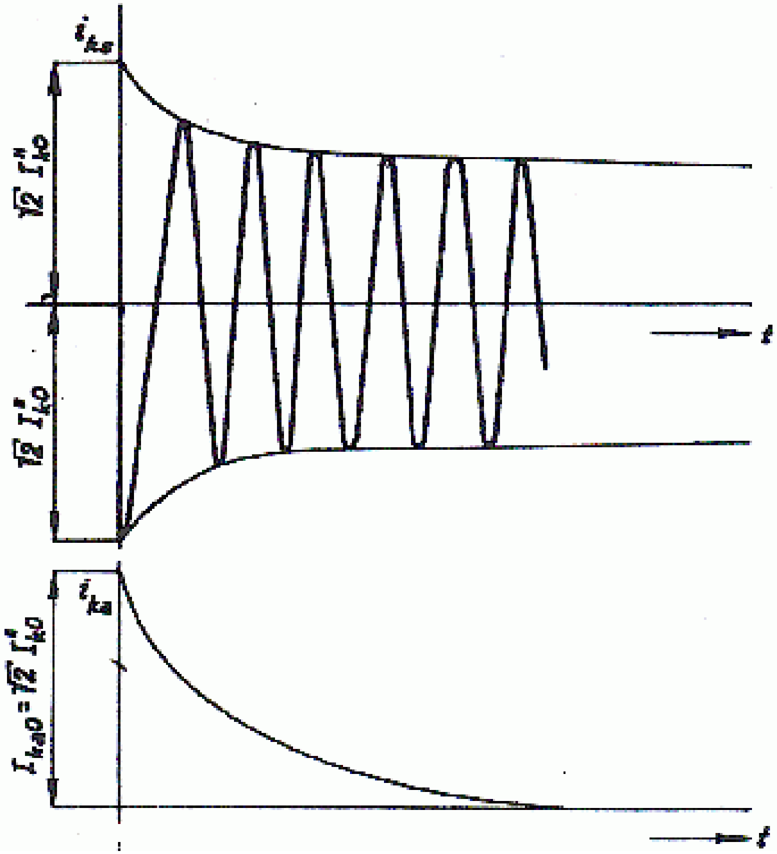


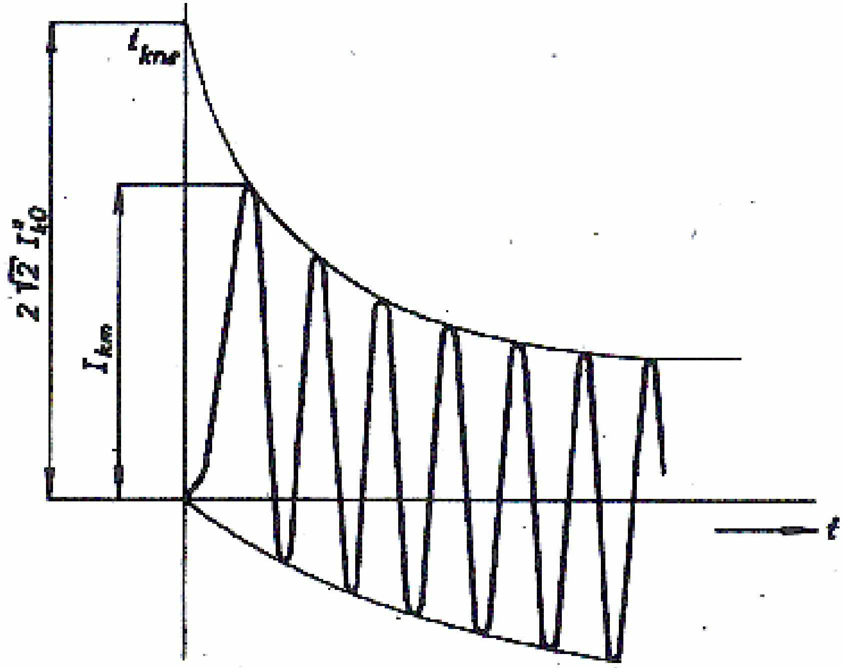
Short-circuit components (f = 50 Hz):

- sub-transient – exponential envelope, T_k'' (damping winding)
- transient – exponential envelope, T_k' (field winding)
- steady-state – constant magnitude

It is caused by synchronous machine behaviour during short-circuit → more significant during short-circuits near the machine.

U = 0 in the short-circuit moment → I_k starts from max. value





Values

- symmetrical short-circuit current I_{ks} - steady-state, transient and sub-transient component sum, RMS value
- sub-transient short-circuit current I_k'' - I_{ks} RMS value in the period of sub-transient component $t \doteq (0 \div 3T_k'')$
- initial sub-transient short-circuit current I_{k0}'' - I_k'' value in the moment of short-circuit origin t = 0
- DC component I_{ka} - disappears exponentially, T_{ka}
- peak short-circuit current I_{km} - the first half-period magnitude during the maximal DC component

Short-circuits in 3ph system

Conversion between phase values and symmetrical components

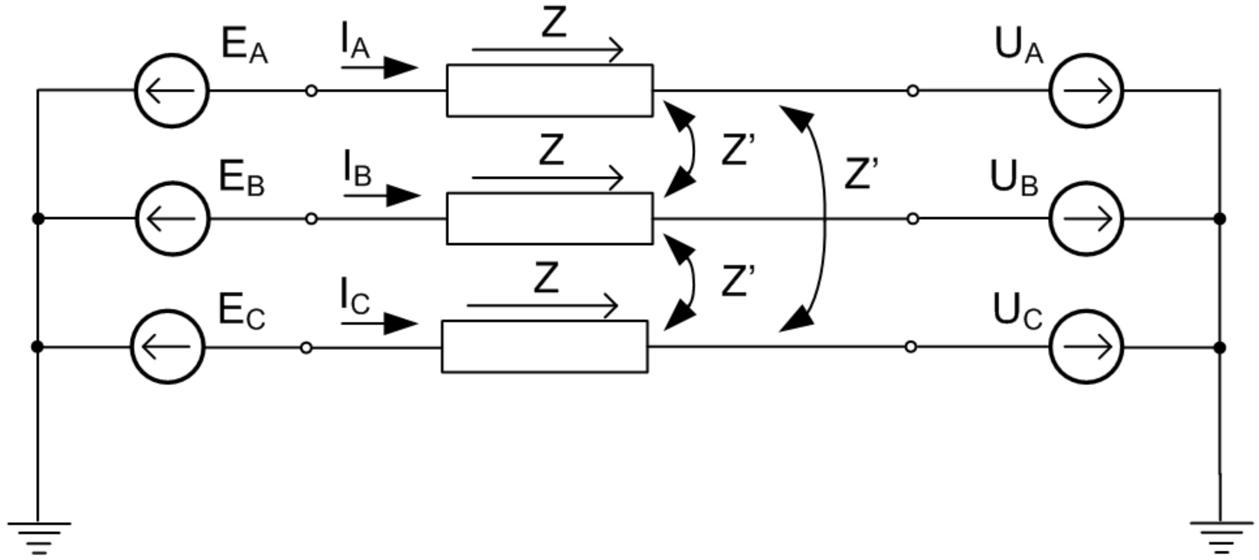
$$(U_{ABC}) = \begin{pmatrix} \hat{U}_A \\ \hat{U}_B \\ \hat{U}_C \end{pmatrix} = \begin{pmatrix} 1 & 1 & 1 \\ \hat{a}^2 & \hat{a} & 1 \\ \hat{a} & \hat{a}^2 & 1 \end{pmatrix} \begin{pmatrix} \hat{U}_1 \\ \hat{U}_2 \\ \hat{U}_0 \end{pmatrix} = (T)(U_{120})$$

$$(U_{120}) = \begin{pmatrix} \hat{U}_1 \\ \hat{U}_2 \\ \hat{U}_0 \end{pmatrix} = \frac{1}{3} \begin{pmatrix} 1 & \hat{a} & \hat{a}^2 \\ 1 & \hat{a}^2 & \hat{a} \\ 1 & 1 & 1 \end{pmatrix} \begin{pmatrix} \hat{U}_A \\ \hat{U}_B \\ \hat{U}_C \end{pmatrix} = (T^{-1})(U_{ABC})$$

Impedance matrix in symmetrical components (for series sym. segment)

$$(Z_{120}) = \begin{pmatrix} \hat{Z}_1 & 0 & 0 \\ 0 & \hat{Z}_2 & 0 \\ 0 & 0 & \hat{Z}_0 \end{pmatrix} = \begin{pmatrix} \hat{Z} - \hat{Z}' & 0 & 0 \\ 0 & \hat{Z} - \hat{Z}' & 0 \\ 0 & 0 & \hat{Z} + 2\hat{Z}' \end{pmatrix}$$

3ph system during short-circuit – internal generator voltage E (or U_i)



$$(E_{ABC}) = (Z_{ABC})(I_{ABC}) + (U_{ABC})$$

Symmetrical system (independent systems 1, 2, 0)

$$(E_{120}) = (Z_{120})(I_{120}) + (U_{120})$$

$$\hat{E}_1 = \hat{Z}_1\hat{I}_1 + \hat{U}_1$$

$$\hat{E}_2 = \hat{Z}_2\hat{I}_2 + \hat{U}_2$$

$$\hat{E}_0 = \hat{Z}_0\hat{I}_0 + \hat{U}_0$$

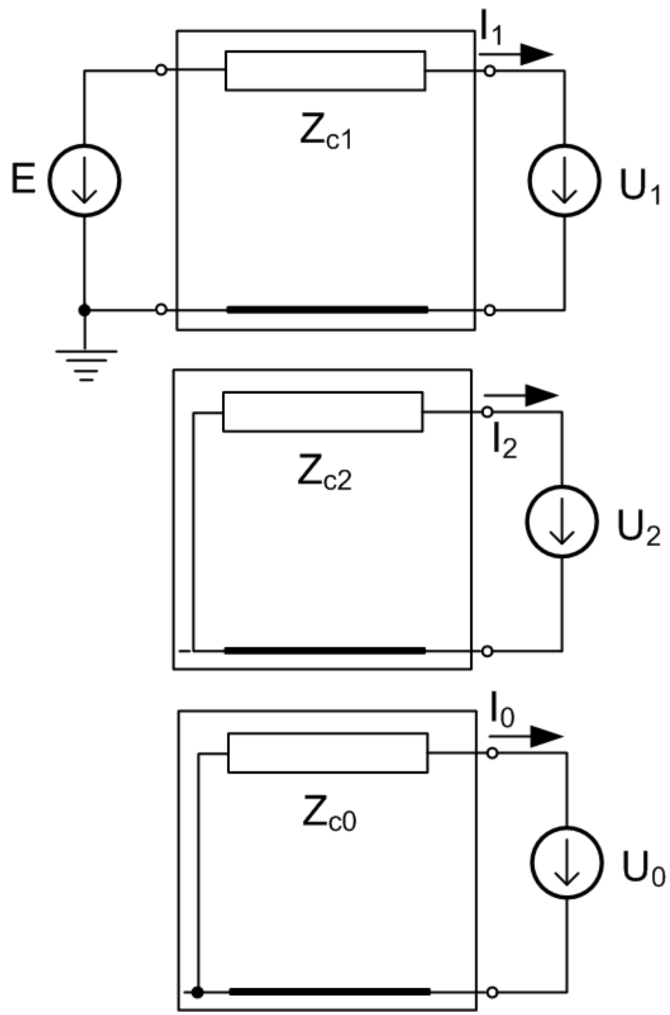
Generator symmetrical voltage → only positive sequence component
Reference phase A:

$$(E_{120}) = (T^{-1})(E_{ABC}) = \frac{1}{3}\begin{pmatrix} 1 & \hat{a} & \hat{a}^2 \\ 1 & \hat{a}^2 & \hat{a} \\ 1 & 1 & 1 \end{pmatrix}\begin{pmatrix} \hat{E}_A \\ \hat{a}^2\hat{E}_A \\ \hat{a}\hat{E}_A \end{pmatrix} = \begin{pmatrix} \hat{E}_A \\ 0 \\ 0 \end{pmatrix} = \begin{pmatrix} \hat{E} \\ 0 \\ 0 \end{pmatrix}$$

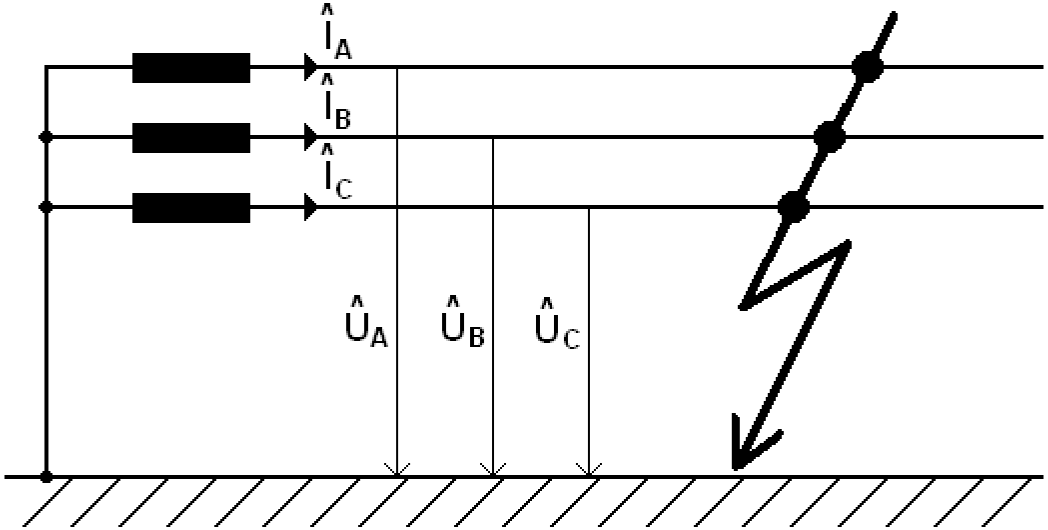
$$\begin{pmatrix} \hat{E}_1 \\ \hat{E}_2 \\ \hat{E}_0 \end{pmatrix} = \begin{pmatrix} \hat{E} \\ 0 \\ 0 \end{pmatrix} = \begin{pmatrix} \hat{Z}_1 & 0 & 0 \\ 0 & \hat{Z}_2 & 0 \\ 0 & 0 & \hat{Z}_0 \end{pmatrix}\begin{pmatrix} \hat{I}_1 \\ \hat{I}_2 \\ \hat{I}_0 \end{pmatrix} + \begin{pmatrix} \hat{U}_1 \\ \hat{U}_2 \\ \hat{U}_0 \end{pmatrix}$$

Negative and zero sequence are caused by voltage unbalance in the faulted place.

In the fault point 6 quantities (U_{120}, I_{120}) → 3 equations necessary to be added by other 3 equations according to the short-circuit type (local unbalance description).



Three-phase (to-ground) short-circuit



3 char. equations

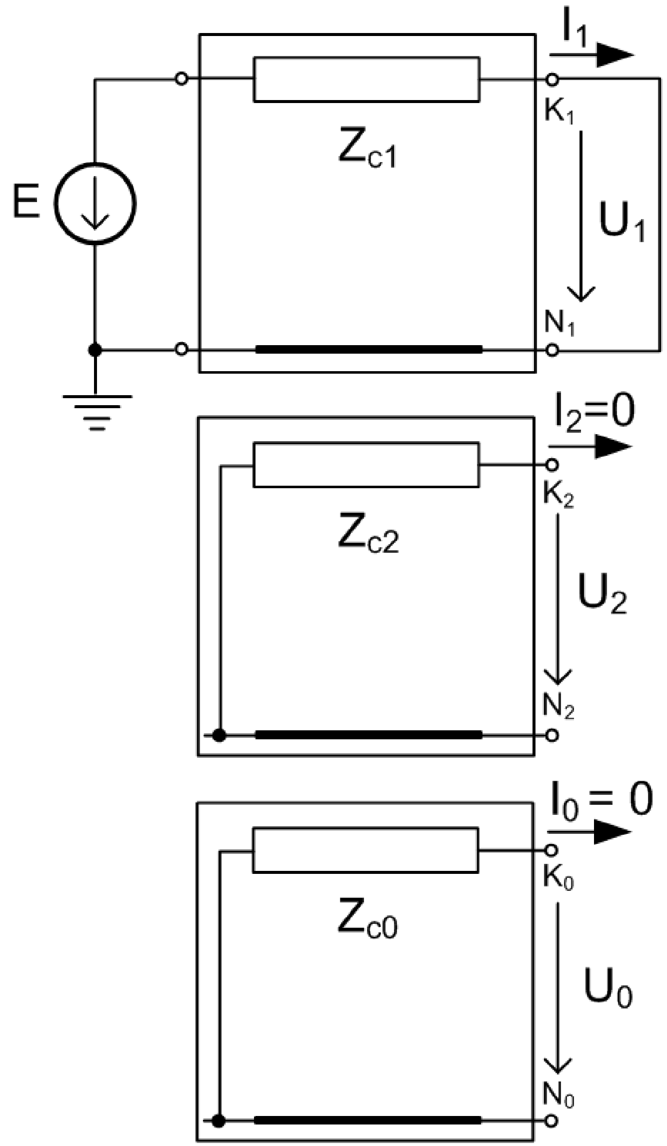
$$\hat{U}_A = \hat{U}_B = \hat{U}_C = 0$$

Components

$$(U_{120}) = (T^{-1})(U_{ABC}) = \frac{1}{3}\begin{pmatrix} 1 & \hat{a} & \hat{a}^2 \\ 1 & \hat{a}^2 & \hat{a} \\ 1 & 1 & 1 \end{pmatrix}\begin{pmatrix} 0 \\ 0 \\ 0 \end{pmatrix} = \begin{pmatrix} 0 \\ 0 \\ 0 \end{pmatrix}$$

$$\hat{U}_1 = \hat{U}_2 = \hat{U}_0 = 0$$

$$\hat{I}_1 = \frac{\hat{E}}{\hat{Z}_1}; \ \hat{I}_2 = 0; \ \hat{I}_0 = 0$$



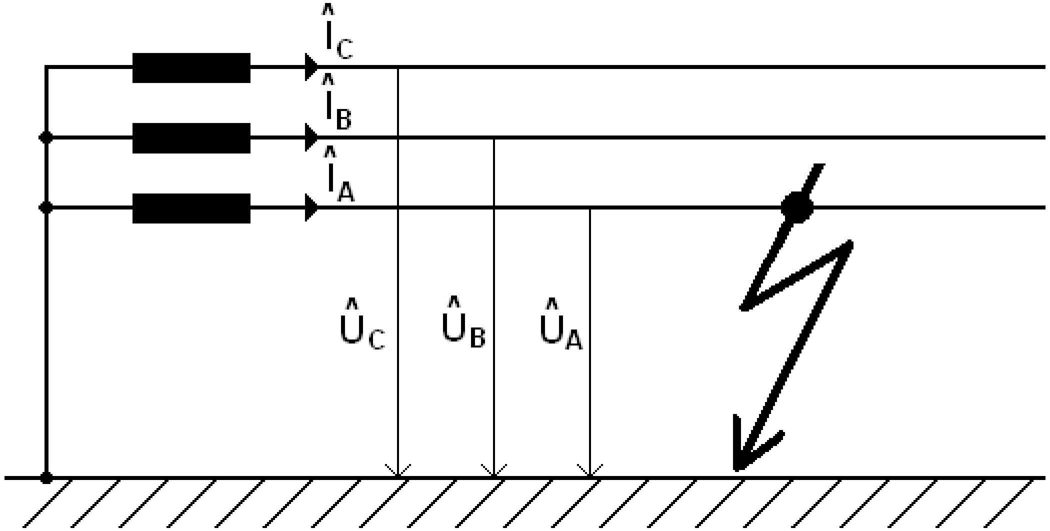
Phases

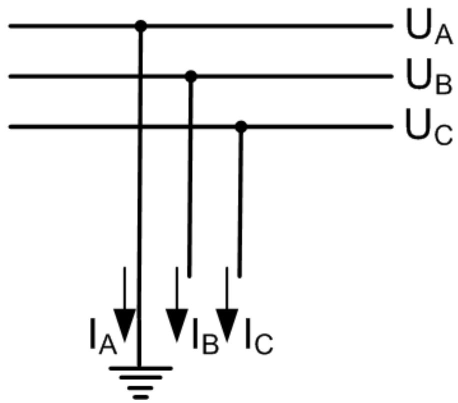
$$(I_{ABC}) = (T)(I_{120})$$

$$\hat{I}_A = \frac{\hat{E}}{\hat{Z}_1}; \ \hat{I}_B = \hat{a}^2\frac{\hat{E}}{\hat{Z}_1}; \ \hat{I}_C = \hat{a}\frac{\hat{E}}{\hat{Z}_1}$$

Only the positive-sequence component included.

Single-phase-to-ground short-circuit



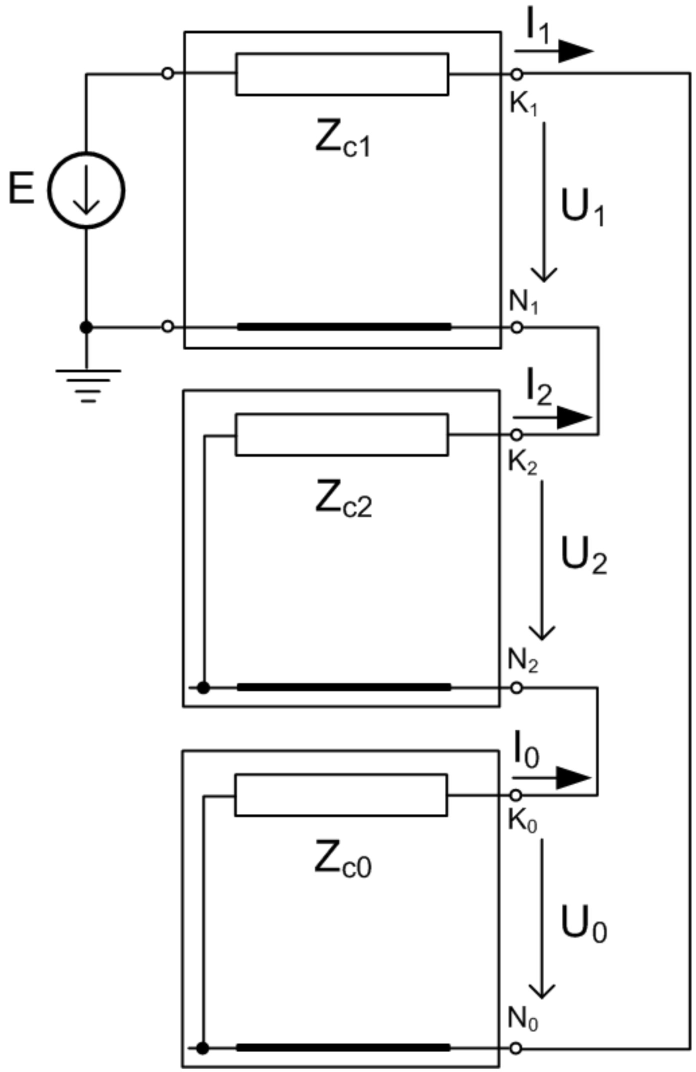


3 char. equations

$$\hat{U}_A = 0; \;\; \hat{I}_B = \hat{I}_C = 0$$

Components

$$(I_{120}) = (T^{-1})(I_{ABC}) = \frac{1}{3}\begin{pmatrix} 1 & \hat{a} & \hat{a}^2 \\ 1 & \hat{a}^2 & \hat{a} \\ 1 & 1 & 1 \end{pmatrix}\begin{pmatrix} \hat{I}_A \\ 0 \\ 0 \end{pmatrix} = \frac{1}{3}\begin{pmatrix} \hat{I}_A \\ \hat{I}_A \\ \hat{I}_A \end{pmatrix}$$



$$\hat{I}_1 = \hat{I}_2 = \hat{I}_0 = \frac{\hat{E}}{\hat{Z}_1 + \hat{Z}_2 + \hat{Z}_0}$$

$$\hat{U}_1 = (\hat{Z}_0 + \hat{Z}_2)\hat{I}_1$$

$$\hat{U}_2 = -\hat{Z}_2\hat{I}_1$$

$$\hat{U}_0 = -\hat{Z}_0\hat{I}_1$$

All three components are in series.

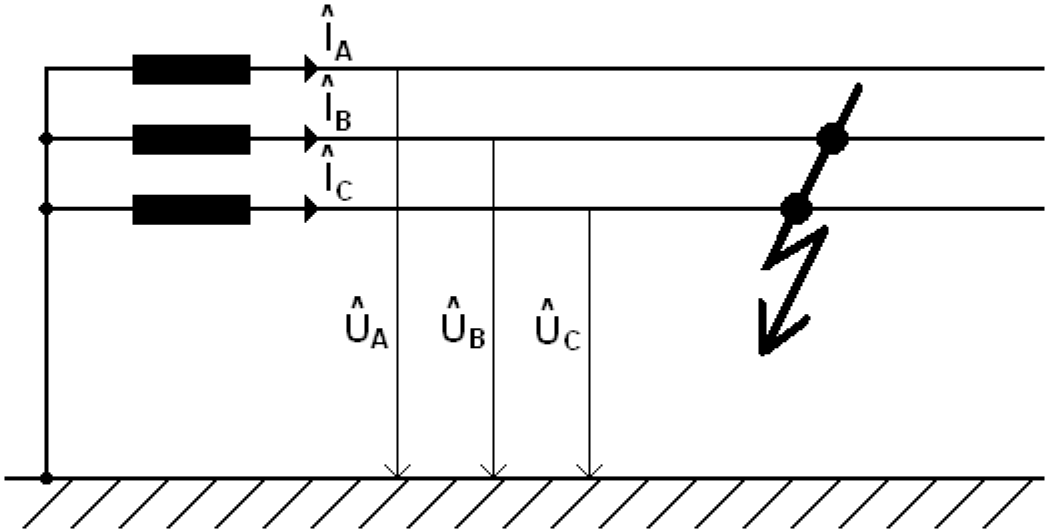
Phases

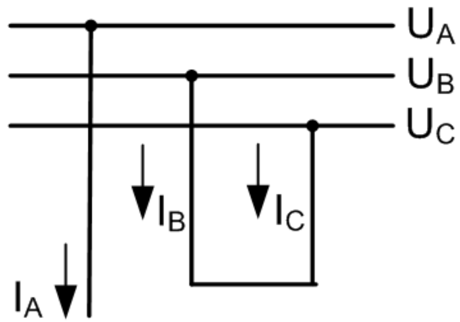
$$\left(I_{ABC}\right)=\left(T\right)\left(I_{120}\right)=\begin{pmatrix}1 & 1 & 1\\ \hat{a}^2 & \hat{a} & 1\\ \hat{a} & \hat{a}^2 & 1\end{pmatrix}\begin{pmatrix}\hat{I}_1\\ \hat{I}_1\\ \hat{I}_1\end{pmatrix}=\begin{pmatrix}3\hat{I}_1\\ 0\\ 0\end{pmatrix}$$

$$\hat{I}_A=\frac{3\hat{E}}{\hat{Z}_1+\hat{Z}_2+\hat{Z}_0};\ \hat{I}_B=0;\ \hat{I}_C=0$$

$$\left(U_{ABC}\right)=\left(T\right)\left(U_{120}\right)=\begin{pmatrix}1 & 1 & 1\\ \hat{a}^2 & \hat{a} & 1\\ \hat{a} & \hat{a}^2 & 1\end{pmatrix}\begin{pmatrix}\left(\hat{Z}_0+\hat{Z}_2\right)\hat{I}_1\\ -\hat{Z}_2\hat{I}_1\\ -\hat{Z}_0\hat{I}_1\end{pmatrix}=\begin{pmatrix}0\\ \left(\hat{a}^2-\hat{a}\right)\hat{Z}_2+\left(\hat{a}^2-1\right)\hat{Z}_0\\ \left(\hat{a}-\hat{a}^2\right)\hat{Z}_2+\left(\hat{a}-1\right)\hat{Z}_0\end{pmatrix}\hat{I}_1$$

Phase-to-phase short-circuit





3 char. equations

$$\hat{U}_B = \hat{U}_C;\ \ \hat{I}_B = -\hat{I}_C;\ \ \hat{I}_A = 0$$

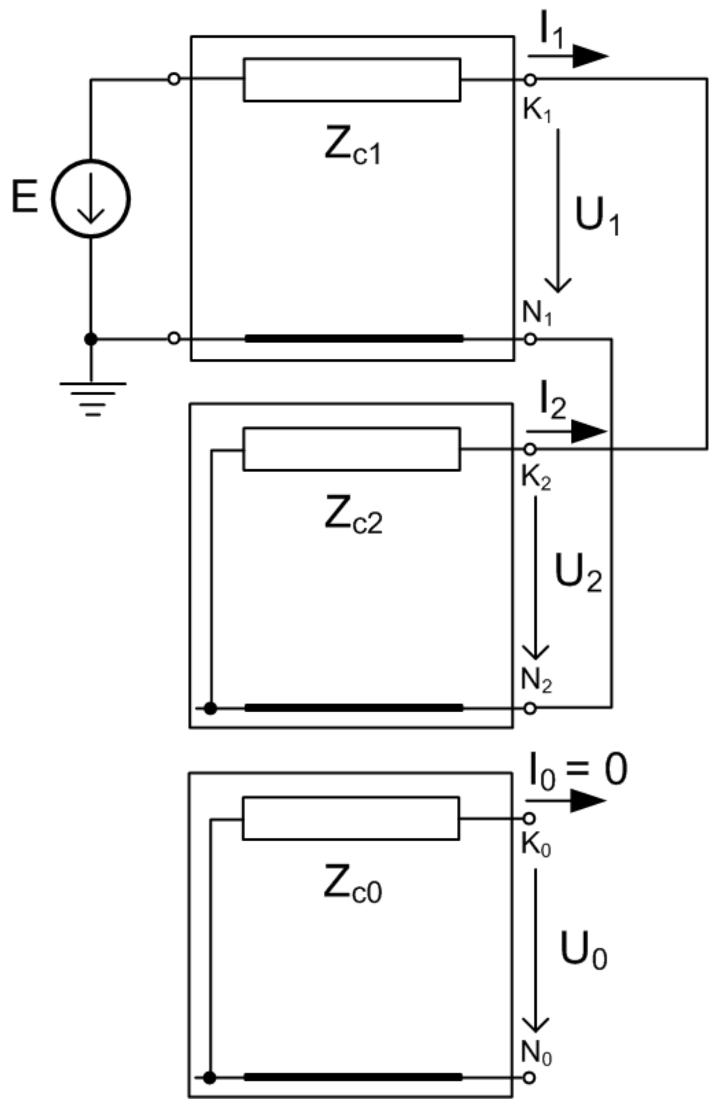
Components

$$\left(I_{120}\right)=\frac{1}{3}\begin{pmatrix}1 & \hat{a} & \hat{a}^2\\ 1 & \hat{a}^2 & \hat{a}\\ 1 & 1 & 1\end{pmatrix}\begin{pmatrix}0\\ \hat{I}_B\\ -\hat{I}_B\end{pmatrix}=\frac{1}{3}\begin{pmatrix}j\sqrt{3}\hat{I}_B\\ -j\sqrt{3}\hat{I}_B\\ 0\end{pmatrix}$$

$$\hat{I}_1=\frac{\hat{E}}{\hat{Z}_1+\hat{Z}_2};\ \hat{I}_2=-\hat{I}_1;\ \hat{I}_0=0$$

$$\hat{U}_1=\hat{U}_2=\frac{\hat{Z}_2\cdot\hat{E}}{\hat{Z}_1+\hat{Z}_2}=\hat{Z}_2\cdot\hat{I}_1$$

$$\hat{U}_0=0$$



Positive and negative components in parallel.

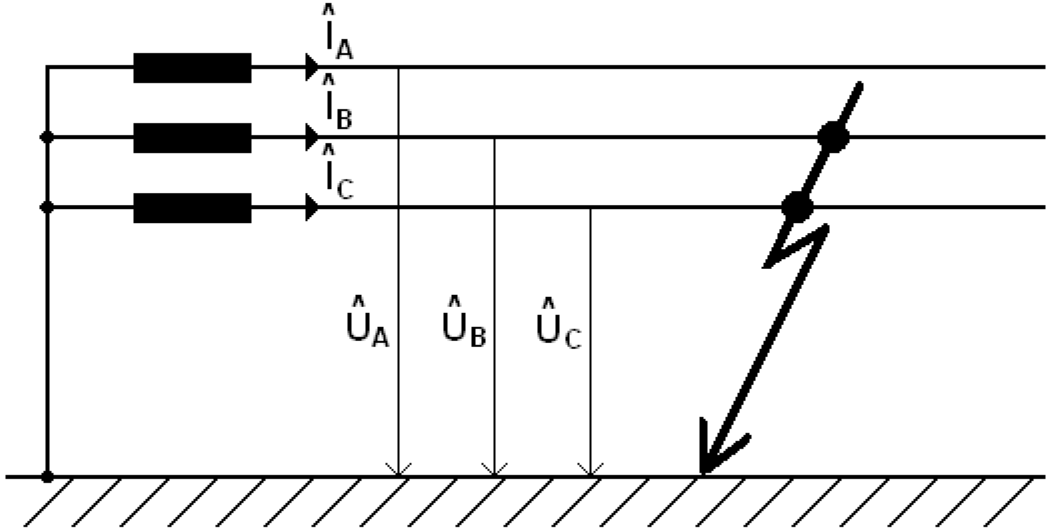
Phases

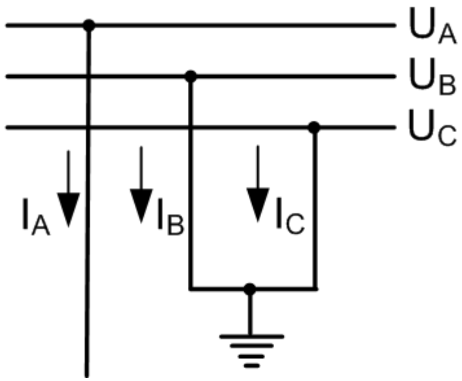
$$\left(I_{ABC}\right)=\left(T\right)\left(I_{120}\right)=\begin{pmatrix}1 & 1 & 1\\ \hat{a}^2 & \hat{a} & 1\\ \hat{a} & \hat{a}^2 & 1\end{pmatrix}\begin{pmatrix}\hat{I}_1\\ -\hat{I}_1\\ 0\end{pmatrix}=\begin{pmatrix}0\\ -j\sqrt{3}\hat{I}_1\\ j\sqrt{3}\hat{I}_1\end{pmatrix}$$

$$\hat{I}_A=0;\ \ \hat{I}_B=\frac{-j\sqrt{3}\hat{E}}{\hat{Z}_1+\hat{Z}_2};\ \ \hat{I}_C=\frac{j\sqrt{3}\hat{E}}{\hat{Z}_1+\hat{Z}_2}$$

$$\left(U_{ABC}\right)=\left(T\right)\left(U_{120}\right)=\begin{pmatrix}1 & 1 & 1\\ \hat{a}^2 & \hat{a} & 1\\ \hat{a} & \hat{a}^2 & 1\end{pmatrix}\begin{pmatrix}\hat{U}_1\\ \hat{U}_1\\ 0\end{pmatrix}=\begin{pmatrix}2\hat{U}_1\\ -\hat{U}_1\\ -\hat{U}_1\end{pmatrix}=\begin{pmatrix}2\hat{Z}_2\cdot\hat{I}_1\\ -\hat{Z}_2\cdot\hat{I}_1\\ -\hat{Z}_2\cdot\hat{I}_1\end{pmatrix}$$

Double-phase-to-ground short-circuit



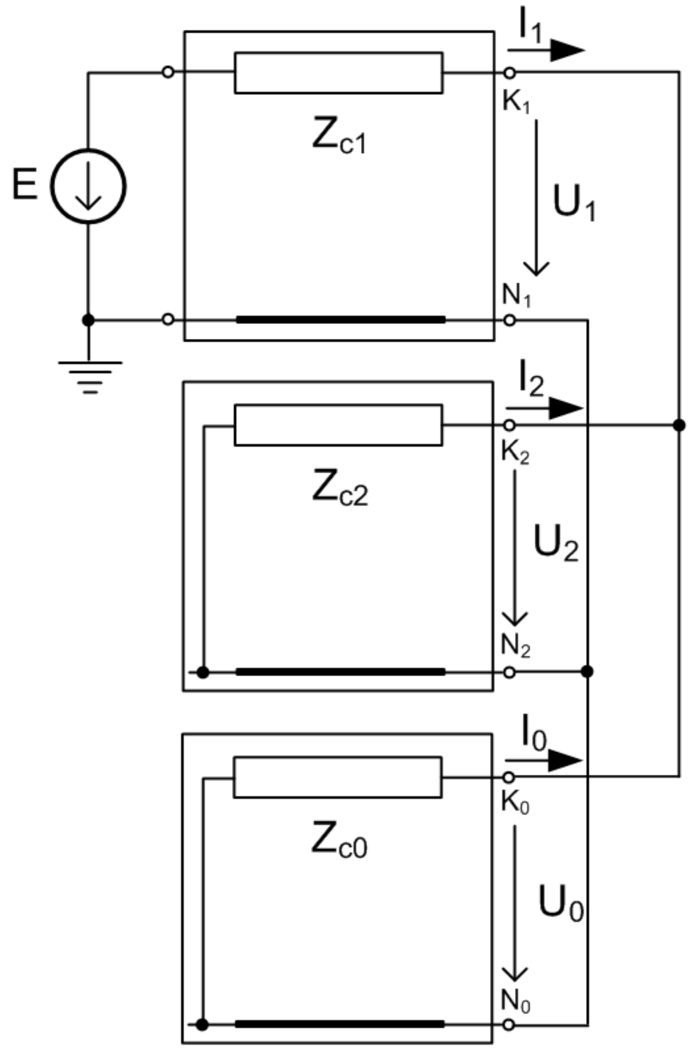


3 char. equations

$$\hat{U}_B = \hat{U}_C = 0;\ \ \hat{I}_A = 0$$

Components

$$(U_{120}) = \frac{1}{3}\begin{pmatrix} 1 & \hat{a} & \hat{a}^2 \\ 1 & \hat{a}^2 & \hat{a} \\ 1 & 1 & 1 \end{pmatrix}\begin{pmatrix} \hat{U}_A \\ 0 \\ 0 \end{pmatrix} = \frac{1}{3}\begin{pmatrix} \hat{U}_A \\ \hat{U}_A \\ \hat{U}_A \end{pmatrix}$$



$$\hat{I}_1 = \frac{\hat{E}}{\hat{Z}_1 + \dfrac{\hat{Z}_0\hat{Z}_2}{\hat{Z}_0 + \hat{Z}_2}}$$

$$\hat{I}_2 = -\frac{\hat{Z}_0}{\hat{Z}_0 + \hat{Z}_2}\hat{I}_1; \quad \hat{I}_0 = -\frac{\hat{Z}_2}{\hat{Z}_0 + \hat{Z}_2}\hat{I}_1$$

$$\hat{U}_1 = \hat{U}_2 = \hat{U}_0 = \frac{\hat{E}\dfrac{\hat{Z}_0\hat{Z}_2}{\hat{Z}_0 + \hat{Z}_2}}{\hat{Z}_1 + \dfrac{\hat{Z}_0\hat{Z}_2}{\hat{Z}_0 + \hat{Z}_2}}$$

All three components are in parallel.

Phases

$$\left(I_{ABC}\right) = \left(T\right)\left(I_{120}\right)$$

$$\hat{I}_B = \frac{\hat{E}\left(\hat{Z}_0(\hat{a}^2 - \hat{a}) + \hat{Z}_2(\hat{a}^2 - 1)\right)}{\hat{Z}_1\hat{Z}_2 + \hat{Z}_0\hat{Z}_1 + \hat{Z}_0\hat{Z}_2}$$

$$\hat{I}_C = \frac{\hat{E}\left(\hat{Z}_0(\hat{a} - \hat{a}^2) + \hat{Z}_2(\hat{a} - 1)\right)}{\hat{Z}_1\hat{Z}_2 + \hat{Z}_0\hat{Z}_1 + \hat{Z}_0\hat{Z}_2}$$

$$\left(U_{ABC}\right) = \left(T\right)\left(U_{120}\right) = \begin{pmatrix} 1 & 1 & 1 \\ \hat{a}^2 & \hat{a} & 1 \\ \hat{a} & \hat{a}^2 & 1 \end{pmatrix} \begin{pmatrix} \hat{U}_1 \\ \hat{U}_1 \\ \hat{U}_1 \end{pmatrix} = \begin{pmatrix} 3\hat{U}_1 \\ 0 \\ 0 \end{pmatrix}$$

Components during short-circuit:

3ph	positive
2ph	positive, negative
2ph ground	positive, negative, zero
1ph	positive, negative, zero

Short-circuits calculation by means of relative values

Relative values – related to a defined base.

base power (3ph)	S_v (VA)
base voltage (phase-to-phase)	U_v (V)
base current	I_v (A)
base impedance	Z_v (Ω)

$$S_v = \sqrt{3} U_v I_v$$

$$Z_v = \frac{U_{vf}}{I_v}$$

Relative impedance

$$z = \frac{Z}{Z_v} = \frac{Z}{\frac{U_{vf}}{I_v}} = Z \frac{I_v}{U_{vf}} \frac{3U_{vf}}{3U_{vf}} = Z \frac{S_v}{3U_{vf}^2} = Z \frac{S_v}{U_v^2}$$

Initial sub-transient short-circuit current (3ph short-circuit)

$$I''_{k0} = \left|\hat{I}_A\right| = \frac{\left|\hat{U}_f\right|}{\left|\hat{Z}_1\right|}$$

$$Z_1 = z_1 \frac{U_v^2}{S_v}$$

$$I''_{k0} = \frac{\frac{U_v}{\sqrt{3}}}{z_1 \frac{U_v^2}{S_v}} = \frac{1}{z_1} \frac{S_v}{\sqrt{3} U_v} = \frac{1}{z_1} I_v$$

Initial sub-transient short-circuit power

$$S''_{k0} = \sqrt{3} U_v I''_{k0} = \sqrt{3} U_v \frac{I_v}{z_1} = \frac{1}{z_1} S_v$$

Similarly for

1ph short-circuit

$$I''^{(1)}_{k0} = \frac{3}{z_1 + z_2 + z_0} I_v$$

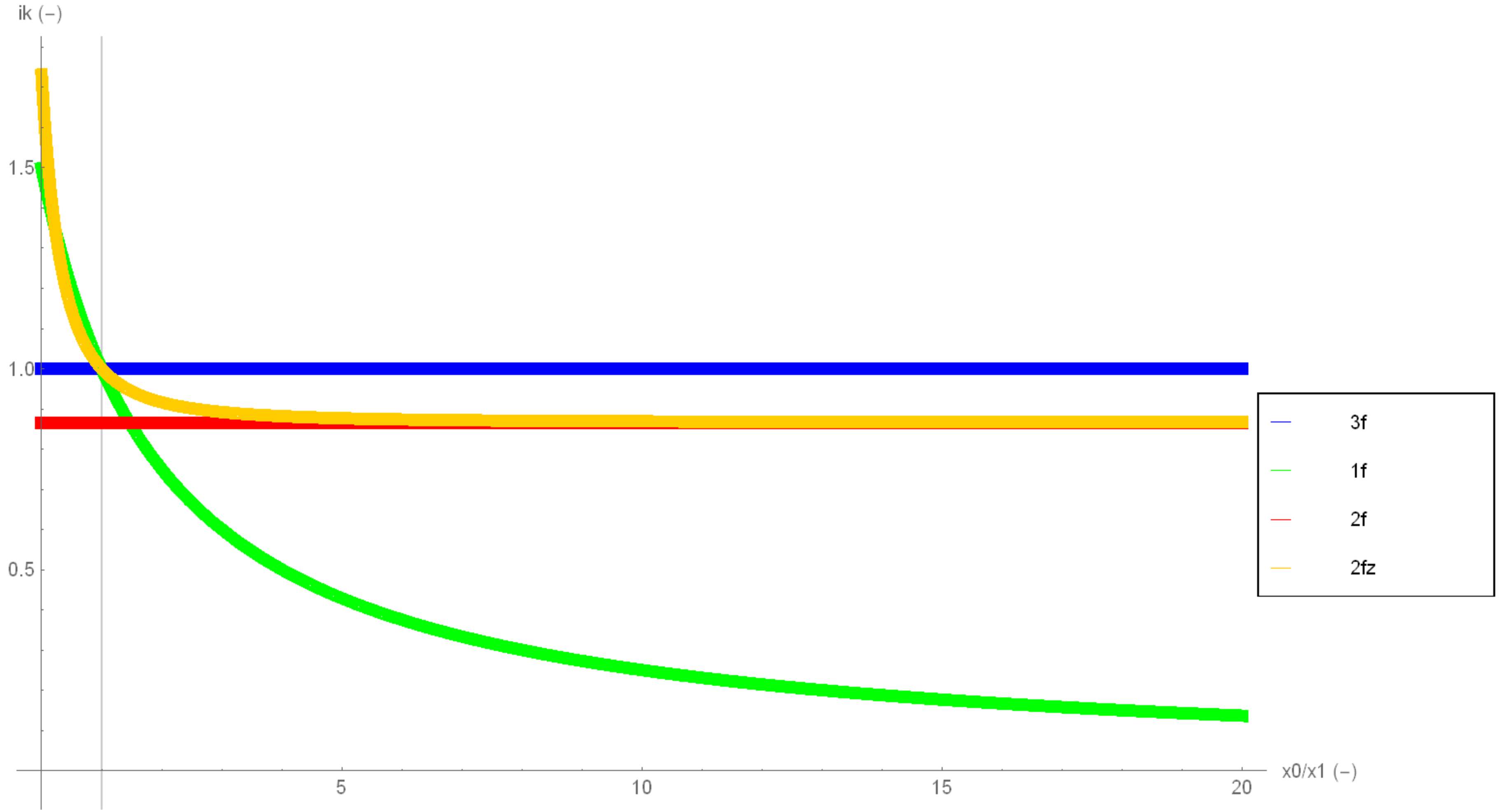
2ph short-circuit

$$I''^{(2)}_{k0} = \frac{\sqrt{3}}{z_1 + z_2} I_v$$

Note: Sometimes it is respected generator loading, more precisely higher internal generator voltage than nominal one.

$$I''_{k0} = k \frac{1}{z_1} I_v$$

$k > 1$



$$I_k''^{(1)} = (0 \div 1{,}5)\, I_k''^{(3)} \qquad I_k''^{(2)} = \frac{\sqrt{3}}{2} I_k''^{(3)} \qquad I_k''^{(2z)} = \left(\frac{\sqrt{3}}{2} \div \sqrt{3} \right) I_k''^{(3)}$$

Short-circuit currents impacts

Mechanical impacts

Influence mainly at tightly placed stiff conductors, supporting insulators, disconnectors, construction elements,…

Forces frequency 2f at AC → dynamic strain.

Force on the conductor in magnetic field

$$F = B \cdot I \cdot l \cdot \sin\alpha \quad (N)$$

$$B = \mu \cdot H \quad (T)$$

$$\mu_0 = 4\pi \cdot 10^{-7} \quad (H/m)$$

α – angle between mag. induction vector and the conductor axis (current direction)

Magnetic field intensity in the distance **a** from the conductor

$$H = \frac{I}{2\pi a} \quad (A/m)$$

2 parallel conductors → force perpendicular to the conductor axis ($\sin\alpha = 1$) → it is the biggest

$$F = 4\pi \cdot 10^{-7} \frac{I}{2\pi a} I \cdot 1 = 2 \cdot 10^{-7} \frac{I^2}{a} 1 \quad (N)$$

The highest force corresponds to the highest immediate current value → <u>peak short-circuit current</u> I_{km} (1st magnitude after s.-c. origin)

$$I_{km} = \sqrt{2} I''_{k0} \left(1 + e^{-0,01/T_k}\right) = \kappa \sqrt{2} I''_{k0} \quad (A)$$

κ – peak coefficient according to grid type ($\kappa_{LV} = 1{,}8$; $\kappa_{HV} = 1{,}7$)
theoretical range $\kappa = 1 \div 2$

T_k – time constant of equivalent short-circuit loop (L_e/R_e)
i.e. for DC component of short-circuit current

I''_{k0} - initial sub-transient short-circuit current

Real value differs according to the short-circuit origin moment.
AC component decreasing slower than for DC therefore neglected.

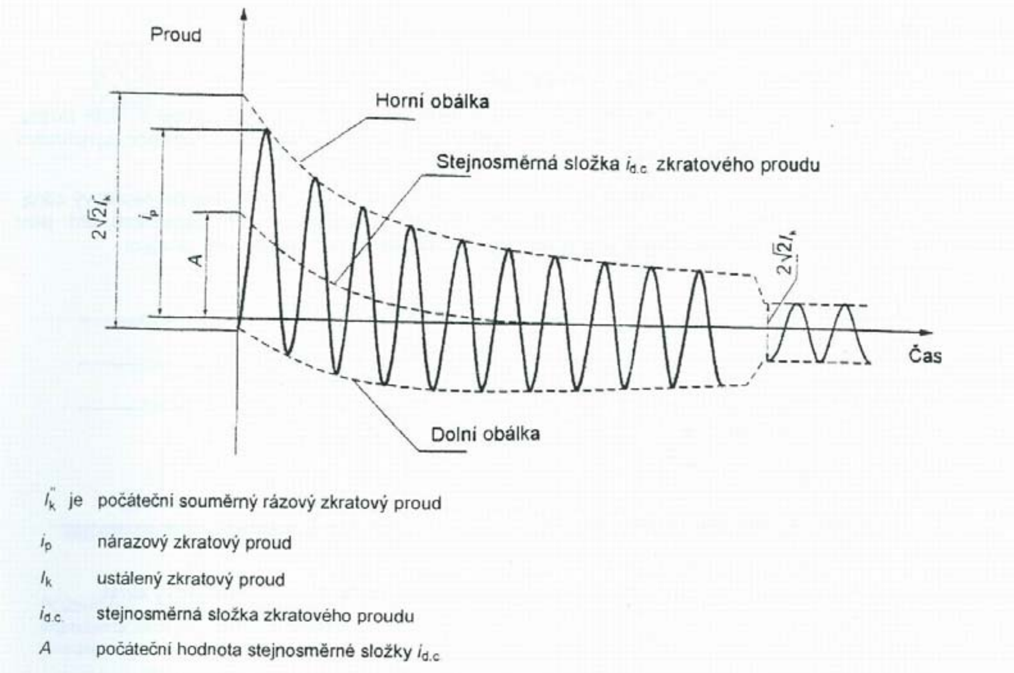
Max. instantaneous force on the conductor length unit

$$f = 2 \cdot k_1 \cdot k_2 \cdot 10^{-7} \frac{I_{km}^2}{a} \quad (N/m)$$

k_1 – conductor shape coefficient

k_2 – conductors configuration and currents phase shift coefficient

a – conductors distance



Heat impacts

Key for dimensioning mainly at freely placed conductors.

They are given by heat accumulation influenced by time-changing current during short-circuit time t_k (adiabatic phenomenon).

Heat produced in conductors

$$Q = \int_0^{t_k} R(\vartheta) \cdot i_k^2(t)dt \quad (\mathrm{J})$$

Thermal equivalent current – current RMS value which has the same heating effect in the short-circuit duration time as the real short-circuit current

$$I_{ke}^2 t_k = \int_0^{t_k} i_k^2(t)dt \qquad I_{ke} = \sqrt{\frac{1}{t_k}\int_0^{t_k} i_k^2(t)dt} \quad (\mathrm{A})$$

Calculation according to k_e coefficient as I_k'' multiple

$$I_{ke} = k_e I_k''$$

Ground fault in three-phase systems

MV grids without a directly grounded neutral point (distribution systems) → single-phase ground fault has a different character than short-circuits (small capacitive current).

Fault current proportional to the system extent.

$I_p > 5$ A → arc formation → conductors, towers, insulators burning → → 2ph, 3ph short-circuits (mainly at cables)

GF compensation → uninterrupted system operation (until the failure clearance, short supply break), arc self-extinguishing

Ground fault

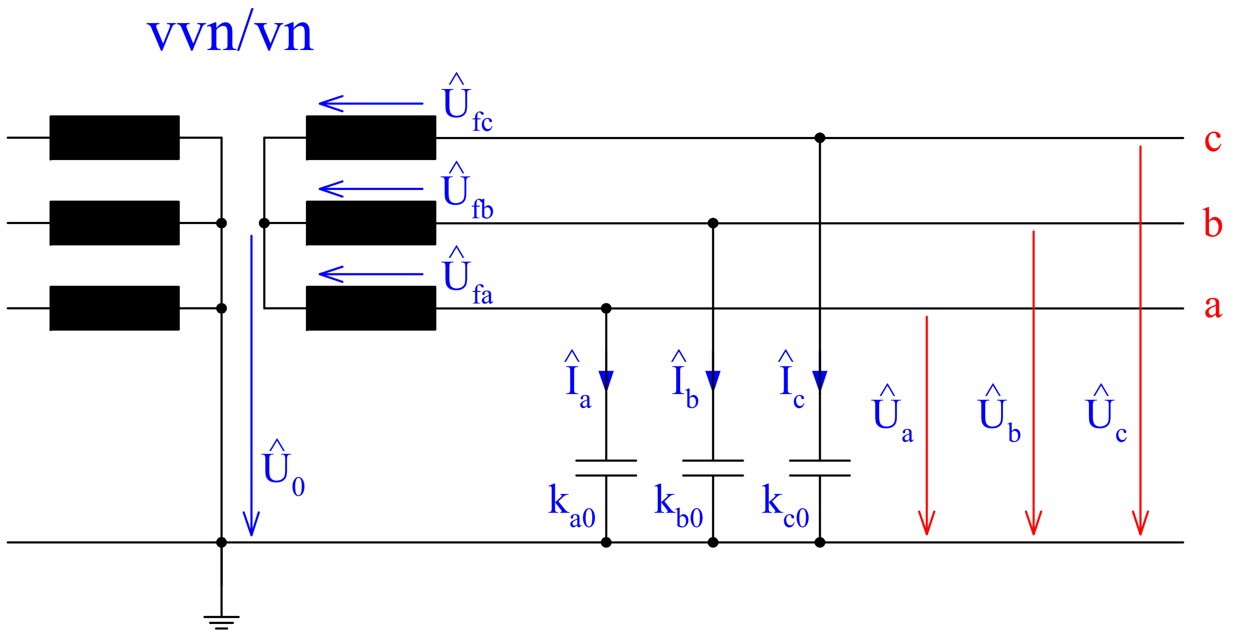
- resistive (100x Ω), metal and arc (x Ω)

Conditions in a system with insulated neutral point

Assumptions: considered only capacities to the ground, symmetrical source voltage, open-circuit system

Insulated neutral point – systems of a small extent, $I_p < 10\ \text{A}$

Before the fault



$$\hat{U}_{a,b,c} - \hat{U}_0 - \hat{U}_{fa,b,c} = 0 \qquad \hat{I}_{a,b,c} = j\omega k_{a,b,c0} \hat{U}_{a,b,c}$$

System with insulated neutral point

$$\hat{I}_a + \hat{I}_b + \hat{I}_c = 0$$

Symmetrical source

$$\hat{U}_{fb} = \hat{a}^2 \hat{U}_{fa}, \quad \hat{U}_{fc} = \hat{a} \hat{U}_{fa}$$

Neutral point voltage

$$\hat{U}_0 = -\frac{k_{a0} + \hat{a}^2 k_{b0} + \hat{a} k_{c0}}{k_{a0} + k_{b0} + k_{c0}} \hat{U}_{fa}$$

Unbalanced capacities

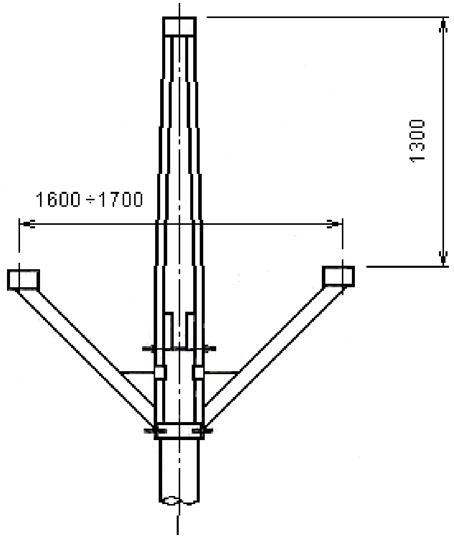
$$\hat{U}_0 \neq 0$$

Symmetrical capacities

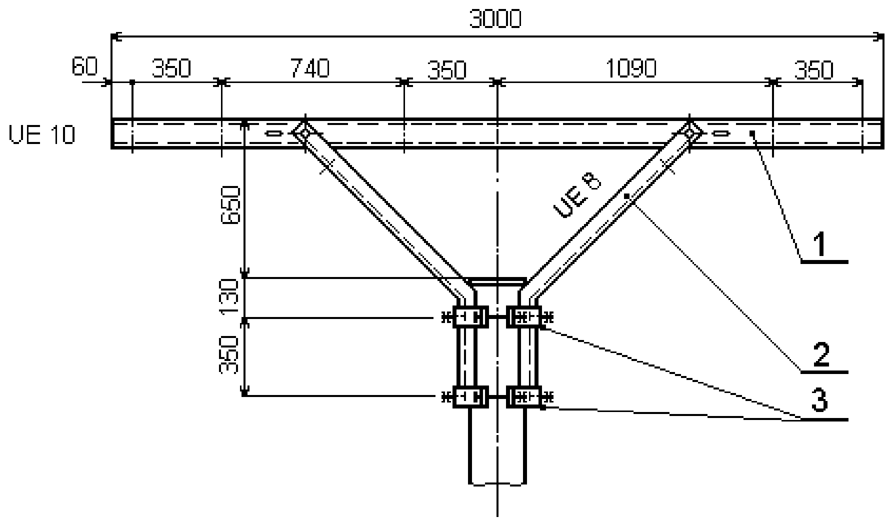
$$k_{a0} = k_{b0} = k_{c0} = k_0 \quad \Rightarrow \quad \hat{U}_0 = 0$$

Ex.: 2 tower terminals 22 kV, l = 50 km

"Talon"



Horizontal



"Talon":

$$k_{a0} = k_{c0} = 4{,}16\ \mathrm{nF/km}$$

$$k_{b0} = 4{,}00\ \mathrm{nF/km} \quad (\Delta = 3{,}8\ \%)$$

$$U_0 = 165\ \mathrm{V} \ \ (1{,}3\ \%)$$

$$U_a = U_c = 12620\ \mathrm{V}$$

$$U_b = 12867\ \mathrm{V}$$

Horizontal:

$$k_{a0} = k_{c0} = 4{,}48\ \mathrm{nF/km}$$

$$k_{b0} = 3{,}90\ \mathrm{nF/km} \quad (\Delta = 12{,}9\ \%)$$

$$U_0 = 573\ \mathrm{V} \ \ (4{,}5\ \%)$$

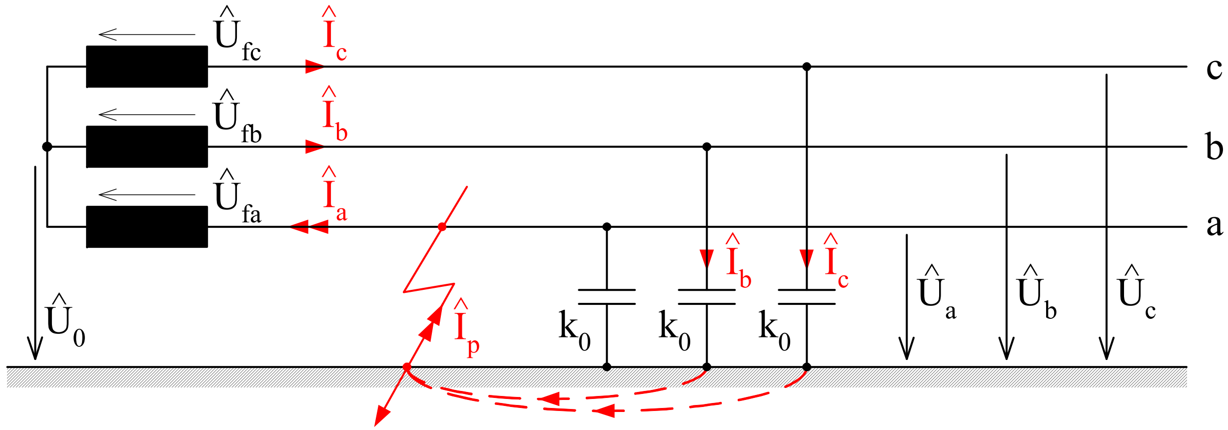
$$U_a = U_c = 12425\ \mathrm{V}$$

$$U_b = 13275\ \mathrm{V}$$

$$U_{fn} = 12702\ \mathrm{V}$$

Perfect (metal) durable ground fault

Symmetrical system



Fault current composed of 2 capacitive currents in the disaffected phases.

$$\hat{U}_a = 0$$

$$\hat{I}_p = \hat{I}_a = \hat{I}_b + \hat{I}_c$$

$$\hat{I}_b = j\omega k_0 \hat{U}_b \qquad \hat{I}_c = j\omega k_0 \hat{U}_c$$

$$\hat{U}_a - \hat{U}_0 - \hat{U}_{fa} = 0 \quad \Rightarrow \quad \hat{U}_0 = -\hat{U}_{fa} \quad !$$

$$\hat{U}_b - \hat{U}_0 - \hat{U}_{fb} = 0 \quad \Rightarrow \hat{U}_b = \hat{U}_0 + \hat{U}_{fb} = \left(-1 + \hat{a}^2\right)\hat{U}_{fa} = -\sqrt{3}e^{j30^\circ}\hat{U}_{fa} \quad !$$

$$\hat{U}_c - \hat{U}_0 - \hat{U}_{fc} = 0 \quad \Rightarrow \hat{U}_c = \hat{U}_0 + \hat{U}_{fc} = \left(-1 + \hat{a}\right)\hat{U}_{fa} = -\sqrt{3}e^{-j30^\circ}\hat{U}_{fa} \quad !$$

→ affected phase voltage – zero
neutral point voltage – phase-to-ground value
disaffected phases voltage – phase-to-phase value

Ground fault current

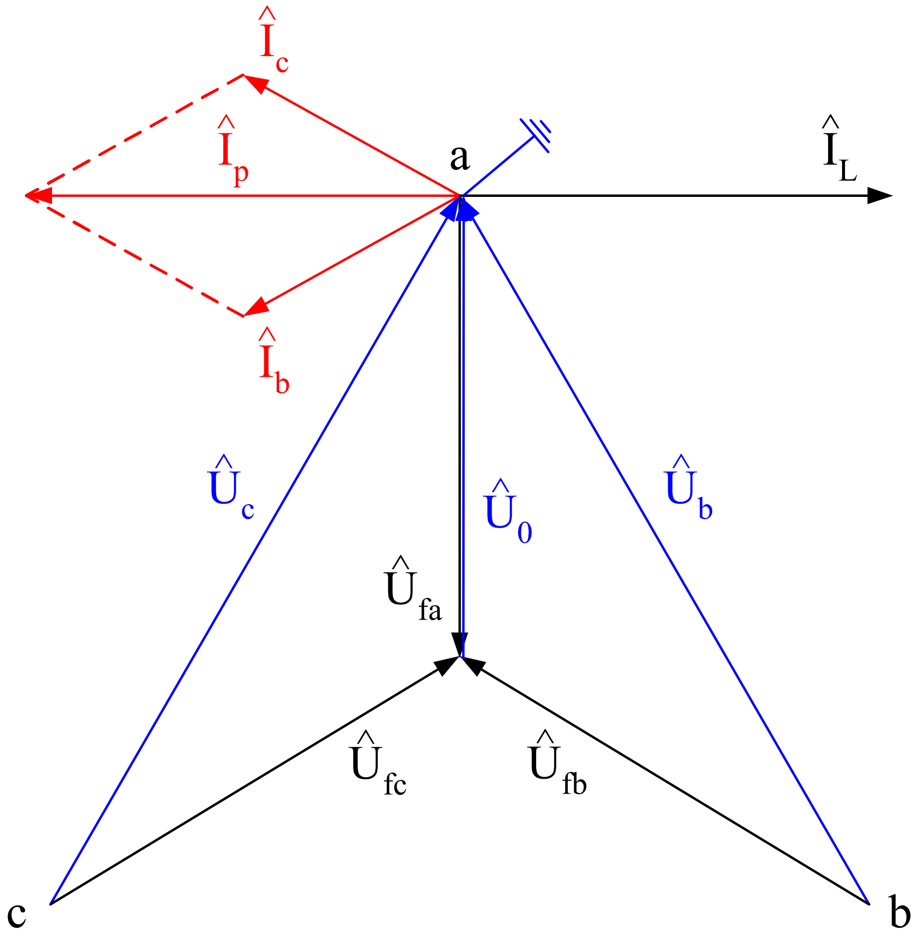
$$\hat{I}_p = \hat{I}_b + \hat{I}_c = j\omega k_0\left(\hat{U}_b + \hat{U}_c\right)$$

$$= j\omega k_0\left[\left(-1 + \hat{a}^2\right) + \left(-1 + \hat{a}\right)\right]\hat{U}_{fa}$$

$$= j\omega k_0\left(-2 + \hat{a}^2 + \hat{a} + 1 - 1\right)\hat{U}_{fa}$$

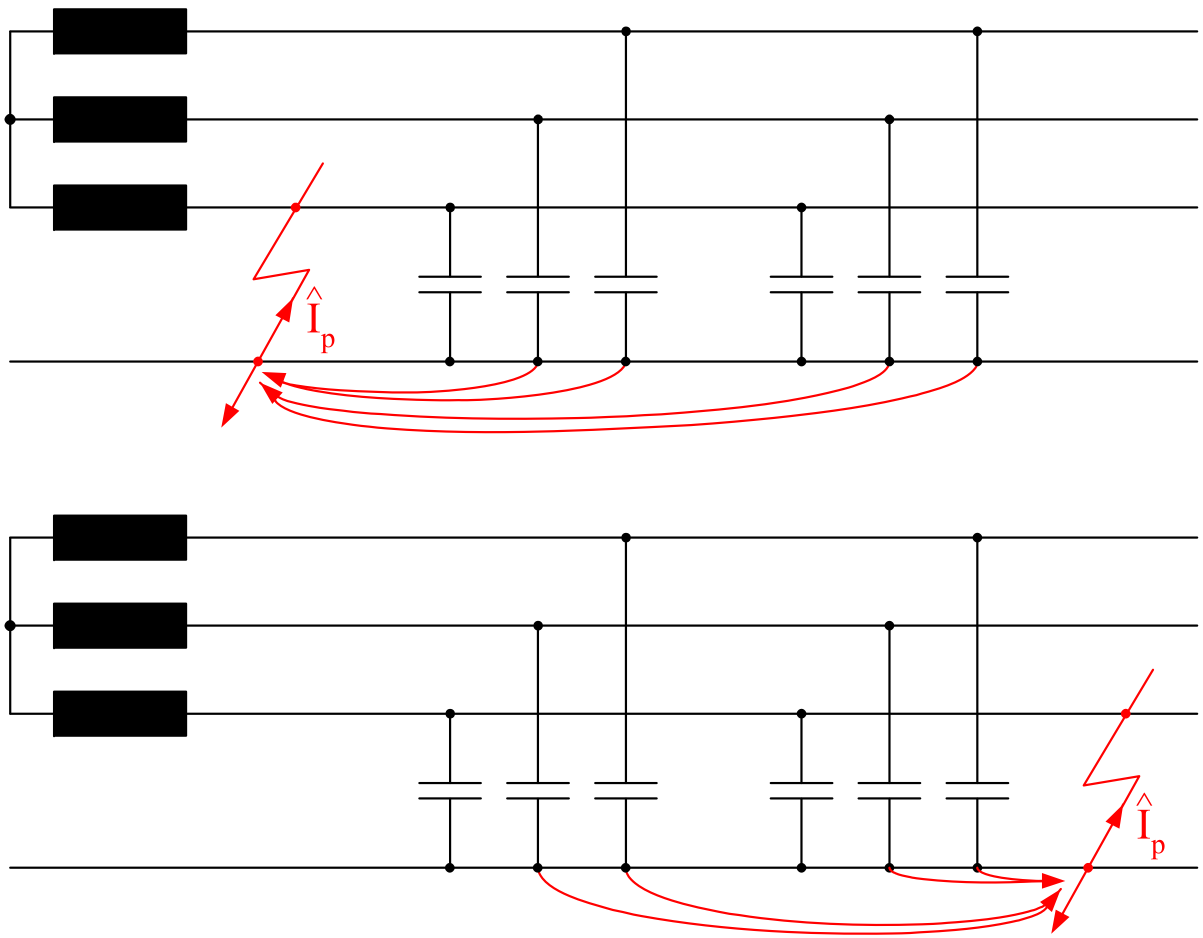
$$\underline{\hat{I}_p = -3j\omega k_0\hat{U}_{fa} = 3j\omega k_0\hat{U}_0 \quad \left(A; s^{-1}, F, V\right)}$$

Voltage and current conditions



Fault current depends on the total system extent and almost doesn't depend on the fault point distance from the transformer.

$$I_p = 3\omega k_{01} l U_f \quad \left(A; s^{-1}, F/km, km, V\right)$$



Note: overhead 22 kV – current c. 0,06 A/km
cables 22 kV – current c. 4 A/km

Note: MV system can be operated also with GF, on LV level again 3-phase supplying due to transformers MV/LV D/yn (Y/zn)

Talon

$$I_{pa} = I_{pc} = 2{,}44\ \text{A}$$

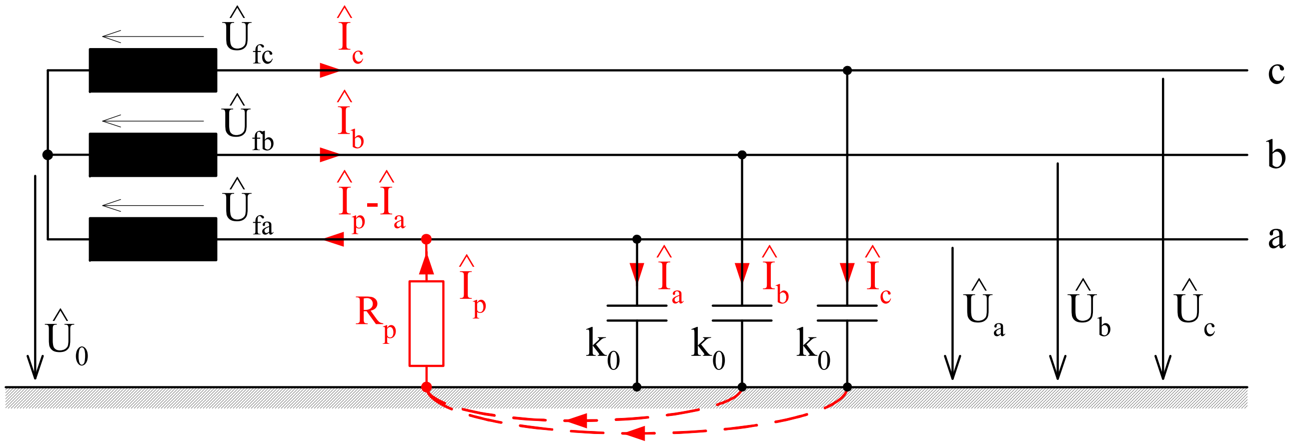
$$I_{pb} = 2{,}49\ \text{A}$$

Horizontal

$$I_{pa} = I_{pc} = 2{,}51\ \text{A}$$

$$I_{pb} = 2{,}68\ \text{A}$$

Resistive ground fault



Affected phase voltage non-zero

$$\hat{I}_p = -\hat{U}_a / R_p = \hat{I}_a + \hat{I}_b + \hat{I}_c$$

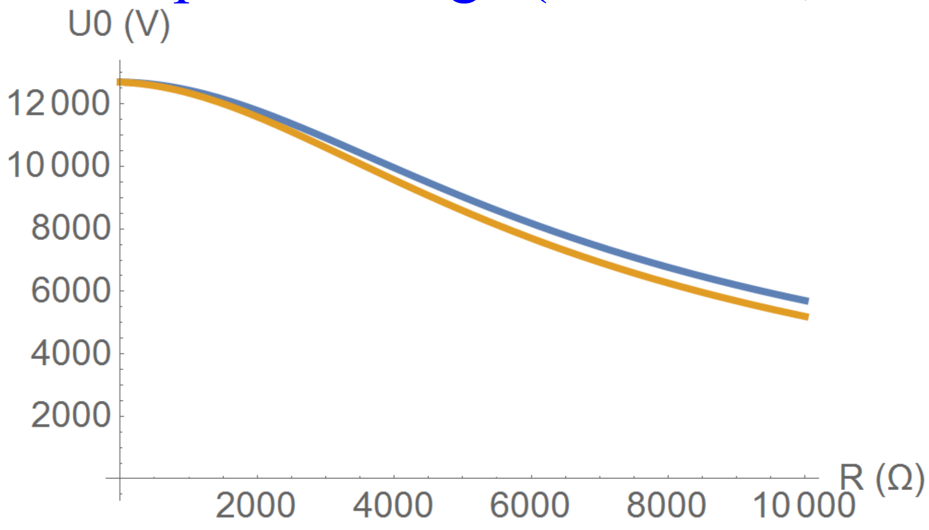
Neutral point voltage

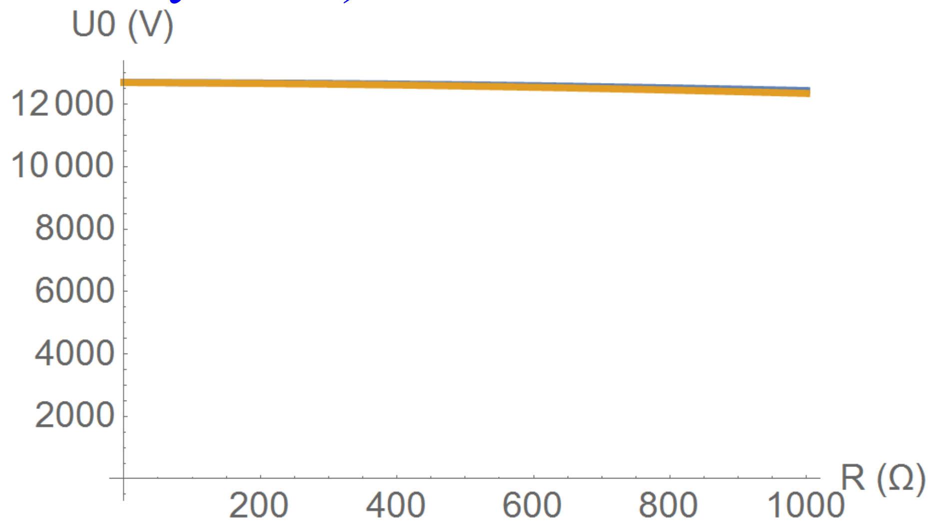
$$\hat{U}_0 = -\frac{j\omega\left(k_{a0} + \hat{a}^2 k_{b0} + \hat{a} k_{c0}\right) + R_p^{-1}}{j\omega\left(k_{a0} + k_{b0} + k_{c0}\right) + R_p^{-1}} \hat{U}_{fa}$$

$R_p = 0$ $\qquad$ $\hat{U}_0 = -\hat{U}_{fa}$

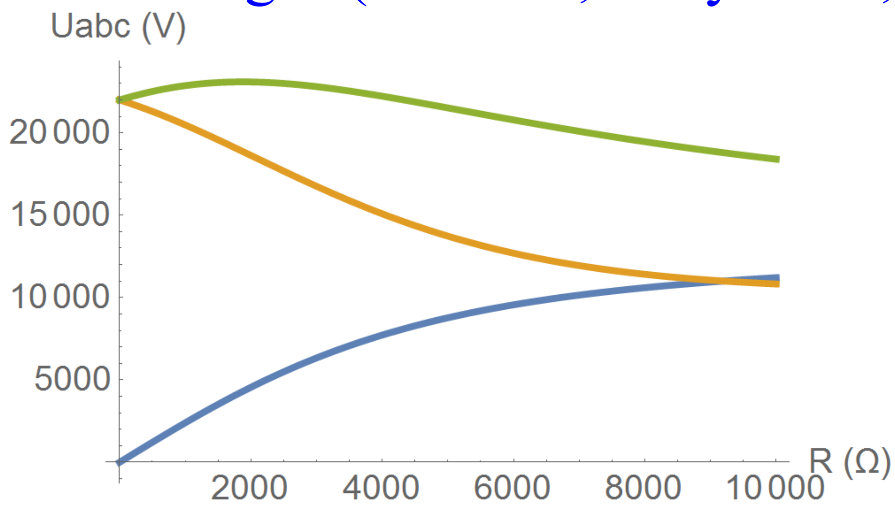
$R_p = \infty$ $\qquad$ $\hat{U}_0 = 0$ (for symmetrical capacities)

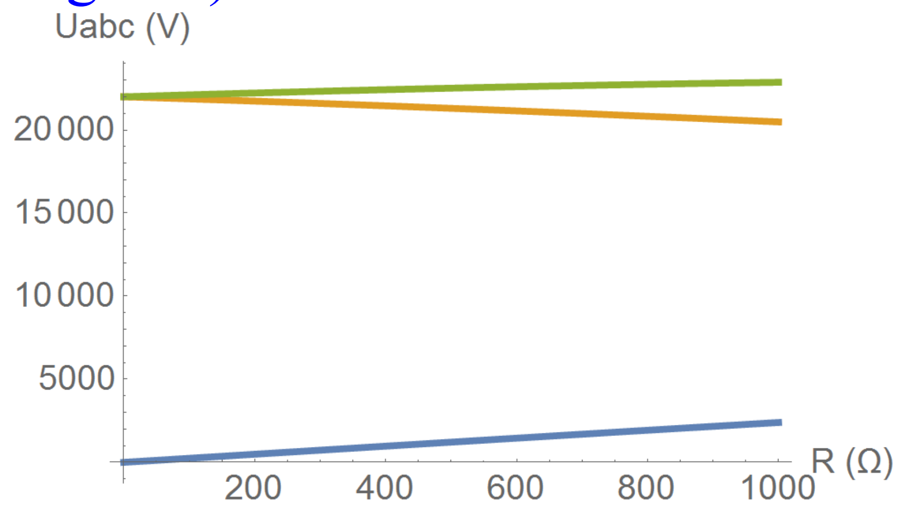
Neutral point voltage (talon blue, horizontal yellow)



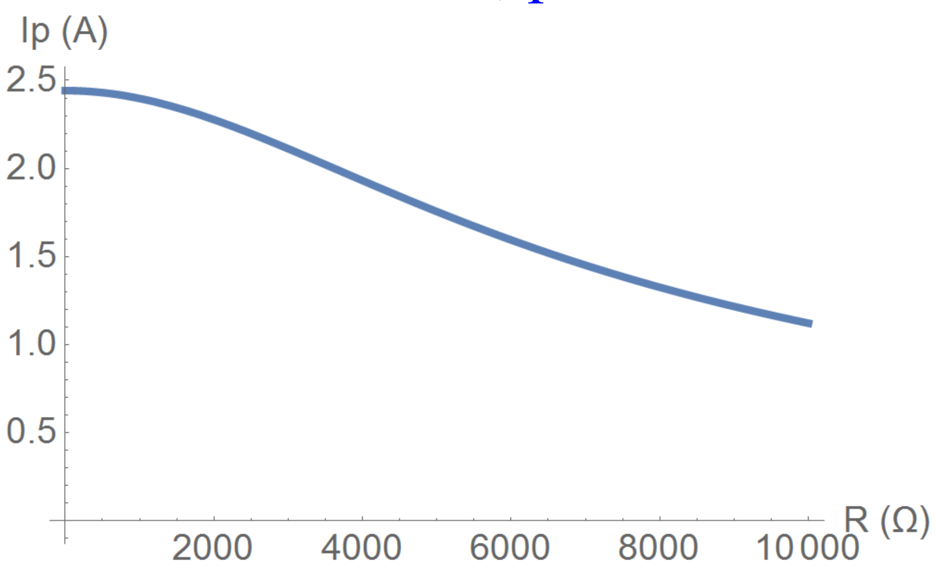


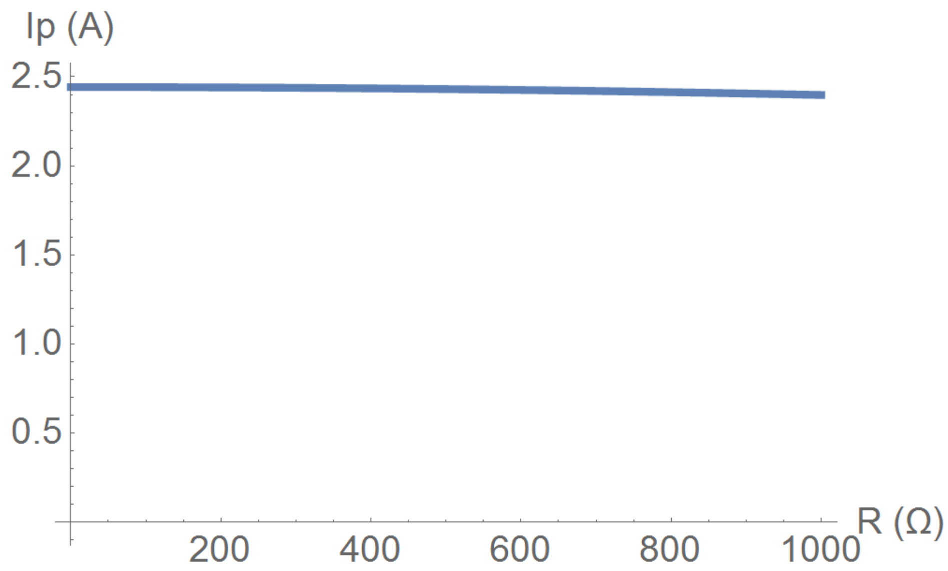
Phase voltages (A - blue, B - yellow, C - green) - talon





Fault current – talon, phase A



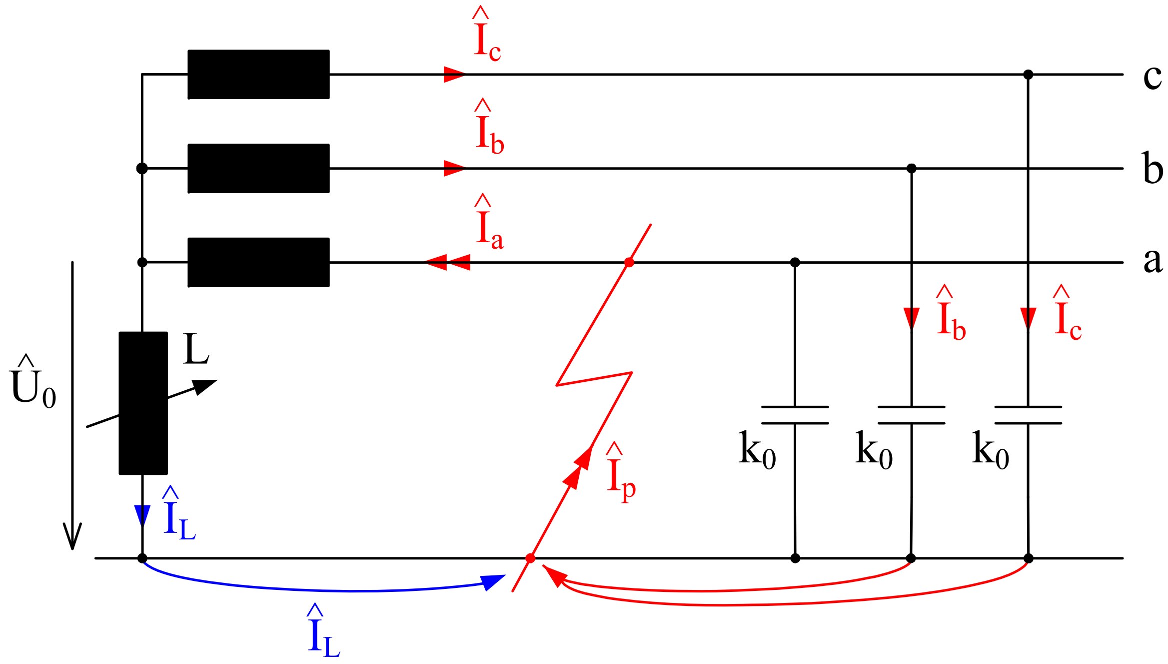


Ground fault current compensation

Compensation in systems where $I_p > 5A$ - suitable

$I_p > 10A$ - necessary

Method: continuously controlled arc-suppression coil (Petersen coil) between the transformer neutral point and the ground (in case of transformers with D winding by means of grounding transformer with Zn, Yn – artificial neutral point)



Faultless state

$$U_0 = 0$$ - symmetrical capacities

$$U_0 \approx x \cdot 0{,}01\, U_f$$ - usual unbalance

Perfect ground fault

$$\hat{U}_0 = -\hat{U}_{fa}$$

Arc-suppression coil current

$$\hat{I}_L = -j\frac{\hat{U}_0}{\omega L}$$

Total compensation

$$\hat{I}_L = -\hat{I}_p$$

$$-j\frac{\hat{U}_0}{\omega L} = -3j\omega k_0 \hat{U}_0$$

Hence

$$\underline{L = \frac{1}{3\omega^2 k_0} \quad (H;\, s^{-1},\, F)}$$

Coil power (reactive inductive)

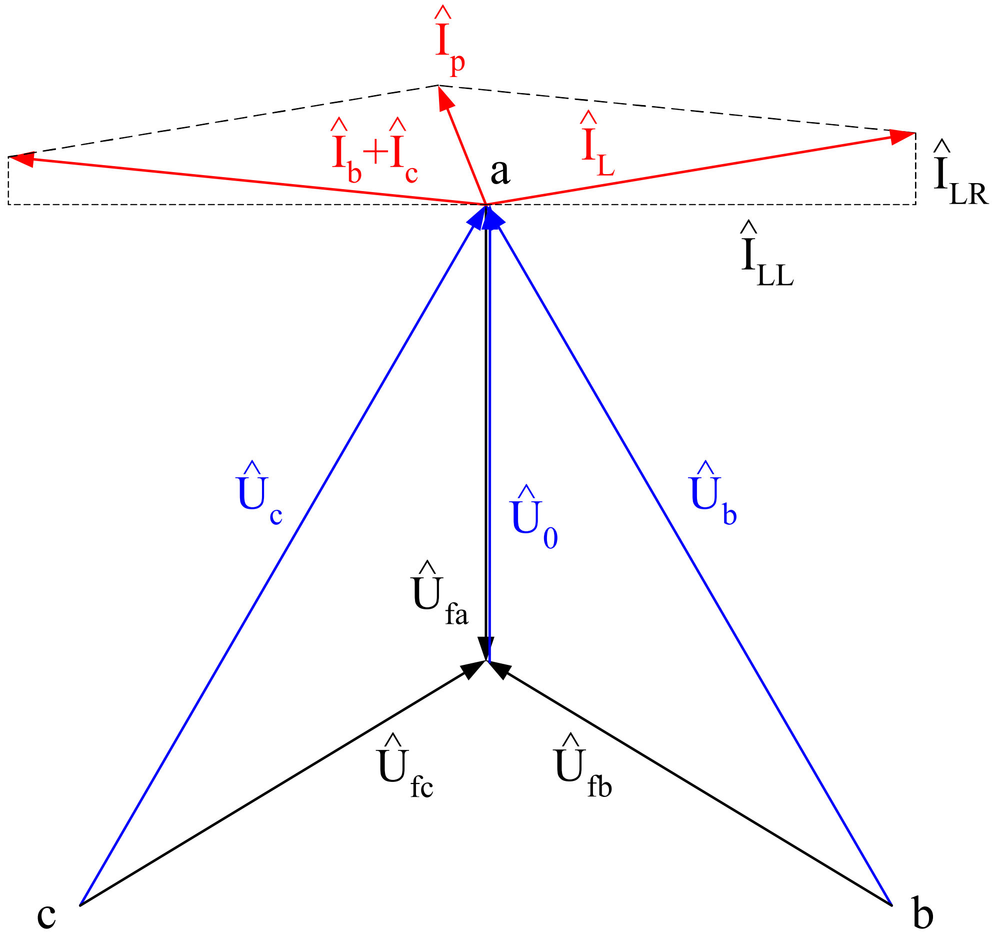
$$\hat{S} = \hat{U}_0 \hat{I}_L^* = 3 j\omega k_0 \hat{U}_0 \hat{U}_0^* = j\omega k_0 U^2 = Q_L$$

Ideal compensation: $I_p = 0$ in the fault point

Real situation: residual current (small active)

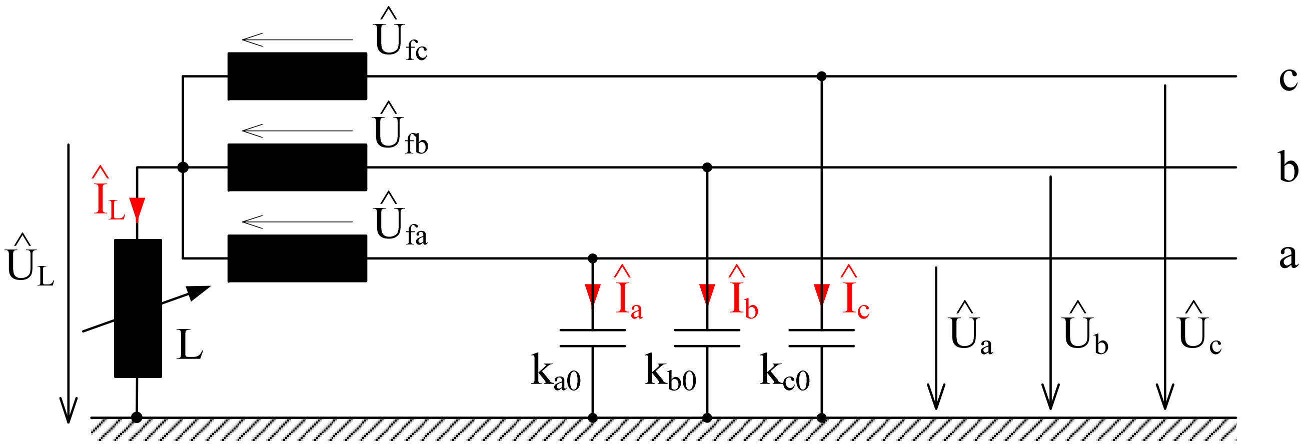
- inaccurate inductance setting (error or intention)
- uncompensatable active component (power line conductance, coil R)
- higher harmonics

$$\hat{I}_p = \left[\frac{1}{R_L} + 3G_0 + j\left(3\omega k_0 - \frac{1}{\omega L}\right)\right]\hat{U}_0$$


$\hat{I}_p$
$\hat{I}_b+\hat{I}_c$
a
$\hat{I}_L$
$\hat{I}_{LR}$
$\hat{I}_{LL}$
$\hat{U}_c$
$\hat{U}_0$
$\hat{U}_b$
$\hat{U}_{fa}$
$\hat{U}_{fc}$
$\hat{U}_{fb}$
c
b

Arc-suppression coil tuning

L dimensioning by calculation, setting in the faultless state (for given system configuration).
Tuning is done by magnetic circuit change by means of motor (air gap).



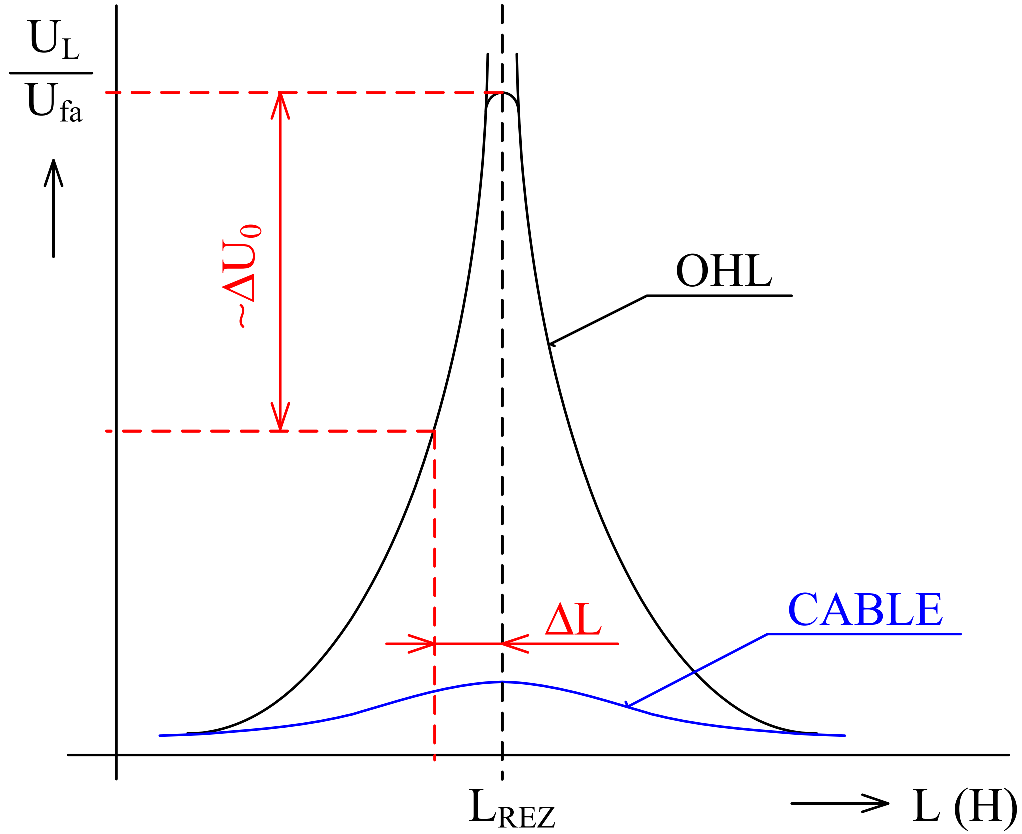
Coil voltage

$$\hat{U}_L = \frac{-\omega^2 L\left(k_{a0} + \hat{a}^2 k_{b0} + \hat{a} k_{c0}\right)}{\omega^2 L\left(k_{a0} + k_{b0} + k_{c0}\right) - 1} \hat{U}_{fa}$$

Resonance dependence

$$\left|\frac{U_L}{U_{fa}}\right| = f(L)$$

$$L_{REZ} = \frac{1}{\omega^2 (k_{a0} + k_{b0} + k_{c0})}$$



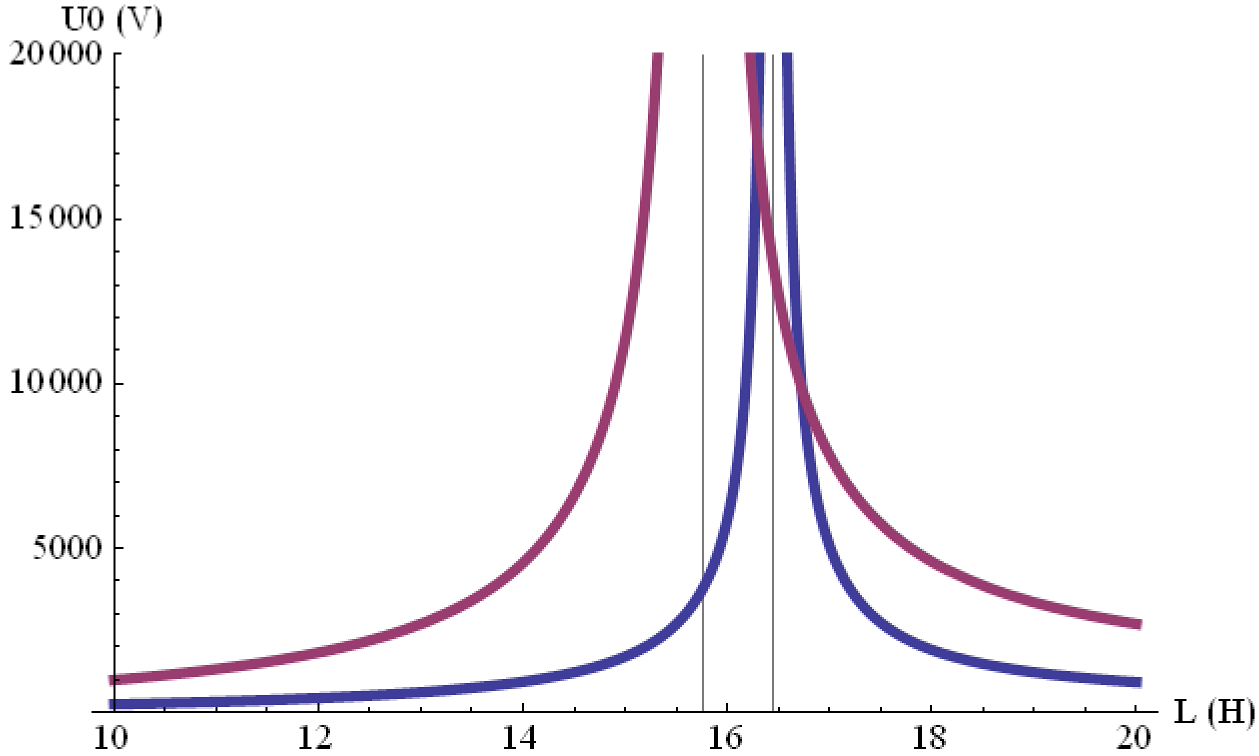
Overhead power lines

- higher capacitive unbalance
- maximum limited by resistances
- L_{REZ} compensates GF totally → resonance coil
- setting by U_L measurement
- with small R the transformer neutral point is strained too much in resonance → intended (small) detuning → dissonance coil

Cable power lines

- small capacitive unbalance → flat curve → difficult tuning

Neutral point voltage (talon blue, horizontal violet)

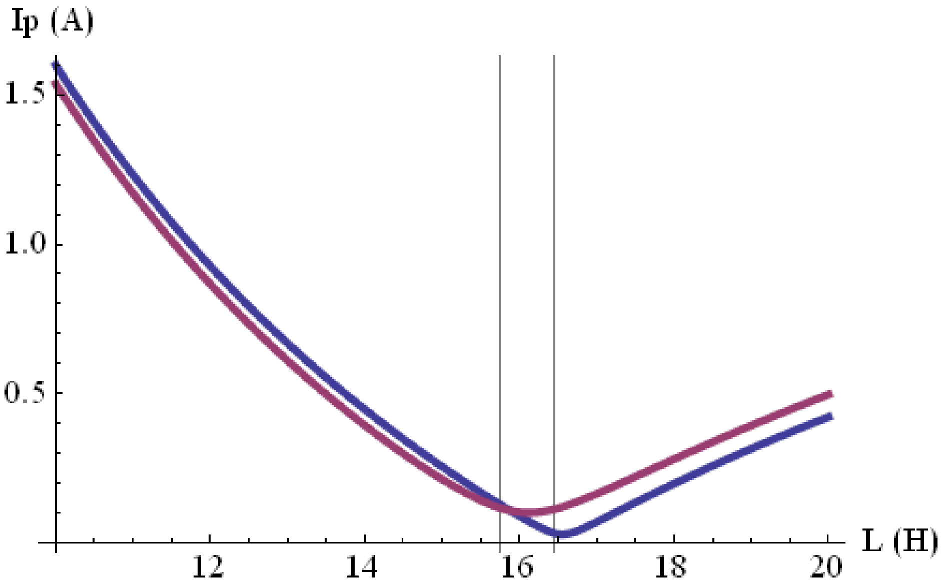


talon $L_{REZ} = 16{,}45\ \mathrm{H}$

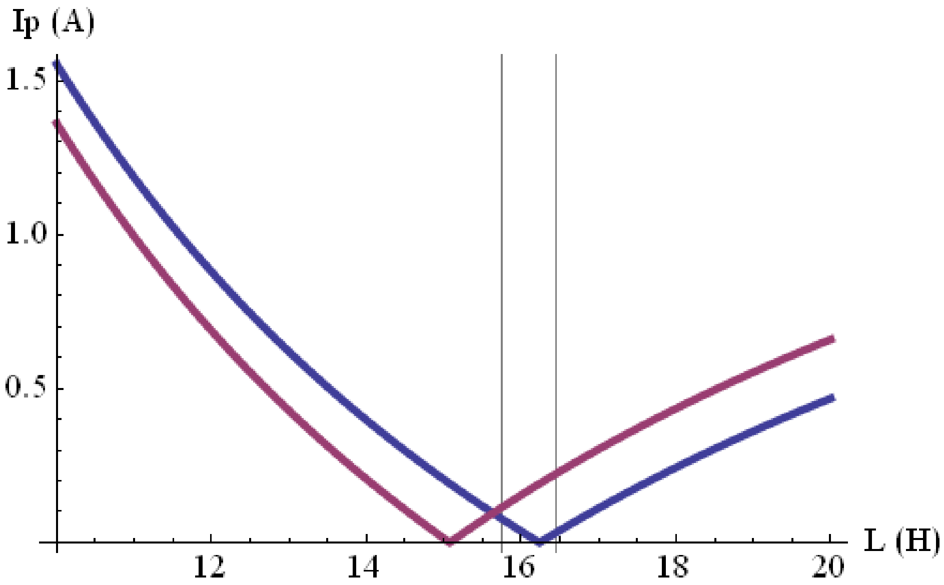
horizontal $L_{REZ} = 15{,}76\ \mathrm{H}$

Fault current for coil detuning (talon blue, horizontal violet)

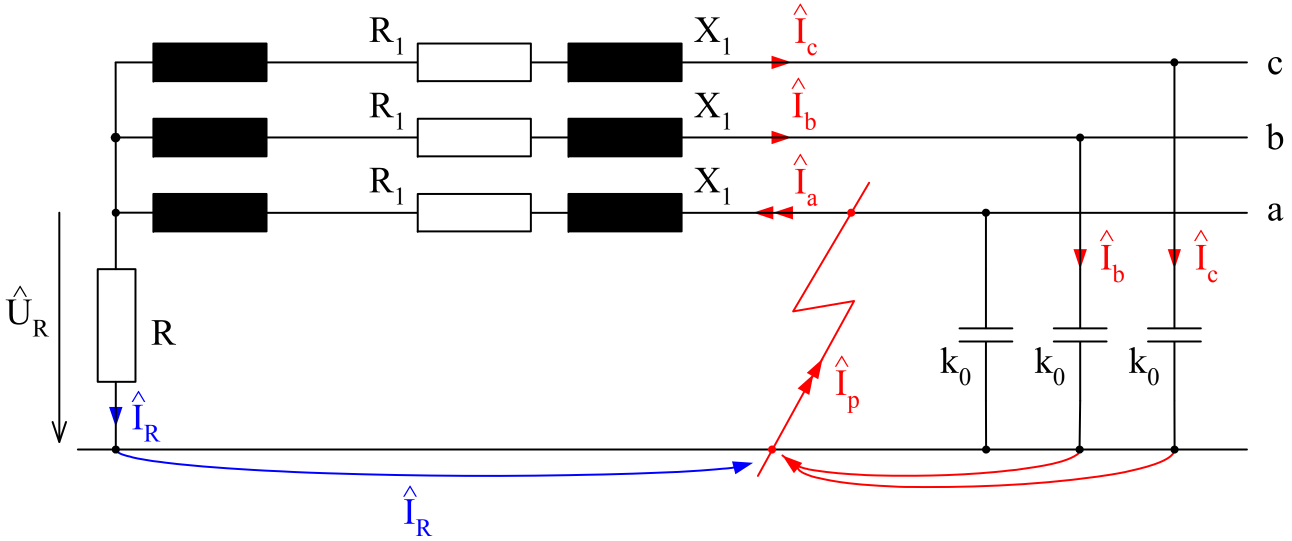
phase A



phase B



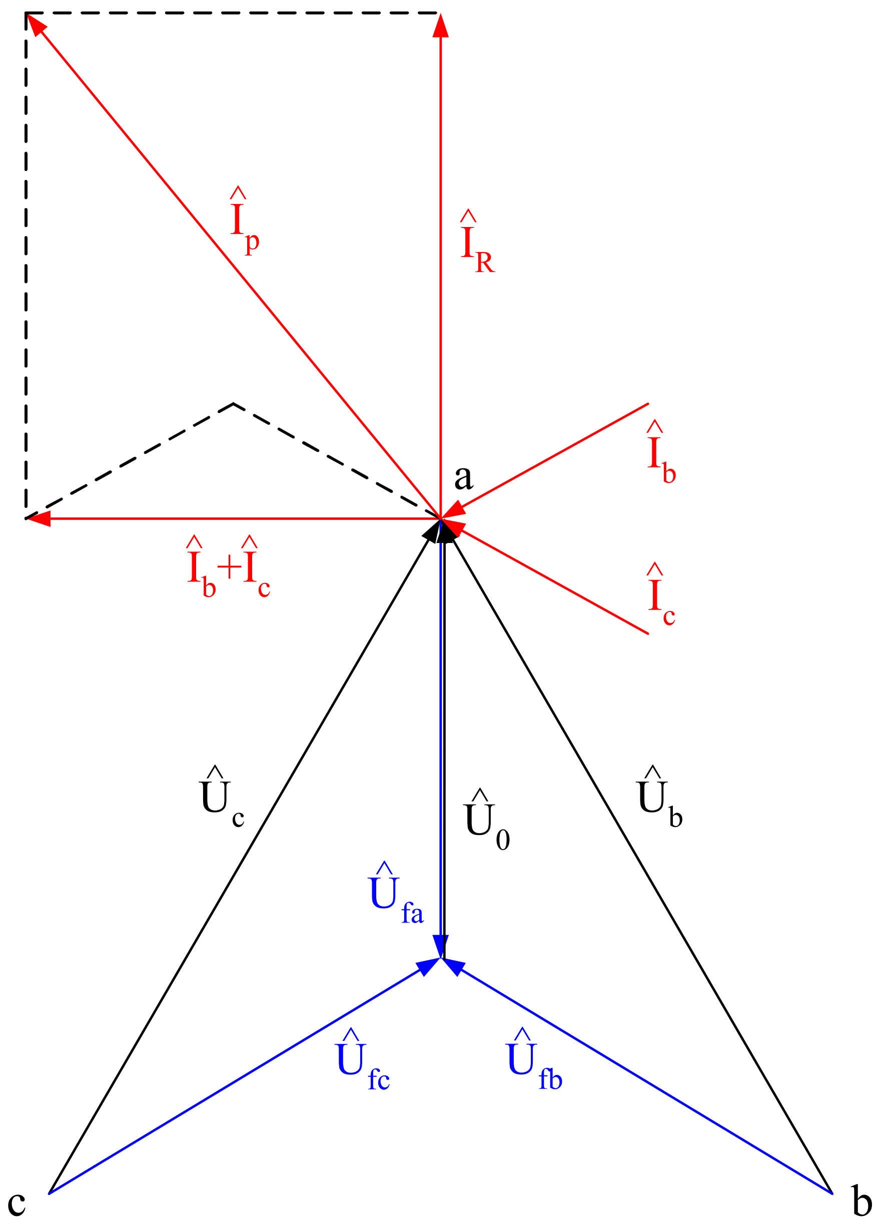
Cable systems grounded with the resistance



During the fault

- neutral point voltage almost phase-to-ground value
- I_p uncompensated
- I_p depends on the system extent x decreases with the distance from the transformer (short-circuit character)
- R value choice can influence I_p size and character

$$\hat{I}_P = -(1/R + j3\omega k_0)U_f$$



$\hat{I}_p$
$\hat{I}_R$
$\hat{I}_b$
a
$\hat{I}_b+\hat{I}_c$
$\hat{I}_c$
$\hat{U}_c$
$\hat{U}_0$
$\hat{U}_b$
$\hat{U}_{fa}$
$\hat{U}_{fc}$
$\hat{U}_{fb}$
c
b

Neutral point voltage in a faultless state

($k_{b0} = (1-\Delta)k_{c0};\ k_{a0} = k_{c0} = 50 \cdot 4\ \mathrm{nF/km} \cdot 50\ \mathrm{km}$)

$R_{uz} = 20\ \Omega$