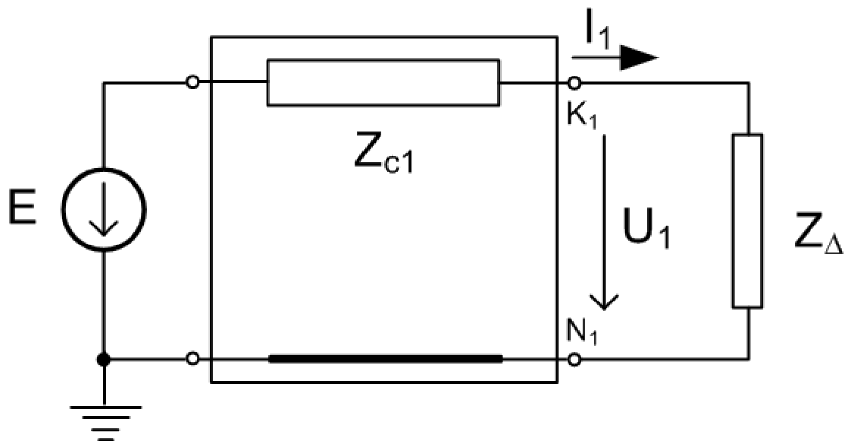
Short-circuits in ES (2nd part)

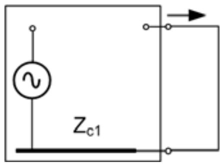
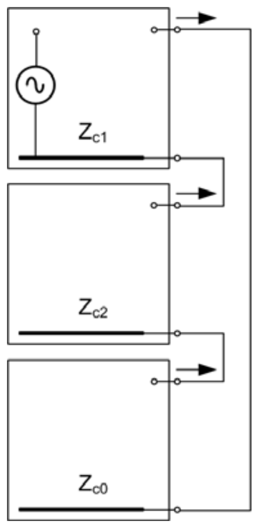
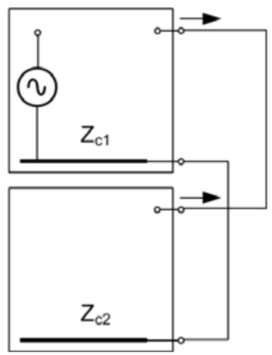
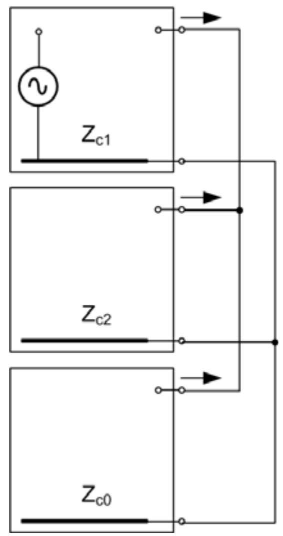
Unbalanced short-circuits equivalence with three-phase short-circuit

Positive-sequence current component calculation by means of an additional impedance (in the short-circuit place according to short-circuit type)



Generalized relation

$$\hat{I}_1 = \frac{\hat{E}}{\hat{Z}_1 + \hat{Z}_\Delta}$$

Short-cir. type	3ph	1ph	2ph	2ph to ground
$\hat{Z}_\Delta$	0	$\hat{Z}_2 + \hat{Z}_0$	$\hat{Z}_2$	$\frac{\hat{Z}_2 \cdot \hat{Z}_0}{\hat{Z}_2 + \hat{Z}_0}$
Current components	$\hat{I}_1$	$\hat{I}_1 = \hat{I}_2 = \hat{I}_0$	$\hat{I}_2 = -\hat{I}_1$	$\hat{I}_1 = -\left(\hat{I}_2 + \hat{I}_0\right)$
m ($I_k = m \cdot I_1$)	1	3	$\sqrt{3}$	$\sqrt{3}\sqrt{1 - \frac{X_2 \cdot X_0}{(X_2 + X_0)^2}}$
Substitution diagram				

Individual short-circuit types comparison

For: $t = 0$ (I''), $R = 0$, $X_1 = X_2$
ratio X_0/X_1 can be changed from 0 to ∞
reference 3ph short-circuit

Three-phase short-circuit

$$I_k''^{(3)} = I_1 = \frac{E''}{X_1}$$

Single-phase-to-ground short-circuit

$$I_k''^{(1)} = 3I_1 = \frac{3E''}{X_1 + X_2 + X_0} = \frac{3X_1}{2X_1 + X_0} I_k''^{(3)} = \frac{3}{2 + \frac{X_0}{X_1}} I_k''^{(3)}$$

$$I_k''^{(1)} = \left(0 \div 1{,}5\right) I_k''^{(3)}$$

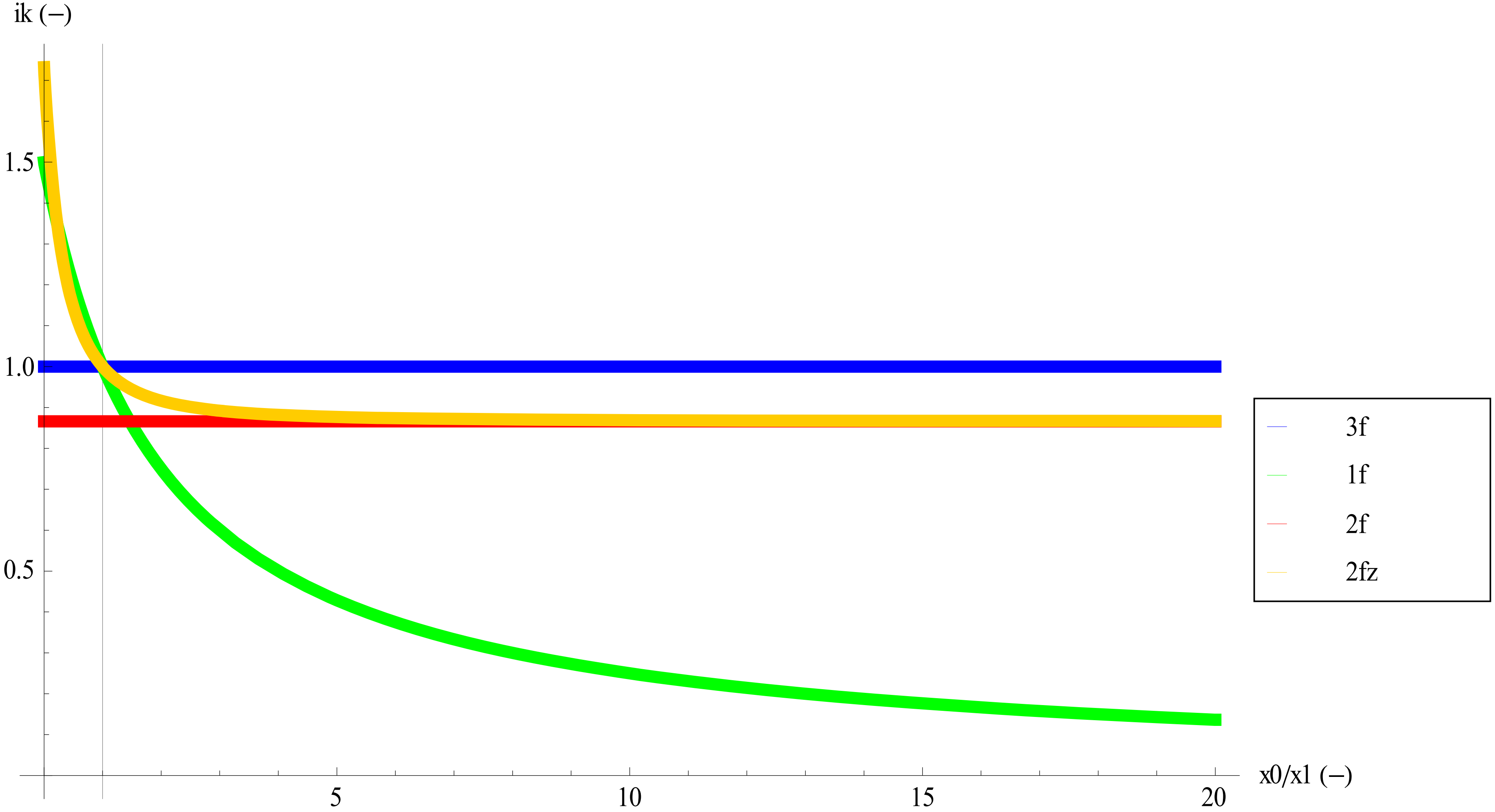
Phase-to-phase short-circuit

$$I_k''^{(2)} = \sqrt{3} I_1 = \frac{\sqrt{3} E''}{X_1 + X_2} = \frac{\sqrt{3} X_1}{2X_1} I_k''^{(3)} = \frac{\sqrt{3}}{2} I_k''^{(3)} \cong 0,866\; I_k''^{(3)}$$

Double-phase-to-ground short-circuit

$$I_k''^{(2z)} = \sqrt{3}\sqrt{1 - \frac{X_2 \cdot X_0}{(X_2 + X_0)^2}}\,\frac{E''}{X_1 + \dfrac{X_2 \cdot X_0}{X_2 + X_0}} = \sqrt{3}\sqrt{1 - \frac{\dfrac{X_0}{X_1}}{\left(1 + \dfrac{X_0}{X_1}\right)^2}}\,\frac{I_k''^{(3)}}{1 + \dfrac{\dfrac{X_0}{X_1}}{1 + \dfrac{X_0}{X_1}}}$$

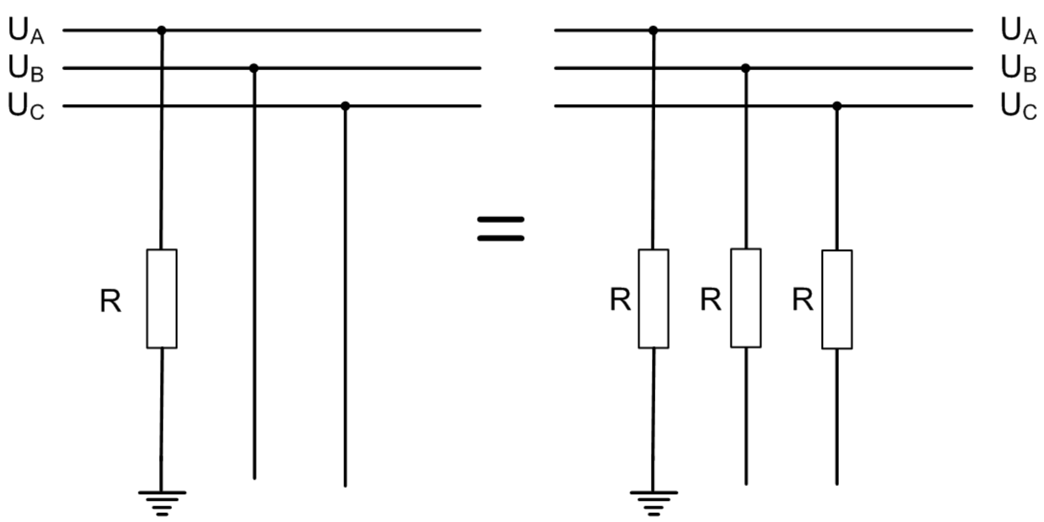
$$I_k''^{(2z)} = \left(\frac{\sqrt{3}}{2} \div \sqrt{3}\right) I_k''^{(3)}$$


ik (−)
1.5
1.0
0.5
5
10
15
20
x0/x1 (−)
3f
1f
2f
2fz

Arc influence during short-circuit

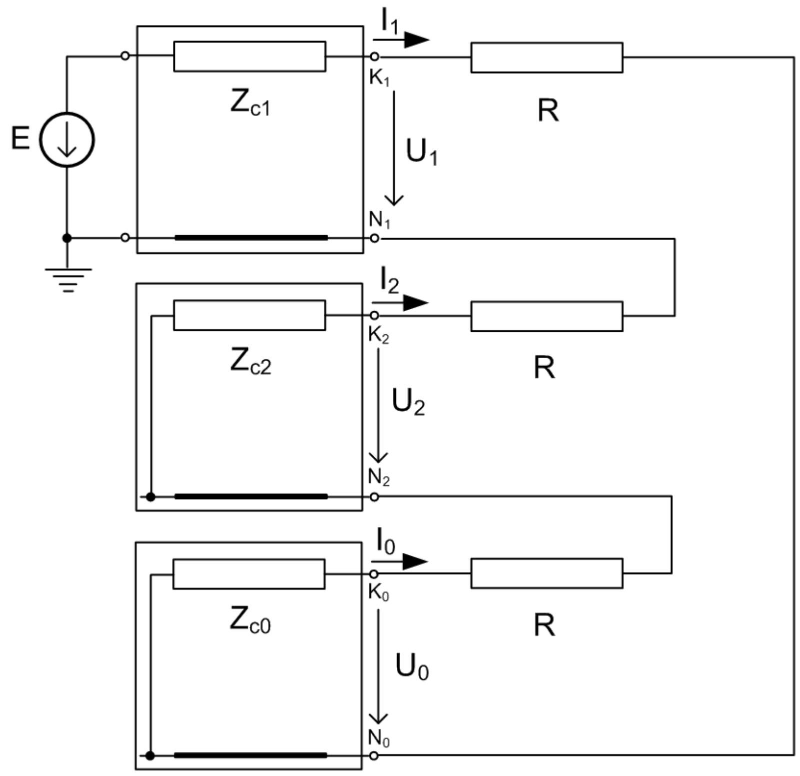
Single-phase-to-ground s.-c.

$$\hat{I}_1 = \frac{\hat{E}}{\hat{Z}_1 + \hat{Z}_2 + \hat{Z}_0 + 3R}$$



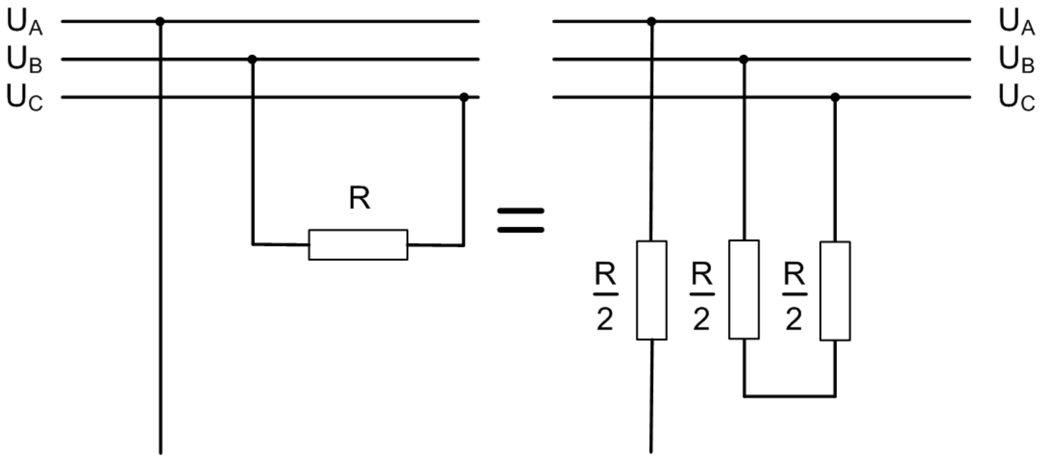
Three-phase s.-c.

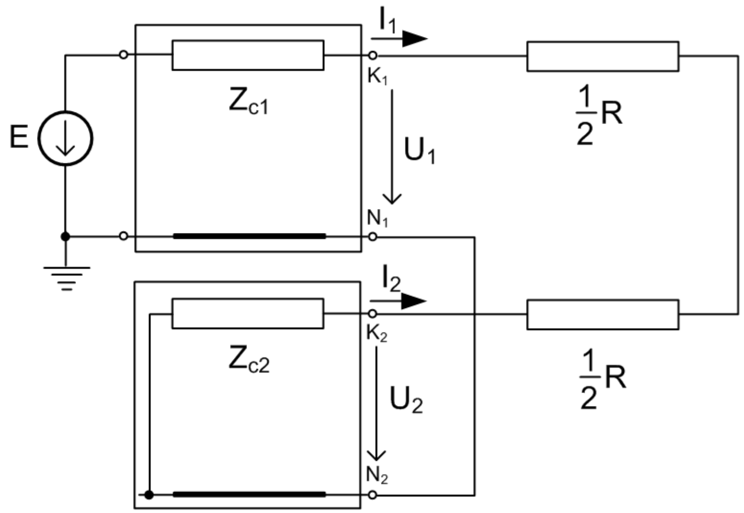
$$\hat{I}_1 = \frac{\hat{E}}{\hat{Z}_1 + R}$$



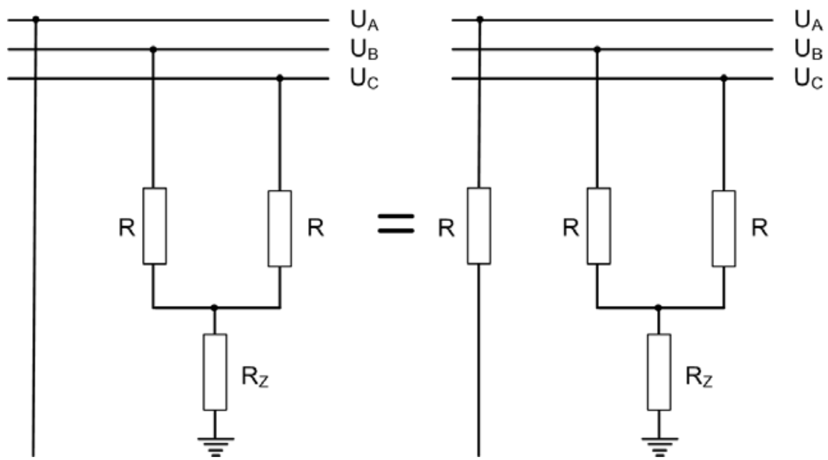
Phase-to-phase s.-c.

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



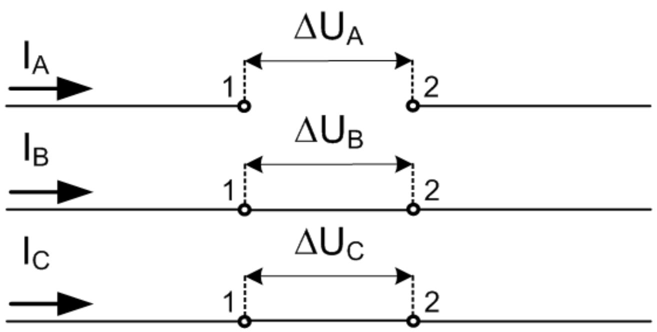


Note: Double-phase-to-ground s.-c. doesn't have a symmetrical resistance segment.

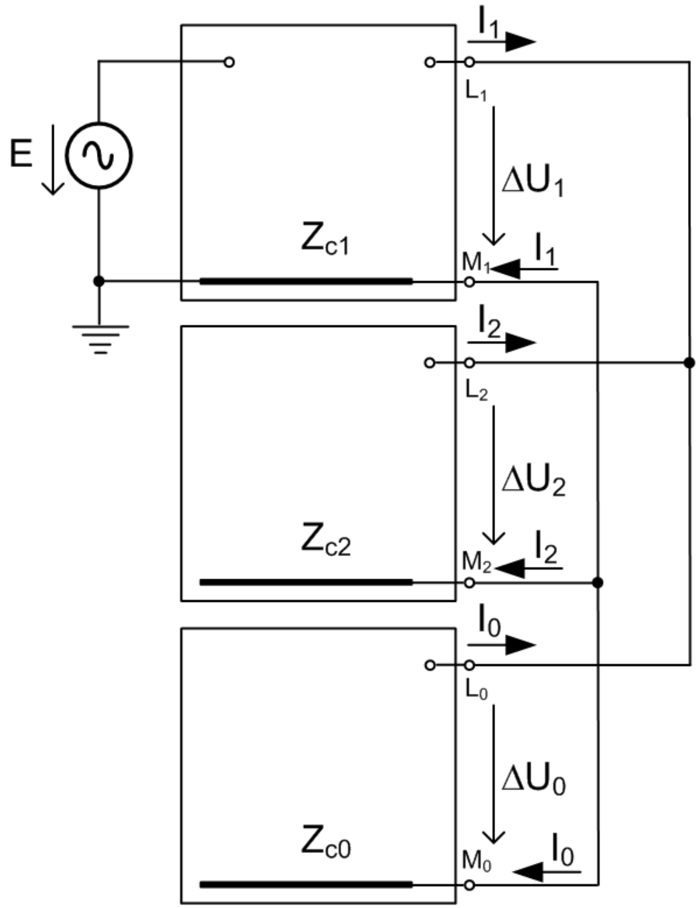


Phase interruption

Single-phase interruption (analogy with double-phase-to-ground s.-c.)



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

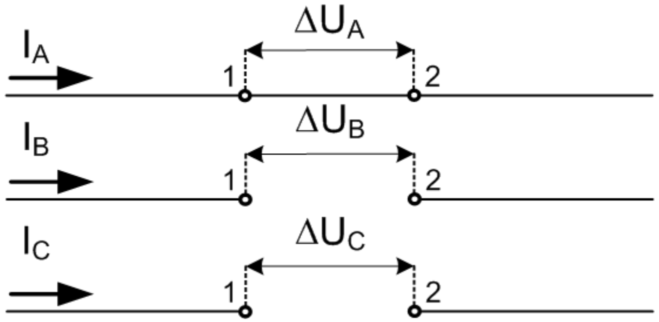


Components

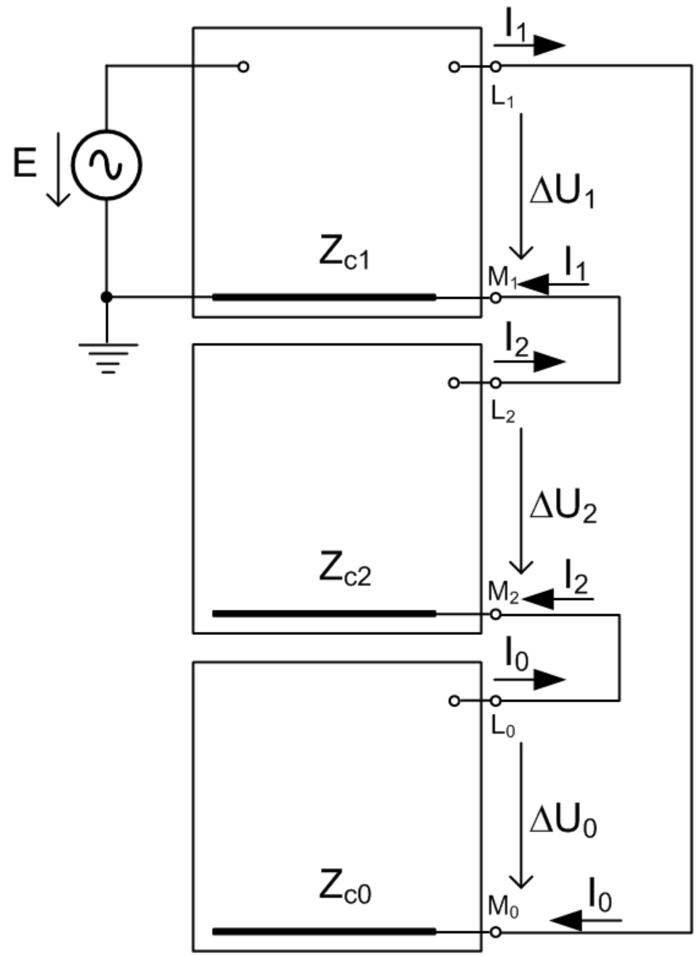
$$\Delta \hat{U}_1 = \Delta \hat{U}_2 = \Delta \hat{U}_0 = \frac{1}{3} \Delta \hat{U}_A$$

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

Double-phase interruption (analogy with single-phase-to-ground s.-c.)



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



Components

$$\hat{I}_1 = \hat{I}_2 = \hat{I}_0 = \frac{\hat{E}}{\hat{Z}_1 + \hat{Z}_2 + \hat{Z}_0} = \frac{1}{3}\hat{I}_A$$

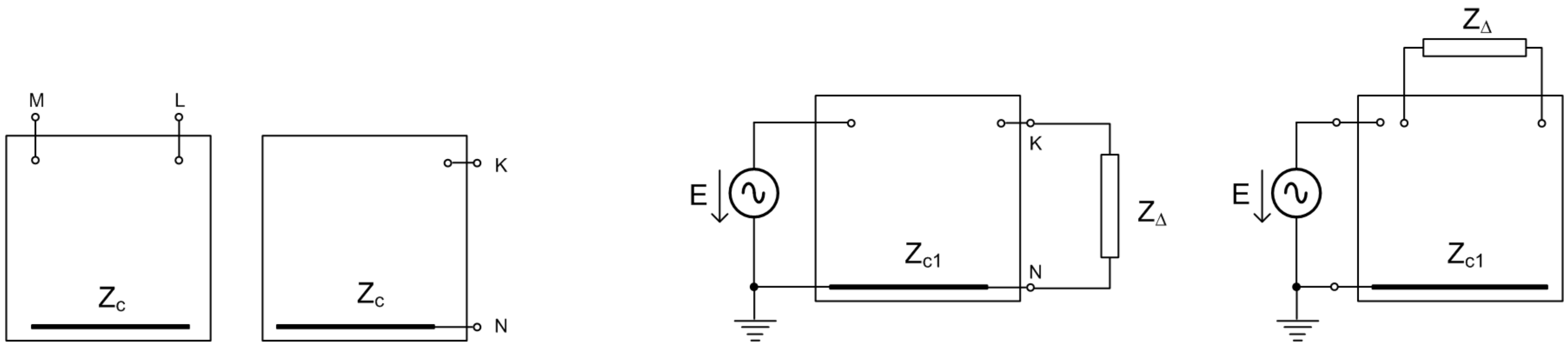
Analogy between interruptions and short-curcuits

Sequence impedances

- short-circuits – between s.-c. place and the ground
- interruption – between places on both sides of the interruption

Similarly for the additional impedance.

Sources always by means of impedances to the ground.



Multiple unbalances in ES

Single-phase-to-ground short-circuit in phase B, reference phase A

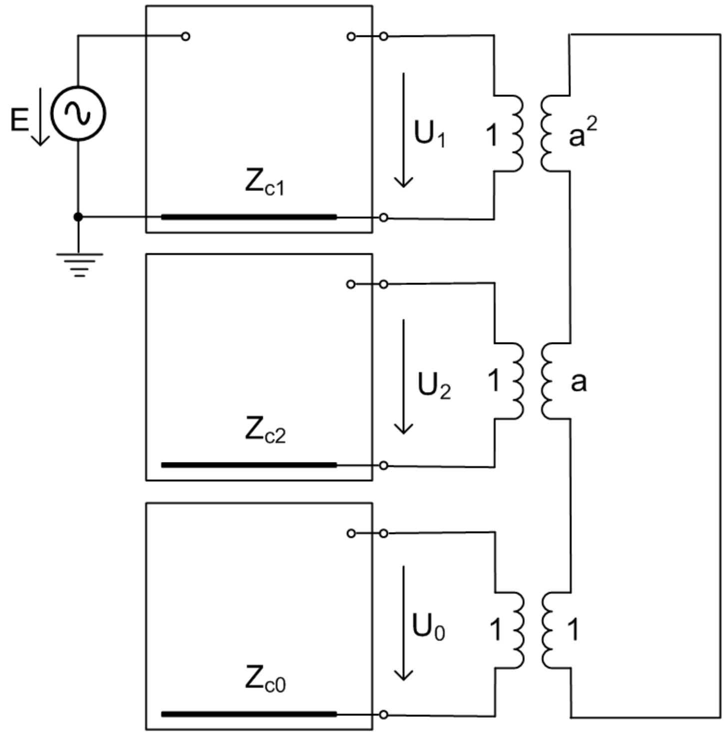
$$\left(I_{120}\right) = \left(T^{-1}\right)\left(I_{ABC}\right) = \frac{1}{3}\begin{pmatrix} 1 & \hat{a} & \hat{a}^2 \\ 1 & \hat{a}^2 & \hat{a} \\ 1 & 1 & 1 \end{pmatrix}\begin{pmatrix} 0 \\ \hat{I}_B \\ 0 \end{pmatrix} = \frac{1}{3}\begin{pmatrix} \hat{a}\hat{I}_B \\ \hat{a}^2\hat{I}_B \\ \hat{I}_B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

$$\hat{I}_1 = \hat{a}\hat{I}_0;\ \hat{I}_2 = \hat{a}^2\hat{I}_0;\ \hat{I}_0 = \frac{1}{3}\hat{I}_B$$

$$\hat{p}_0 = 1$$

$$\hat{p}_1 = \frac{\hat{I}_0}{\hat{I}_1} = \frac{1}{\hat{a}} = \hat{a}^2$$

$$\hat{p}_2 = \frac{\hat{I}_0}{\hat{I}_2} = \frac{1}{\hat{a}^2} = \hat{a}$$



Note: TRF ratio (1ph)

$$\hat{u}_s = \hat{p}_u \hat{u}_p$$

$$\hat{i}_s = \hat{p}_i \hat{i}_p$$

power invariance

$$\hat{u}_s \cdot \hat{i}_s^* = \hat{p}_u \hat{u}_p \cdot \hat{p}_i^* \hat{i}_p^* = \hat{u}_p \cdot \hat{i}_p^*$$

$$\hat{p}_u = \frac{1}{\hat{p}_i^*}$$

If $\hat{p}_u = \hat{a}$ then $\hat{p}_i = \frac{1}{\hat{a}^*} = \frac{1}{\hat{a}^2} = \hat{a} = \hat{p}_u$.

It is valid for reference phase B

$$\hat{U}_1 = \hat{U}_{B1}, \hat{U}_2 = \hat{U}_{B2}, \hat{U}_0 = \hat{U}_{B0}$$

$$\hat{U}_A = \hat{a}\hat{U}_1 + \hat{a}^2\hat{U}_2 + \hat{U}_0$$

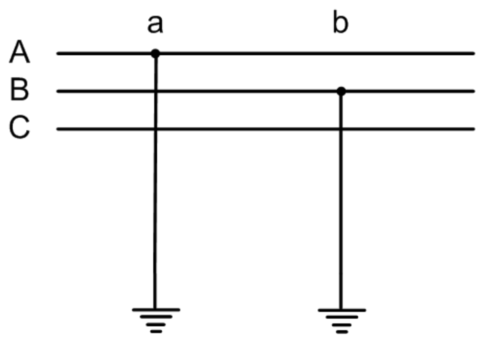
$$\hat{U}_B = \hat{U}_1 + \hat{U}_2 + \hat{U}_0$$

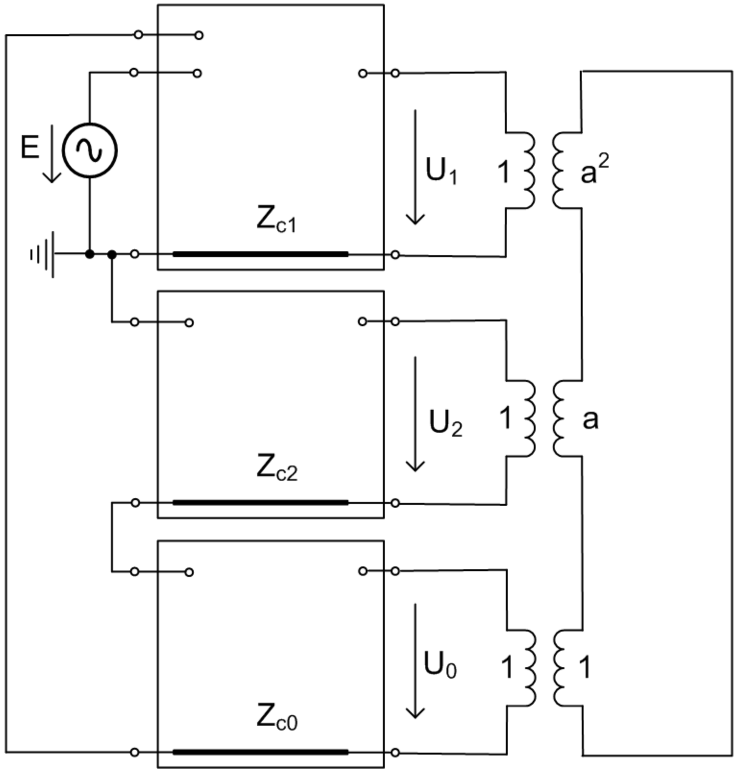
$$\hat{U}_C = \hat{a}^2\hat{U}_1 + \hat{a}\hat{U}_2 + \hat{U}_0$$

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

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

Two simultaneous single-phase-to-ground short-circuits in different ES places

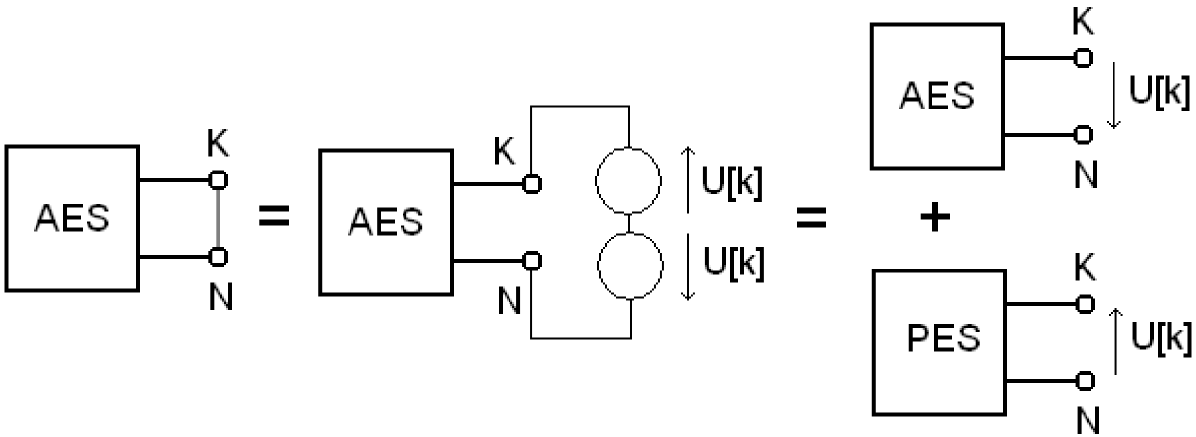




More than 2 faults → sequence diagrams interconnection is complicated → rather calculation in phases.

Short-circuit impedance matrix

- short-circuit is replaces by two sources with U[k] voltage and the opposite orientation
- U[k] voltage size equals to voltage value in the node *k* just before the fault
- superposition principle



- AES (active ES) => ES steady-state just before the short-circuit, sources modelled by an ideal voltage source and generator reactance
- PES (passive ES) => without sources: fault state, generators replaced only by sub-transient reactance against the ground

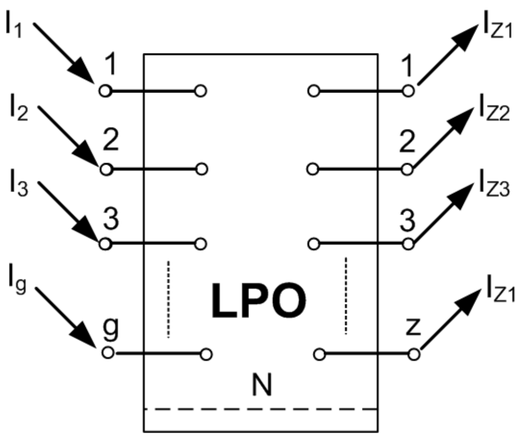
$$(I) = (Y)(U)$$

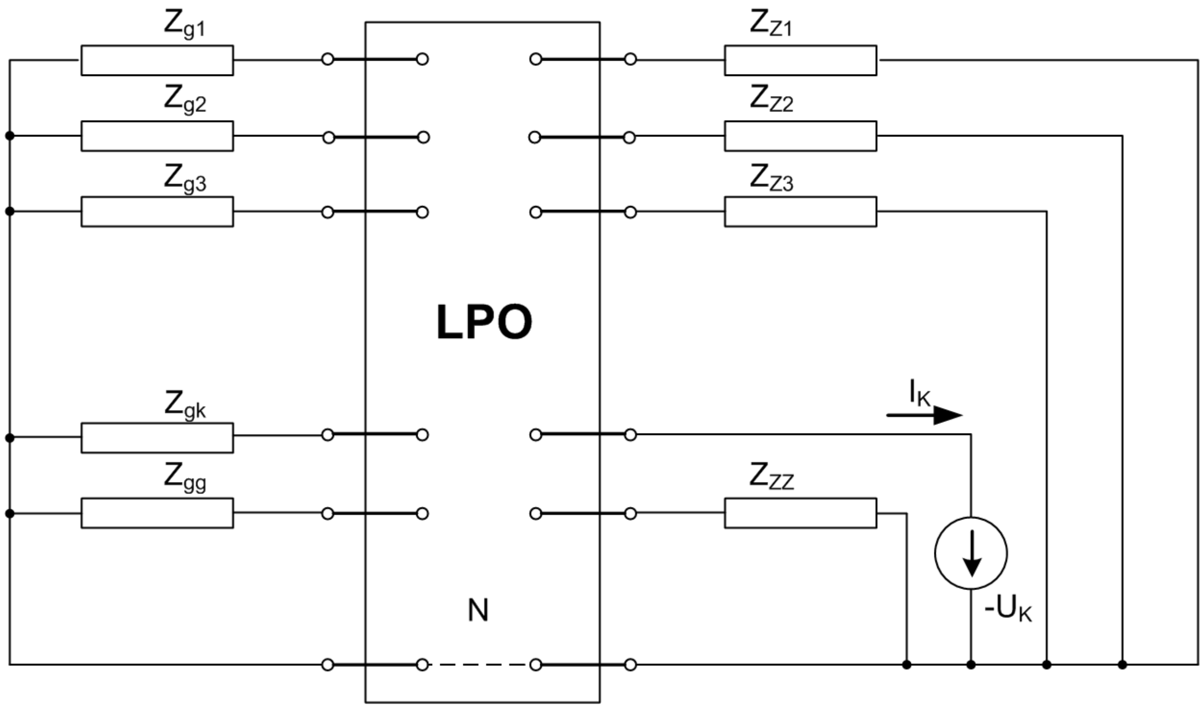
$$\hat{Y}_{(k,k)} = \sum_{m \in M_i} \hat{Y}_{km} \qquad \hat{Y}_{(k,m)} = -\hat{Y}_{km}$$

ES simplified diagram

a) corresponding with node admittance matrix

b) corresponding with short-circuit admittance matrix





All node currents are zero except the short-circuit place, here an ideal voltage source → short-circuit admittance matrix.

$$(I) = (Y_k)(U)$$

$$\begin{pmatrix} 0 \\ \vdots \\ -\hat{I}_k \\ \vdots \\ 0 \end{pmatrix} = (Y_k) \begin{pmatrix} \hat{U}_1 \\ \vdots \\ -\hat{U}_k \\ \vdots \\ \hat{U}_n \end{pmatrix}$$

Conversion to short-circuit impedance matrix

$$(U) = (Y_k)^{-1}(I) = (Z_k)(I)$$

$$
\begin{pmatrix} \hat{U}_1 \\ \vdots \\ -\hat{U}_k \\ \vdots \\ \hat{U}_n \end{pmatrix} = \begin{pmatrix} \hat{Z}_{(1,1)} & & \cdots & & \hat{Z}_{(1,n)} \\ & \ddots & & & \\ \vdots & & \hat{Z}_{(k,k)} & & \vdots \\ & & & \ddots & \\ \hat{Z}_{(n,1)} & & \cdots & & \hat{Z}_{(n,n)} \end{pmatrix} \begin{pmatrix} 0 \\ \vdots \\ -\hat{I}_k \\ \vdots \\ 0 \end{pmatrix}
$$

Short-circuit current

$$
\hat{I}_k = \frac{\hat{U}_k}{\hat{Z}_{(k,k)}}
$$

$\hat{Z}_{(k,k)}$ short-circuit impedance in the node *k*

Voltage in any node

$$
\hat{U}_j = -\hat{Z}_{(j,k)} \hat{I}_k
$$

Current in a branch

$$\hat{I}_{ij} = \frac{\hat{U}_i - \hat{U}_j}{\hat{Z}_{ij}} = \frac{\hat{Z}_{(j,k)} - \hat{Z}_{(i,k)}}{\hat{Z}_{ij}} \hat{I}_k$$

$\hat{Z}_{ij}$ impedance of the branch between the nodes *i* and *j*

Real node voltages and real branch currents during short-circuits are:

fault = AES + PES

$I_{ij}^k = I_{(ij)} + I_{ij}$ $U_j^k = U_{(j)} + U_j$

where: current in the branch between the nodes *i* and *j*, node *j* voltage

I_{ij}^k, U_j^k during short-circuit

$I_{(ij)}$, $U_{(j)}$ just before the short-circuit origin

I_{ij}, U_j self fault state

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

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

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.

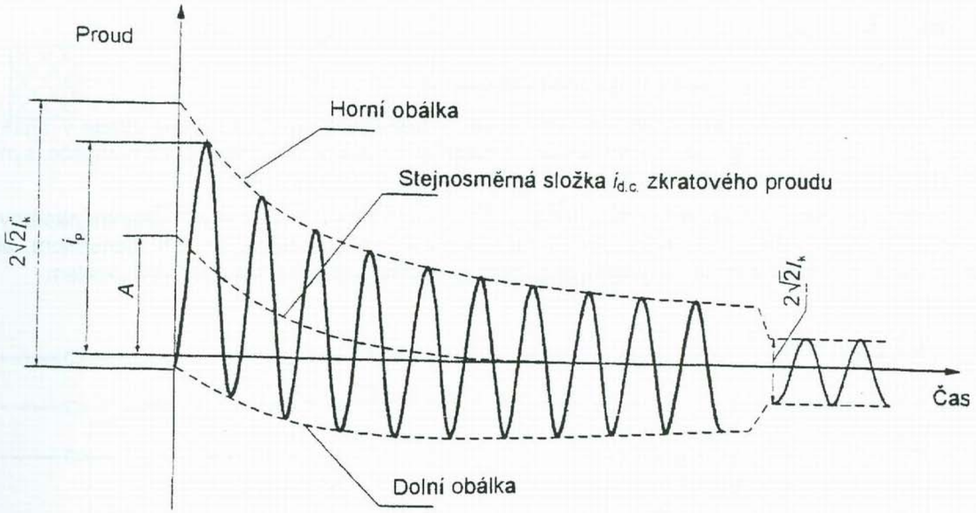
Max. instantaneous force on the conductor length unit

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

k_1 – conductor shape coefficient

k_2 – conductors configuration and currents phase shift coefficient

a – conductors distance



I_k'' je počáteční souměrný rázový zkratový proud

i_p nárazový zkratový proud

I_k ustálený zkratový proud

$i_{d.c.}$ stejnosměrná složka zkratového proudu

A počáteční hodnota stejnosměrné složky $i_{d.c}$

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

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

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

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

Calculation according to k_e coefficient as I''_k multiple

$$I_{ke} = k_e I''_k$$

Short-circuit duration time t_k (s)	Coefficient k_e		
	S.-c. on generator terminals	S.-c. in ES	
		HV, MV	LV
pod 0,05	1,70	1,60	1,50
0,05 – 0,1	1,60	1,50	1,20
0,1 – 0,2	1,55	1,40	1,10
0,2 – 1,0	1,50	1,30	1,05
1,0 – 3,0	1,30	1,10	1,00
nad 3,0	1,15	1,00	1,00