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Short circuits in power system

EUROPEAN UNION
European Structural and Investment Funds
Operational Programme Research,
Development and Education

MINISTRY OF EDUCATION,
YOUTH AND SPORTS

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Short circuits in power system

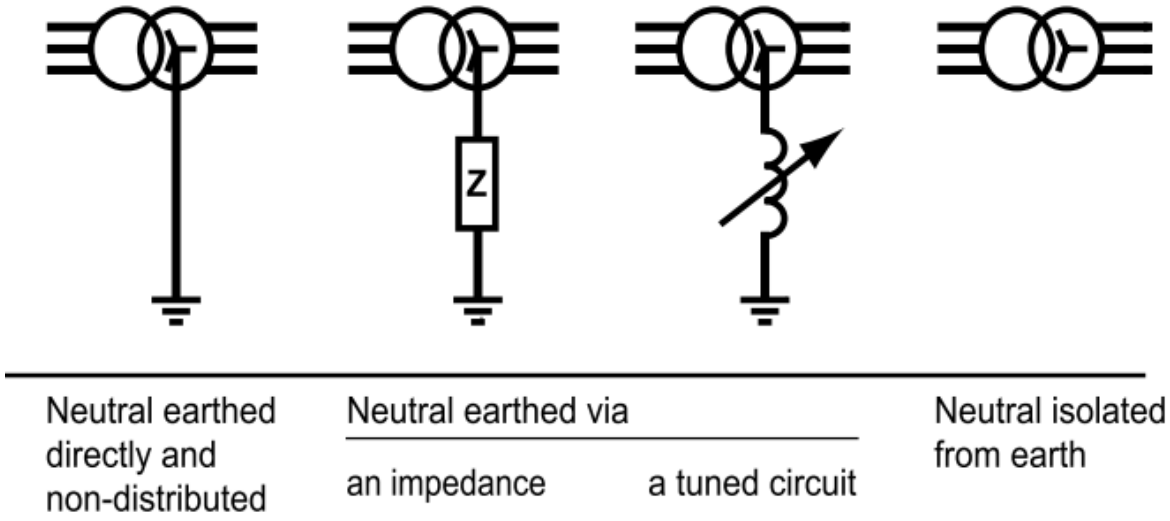
Miloslava Tesařová

University of West Bohemia
Department of Power Engineering

EUROPEAN UNION
European Structural and Investment Funds
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MINISTRY OF EDUCATION, YOUTH AND SPORTS

Neutral earthing/grounding arrangements



3-phase fault – 3-phase short-circuit (fault current and voltages do not depend on neutral earthing)

SLTG (single line to ground) fault – depends on neutral earthing

- neutral directly earthed → 1-phase short-circuit
- neutral earthed via R → 1-phase short-circuit
- neutral earthed via L → earth fault
- isolated neutral → earth fault

Neutral earthing/grounding arrangements

Directly grounded networks

- HV , EHV (in Czech Republic)
- LV (400 V)

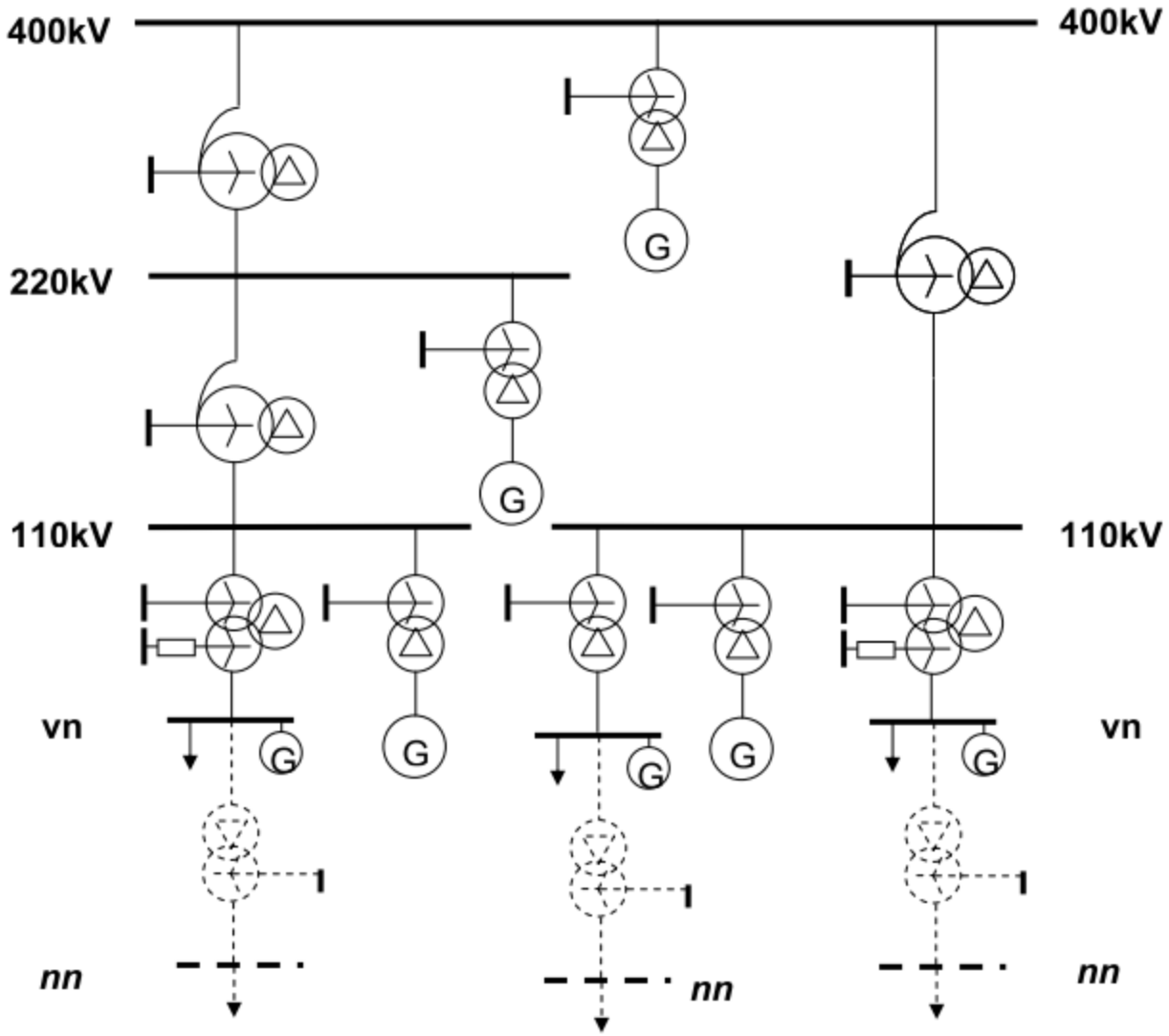
Networks grounded trough impedance

- MV
- Peterson coil – networks with overhead power lines
- Resistor – cable networks

Isolated networks

- MV – small networks, only few km
- LV (500 V), e.g. networks in mines

Czech Power System



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Short circuits

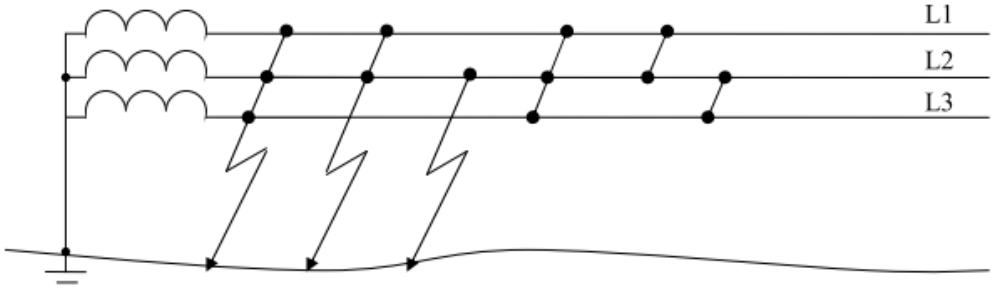
Short-circuit:
- cross fault, quick emergency change in ES
- the most often fault in ES
- transient events occur during short-circuits

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

Short-circuits types



zkraty zleva: trojfázový zemní, dvojfázový zemní, jednofázový, trojfázový, 2x dvojfázový

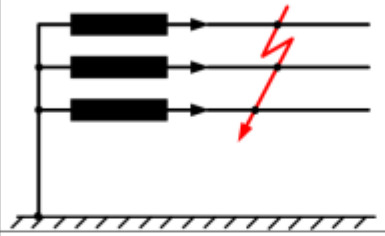
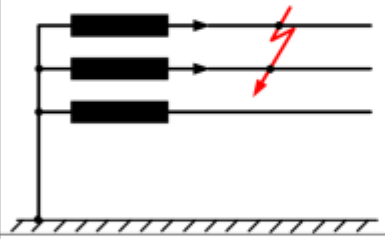
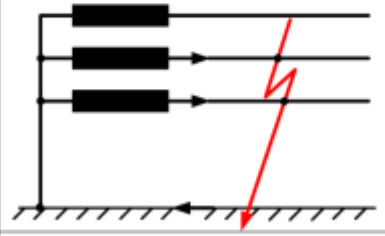
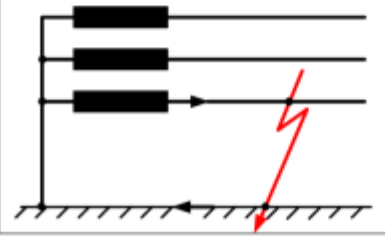
Short-circuits types

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 earth fault**
- **in case of earth 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

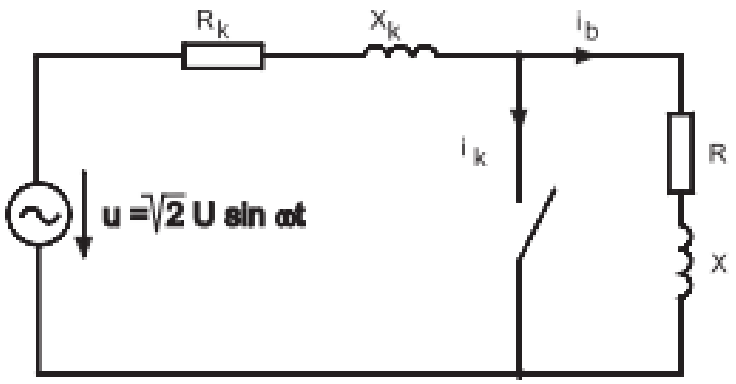
Notice
In cable systems lower rate of single.-phase faults

* Earth faults

Time behavior of short-circuit current

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

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



$$i_k \cdot R_k + L_k \frac{di_k}{dt} = \hat{u} \cdot sin(\omega t + \psi),$$

The total short circuit current is composed of both components:

$$i_k = \frac{-\hat{u}}{\sqrt{(R^2 + X^2)}} [sin(\omega t + \psi - \varphi_k) - e^{\frac{t}{\tau_g}} sin(\psi - \varphi_k)].$$

$$\varphi_k = \psi - \nu = arctan \frac{X}{R}.$$

Time behavior of short-circuit current

For the far-from-generator short circuit, the short circuit current is therefore made up of a constant AC periodic component and the decaying DC aperiodic component. From the simplified calculations, we can now reach the following conclusions:

- The short circuit current always has a decaying DC aperiodic component in addition to the stationary AC periodic component.
- The magnitude of the short circuit current depends on the operating angle of the current. It reaches a maximum at $\gamma = 90°$ (purely inductive load). This case serves as the basis for further calculations.
- The short circuit current is always inductive.

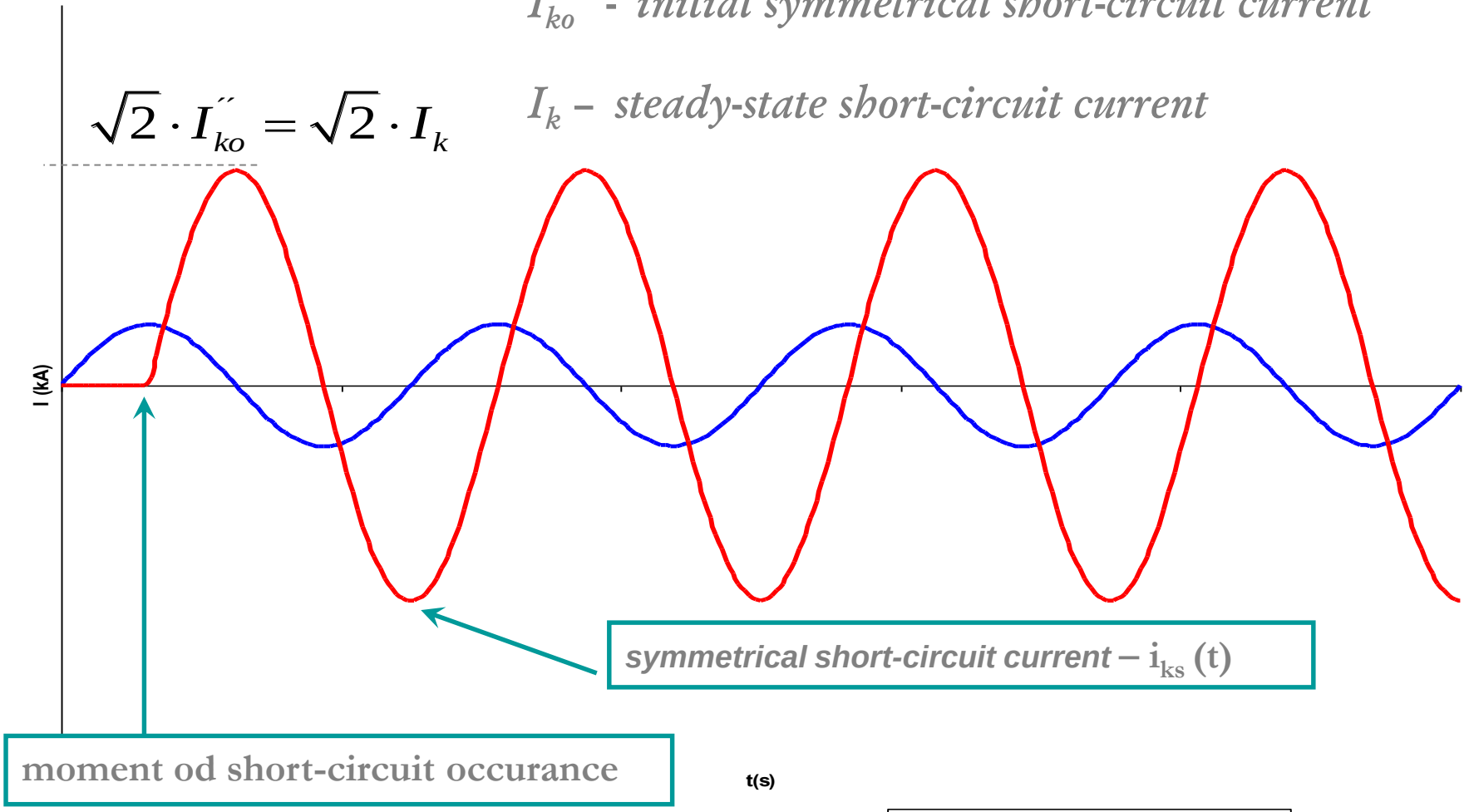
Time behaviour: open-circuit, resistances neglected
→ reactance, current of inductive character, higher I_k values

Symmetrical short-circuit current –far-from-generator fault

I_{ko}" - *initial symmetrical short-circuit current*

I_k – *steady-state short-circuit current*

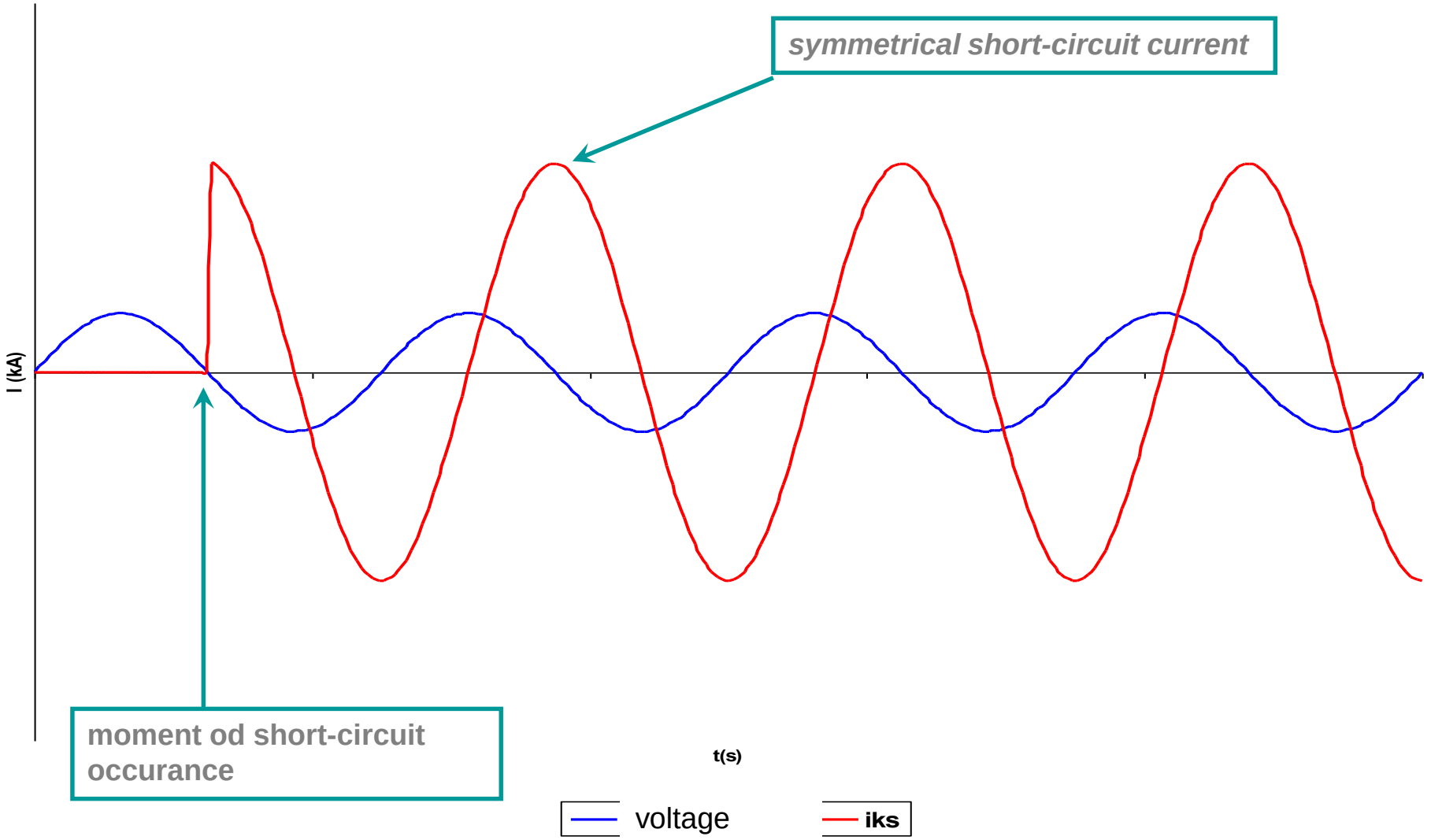
$$\sqrt{2} \cdot I_{ko}^{''} = \sqrt{2} \cdot I_k$$



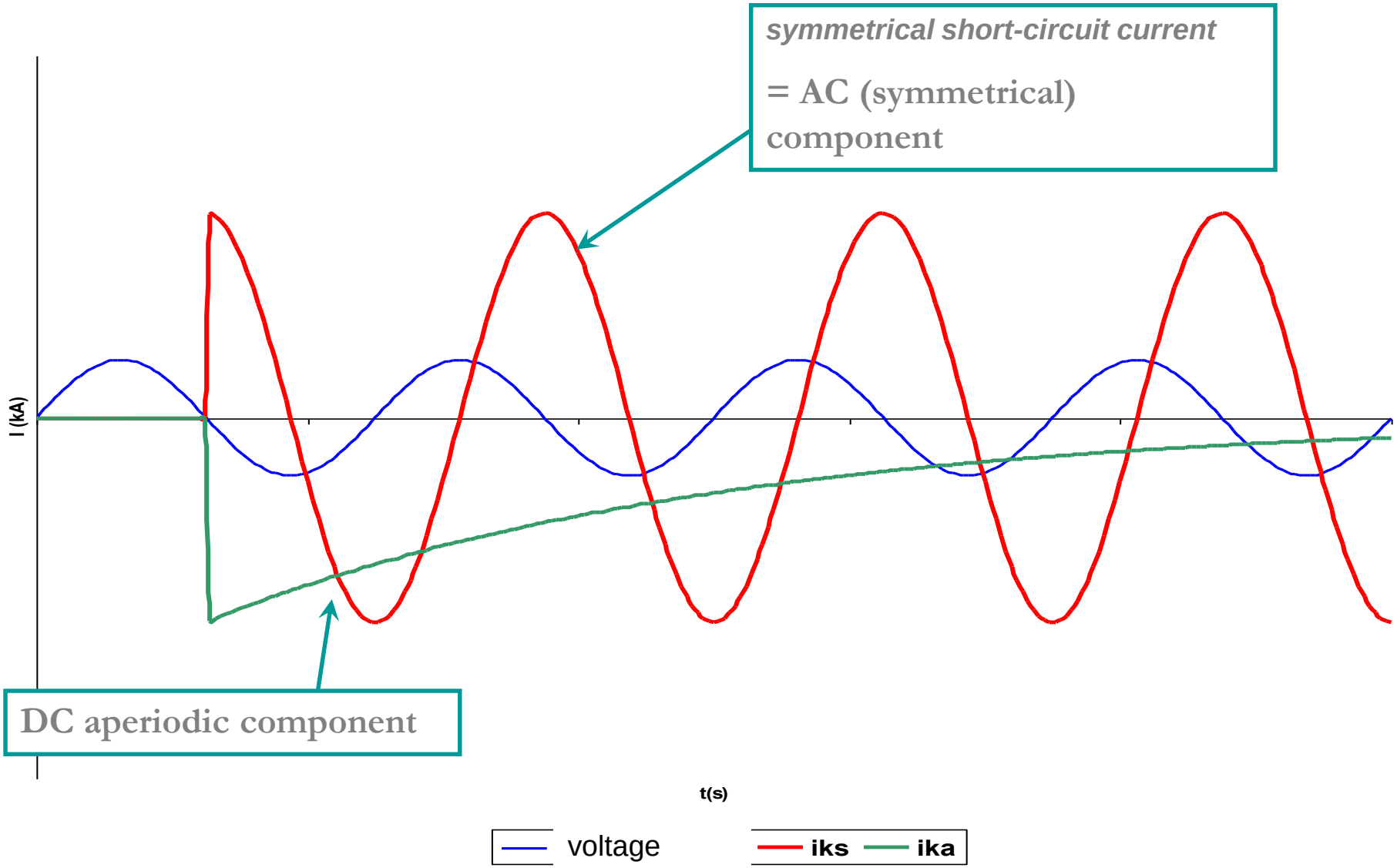
symmetrical short-circuit current – i_{ks} (t)

moment od short-circuit occurance

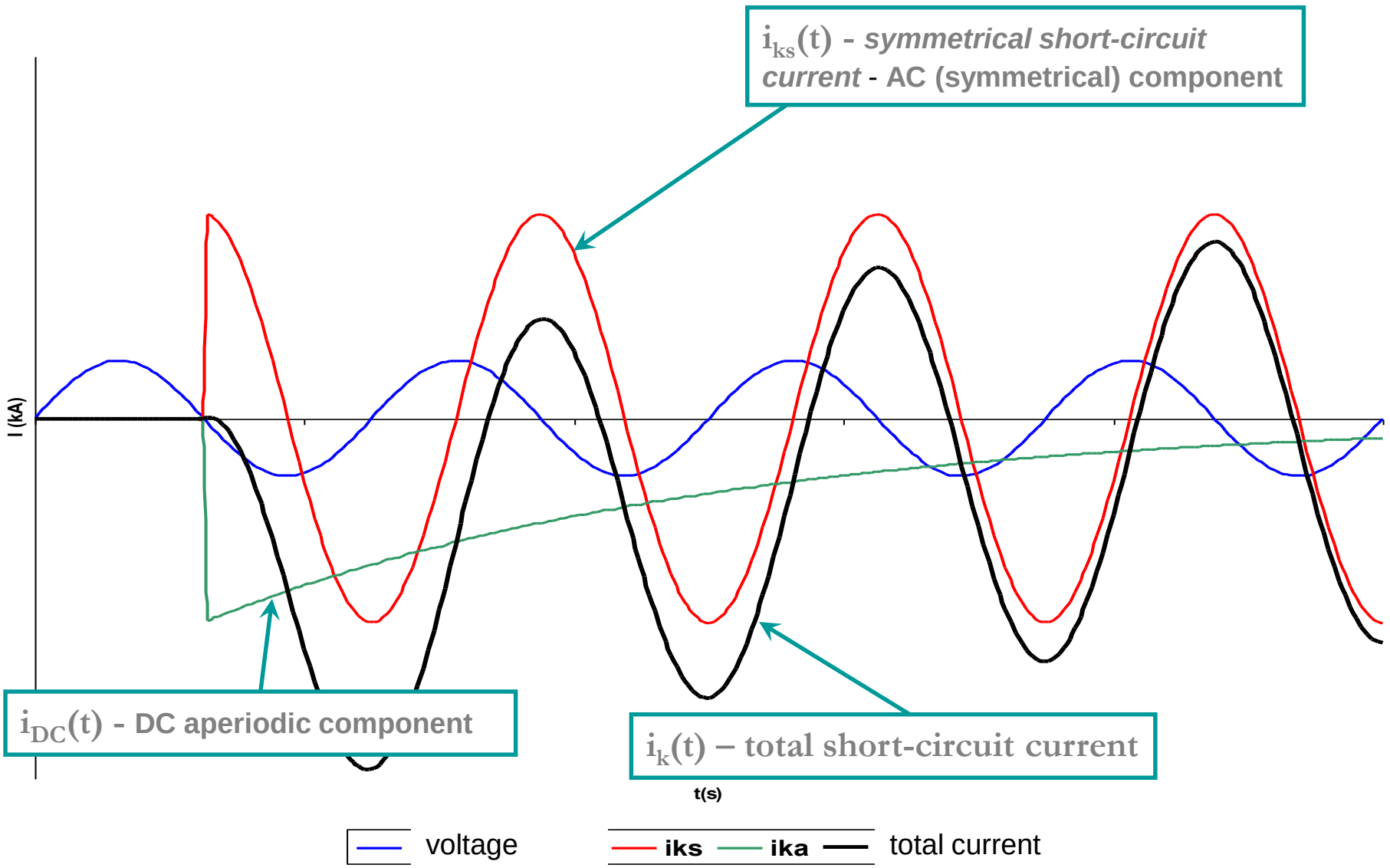
Unbalanced short-circuit current – far-from-generator fault



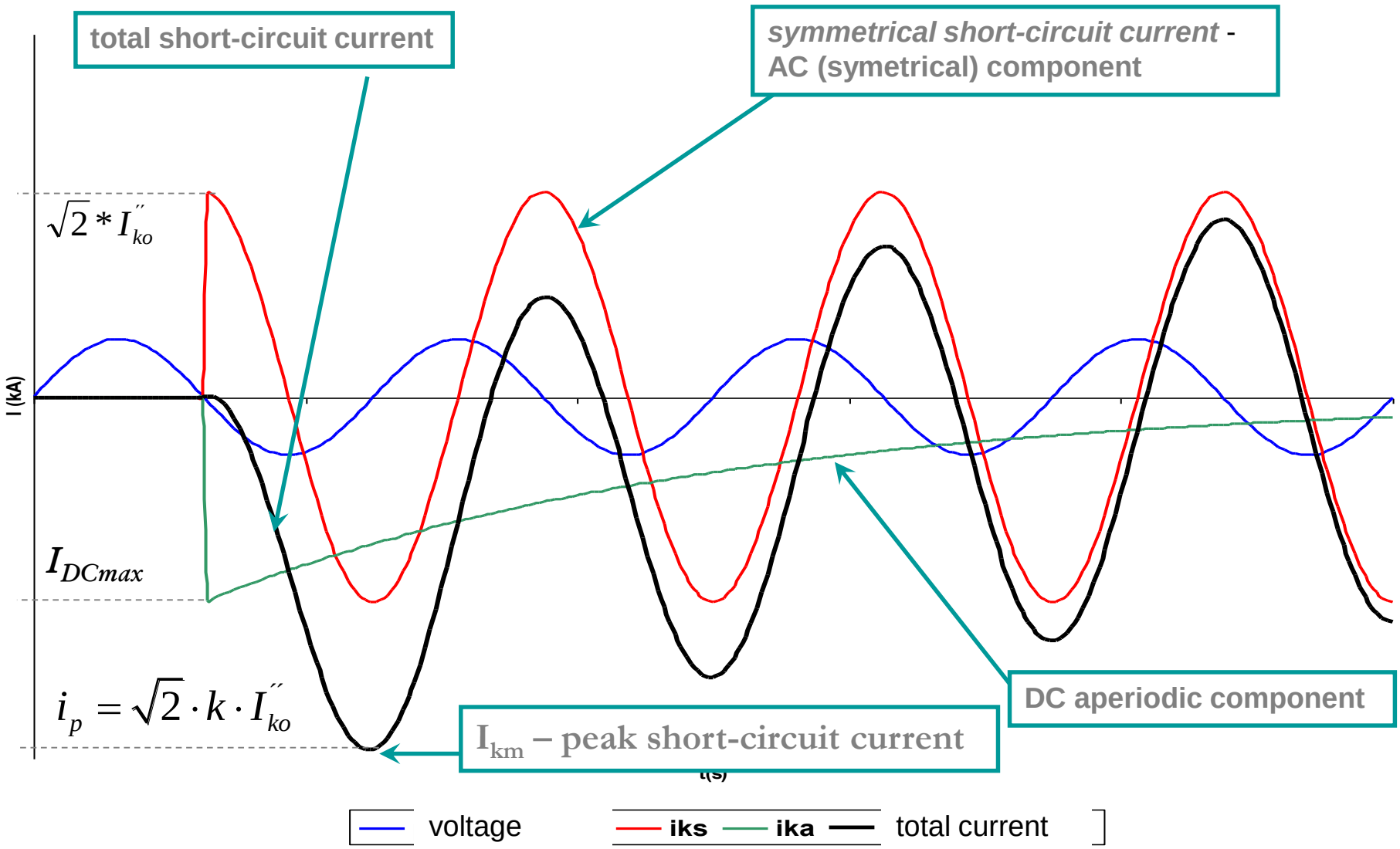
Unbalanced short-circuit current – far-from-generator fault



Unbalanced short-circuit current – far-from-generator fault

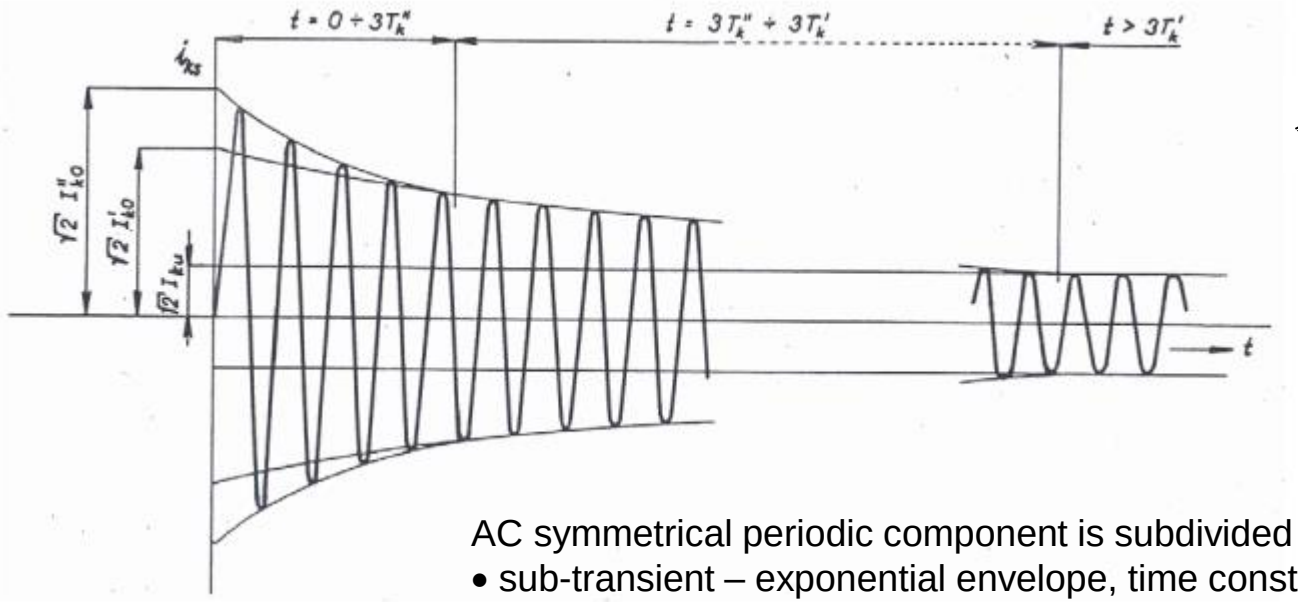


Unbalanced short-circuit current – far-from-generator fault



Symmetrical short-circuit current – near-from-generator fault

Near-from-generator fault - is caused by synchronous machine behaviour during short-circuit → more significant during short-circuits near the machine ⇒ value of AC symmetrical periodic component is not constant



$$\sqrt{2} \cdot I''_{ko} \neq \sqrt{2} \cdot I_k$$

AC symmetrical periodic component is subdivided into components:

- sub-transient – exponential envelope, time constant T_k'' cca 0,2 s
- transient – exponential envelope, time constant T_k' cca 5 to 10 s
- steady-state – constant magnitude

Unsymmetrical short-circuit current – near-from-generator fault

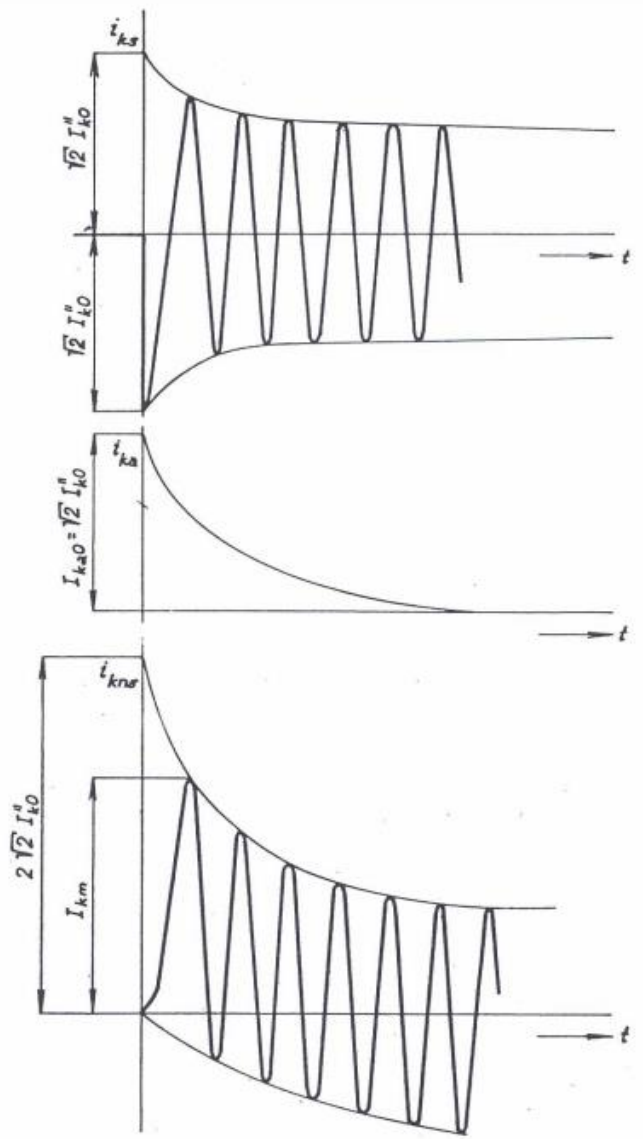
The worst cause:

AC (symmetrical) periodic component starts from its max. value

⇒

maximal DC componet

Peak short-circuit current I_{km} (i_p) = the first half-period magnitude of total short-circut current with the maximal DC component (t = 0,01 s)



Short-circuit current definitions

I_{ks} – symmetrical short-circuit current – the rms value of the AC symmetrical component of a prospective short-circuit current (summa od sub-transient , transient and steady-state components)

I''_k - initial symmetrical short-circuit current - the rms value of the AC symmetrical component of a prospective short-circuit current at the moment of its occurrence (t = 0)
Voltage has a pre-fault value, but circuit impedance is lower due to short-circuit fault.

$$I_k'' = \frac{U_{výp}}{Z_k} = \frac{c \cdot U_n}{\sqrt{3} \cdot Z_k}$$

S''_k - initial symmetrical short-circuit power - $S_k'' = \sqrt{3} I_k'' U_n$

I_k - steady-state short-circuit current - the rms value of the current after the decay of the transient components (for far-from-generator faults $I_k = I''_k$)

i_{DC} - decaying aperiodic DC component of the short-circuit current, determined as the average between the top and bottom envelope curve of the fault current: Time constant $T_a=L_k/R_k$.

$$i_{ka} = I_{ka\max} \cdot e^{-\frac{t}{T_a}}$$

Short-circuit current definitions

i_p (I_{km}) – peak short-circuit current, determined as the maximum instantaneous value of the fault current (t = 0,01 s) with maximal DC component

$$i_\mathrm{p} = \kappa\sqrt{2}I''_k \qquad\qquad \kappa = 1.02 + 0.98\,\mathrm{e}^{-R/X}$$

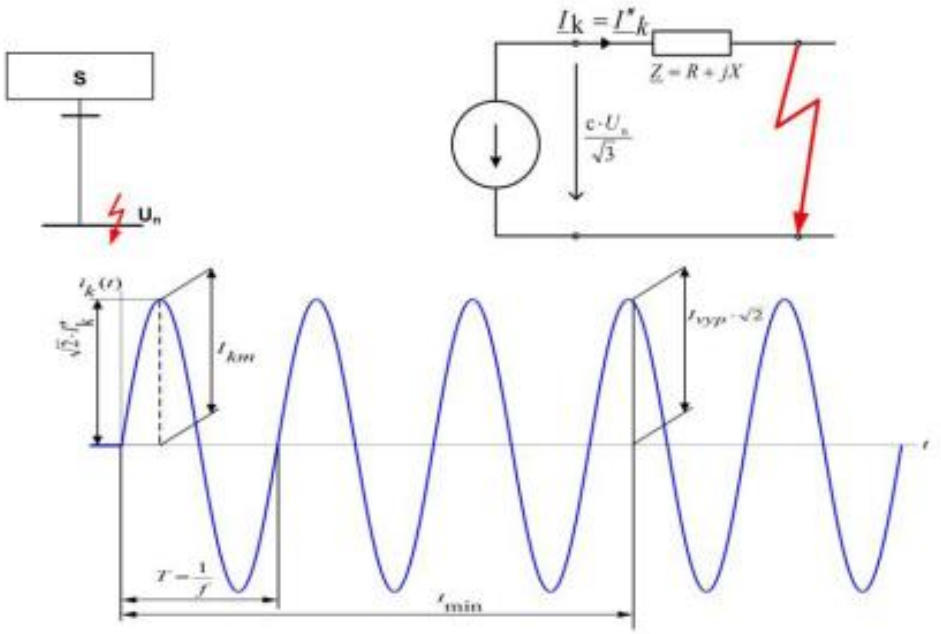
I_{th} (I_{ke}) – thermal equivalent short-circuit current – the rms value of a non-decaying current, having the same thermal effect and duration as the actual current

$$\int_0^{T_k} i^2\,\mathrm{d}t = I''^2_k(m+n) = I^2_\mathrm{th}T_k$$

I_b - symmetrical short-circuit breaking current – the rms value of an integral cycle of the symmetrical ac component of the current, at the instant of contact separation of the first pole to open in a switching device. For far-from-generator $I_b = I''_k$

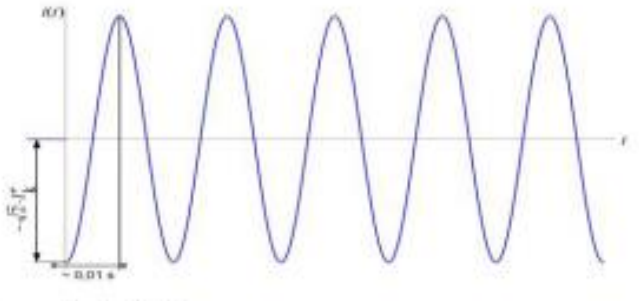
T_k - the duration of the short-circuit current

Time behavior of short-circuit current

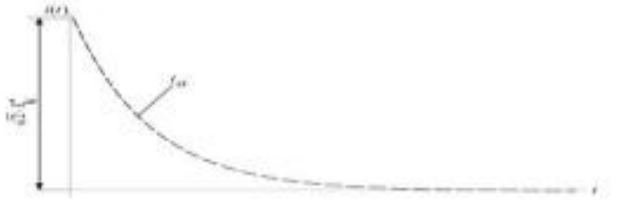


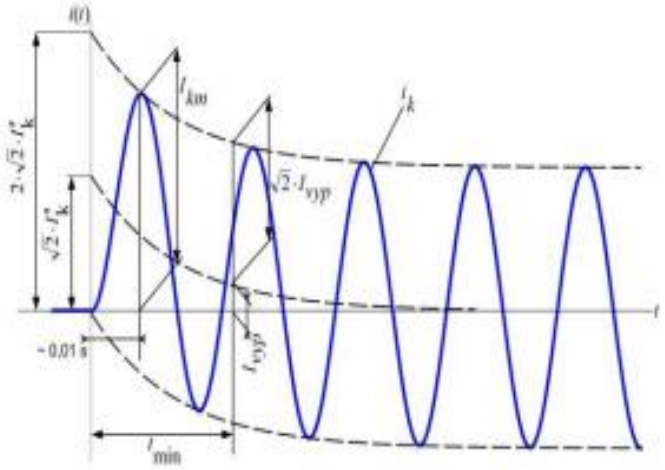
Far-from-generator short circuit without DC aperiodic component

symmetrical short-circuit current

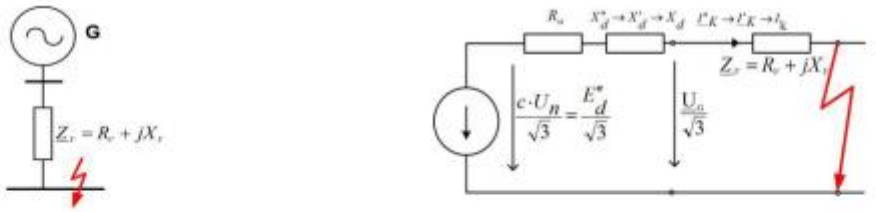


DC component (aperiodic)

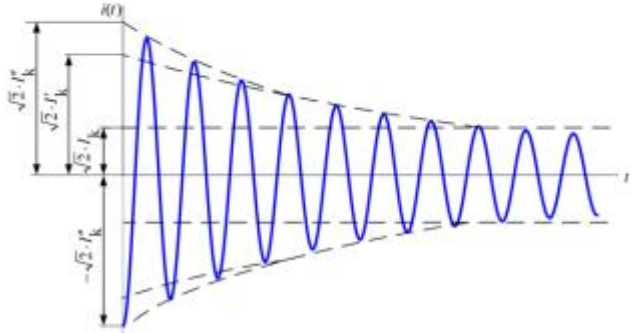




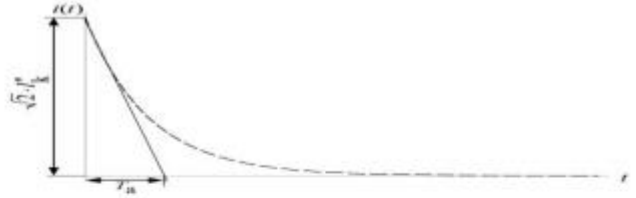
Far-from-generator short circuit with maximal DC aperiodic component



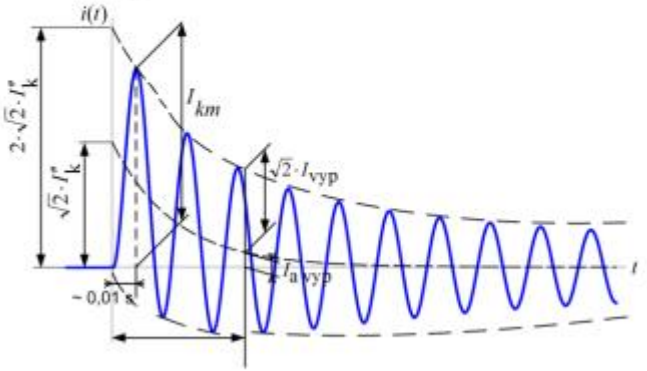
střídavá složka (periodická, souměrný zkratový proud)



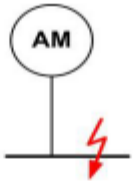
stejnosměrná složka (aperiodická)



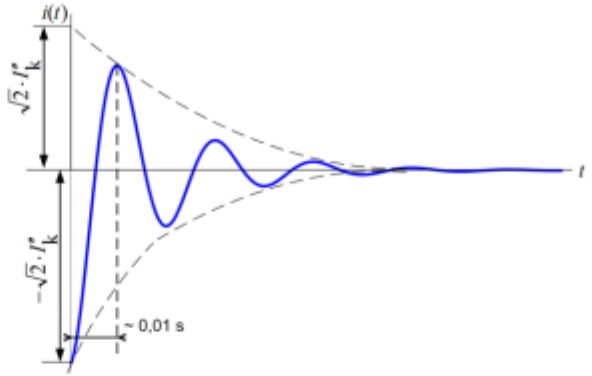
výsledný průběh s největší možnou stejnosměrnou složkou



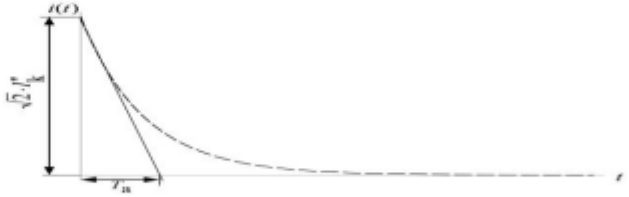
Near-from-generator short circuit with maximal DC aperiodic component



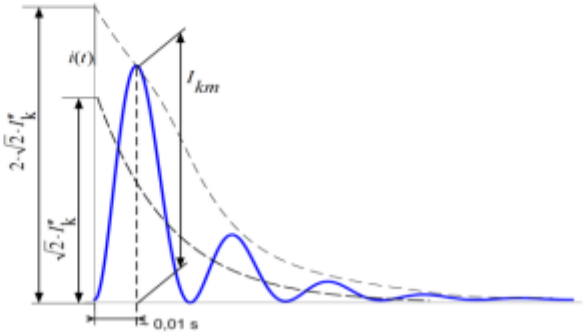
střídavá složka (periodická, souměrný zkratový proud)



stejnosměrná složka (aperiodická)

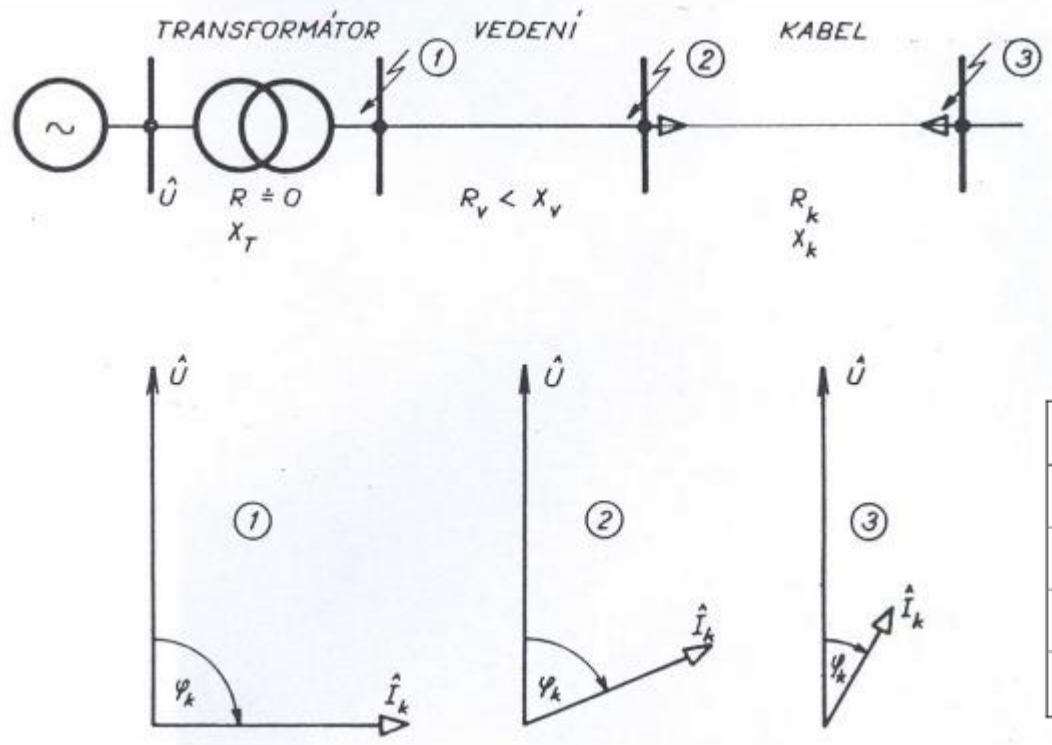


výsledný průběh s největší možnou stejnosměrnou složkou



Asynchronous motor short circuit with maximal DC aperiodic component

Short-circuit current power factor

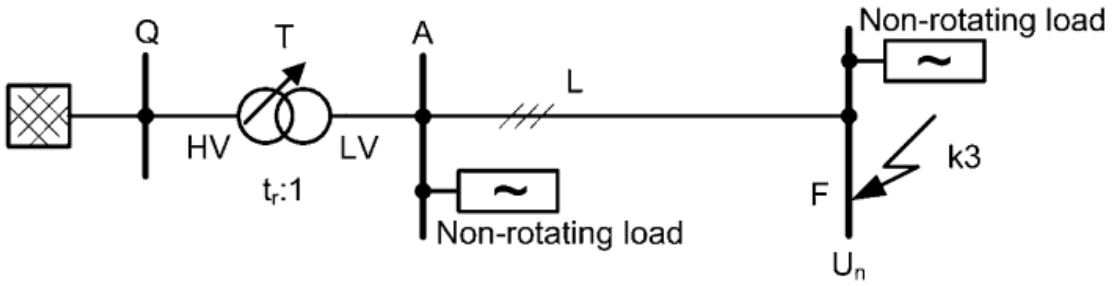


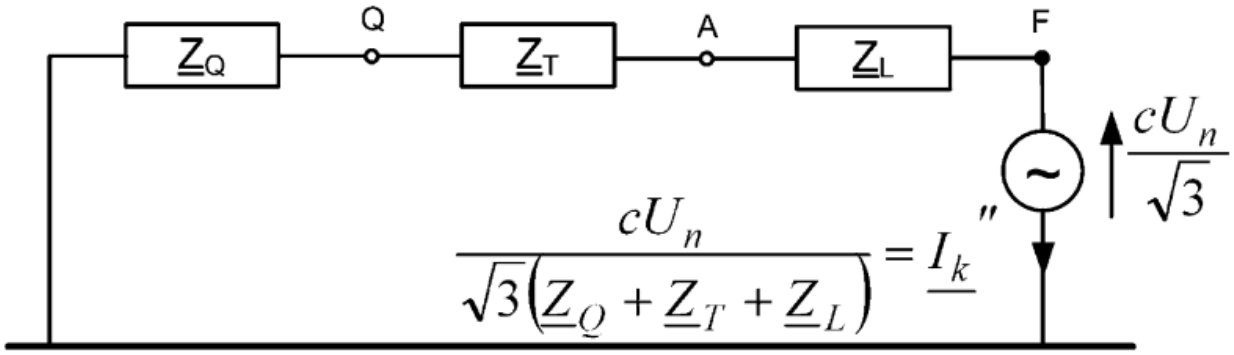
lines	overhead						cable		
U (kV)	22	110	220	400	750	1150	10	35	110
X : R	1/1	2/1	5/1	12/1	15/1	27/1	1/4	1/2	1/0,7
|Z| : X	1,41	1,12	1,02	1,01	1,005	1,00	4,1	2,24	1,22
φ_k (°)	45	64	78,7	85,2	86,2	87,9	13	26	54

$$\varphi_k = \operatorname{arctg}\frac{X_{tot}}{R_{tot}}$$

Calculation of short-circuit currents

IEC 60909 - the equivalent voltage source method





Short-circuit current effects

Mechanical strength

I_{km} (i_p) – peak short-circuit current (t = 0,01 s)

$$i_p = \kappa\sqrt{2}I_k'' \qquad \kappa = 1.02 + 0.98\,e^{-R/X}$$

$(\kappa_{LV} = 1{,}8;\ \kappa_{HV} = 1{,}7)$

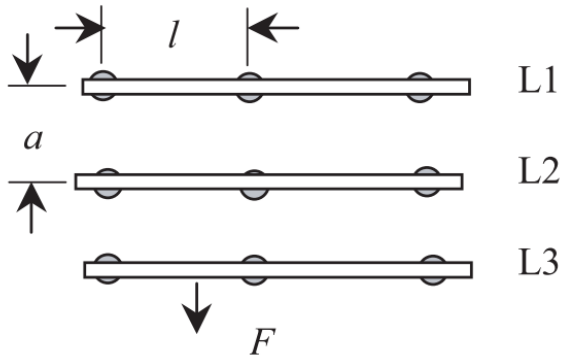
Influence mainly at tightly placed stiff conductors, supporting insulators, disconnectors, construction elements,…
Forces frequency 2f at AC → dynamic strain

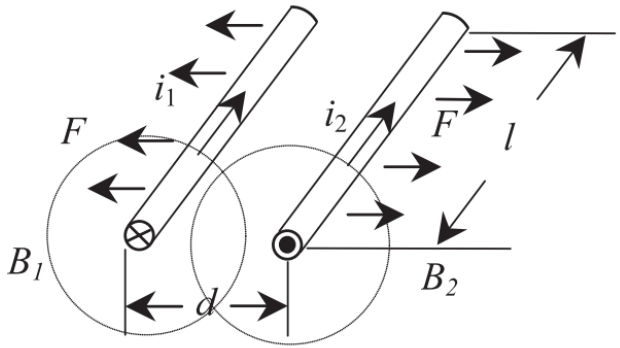
Max. instantaneous force on the conductor length unit

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

k_1 – conductor shape coefficient
k_2 – conductors configuration and currents phase shift coefficient
a – conductors distance

Short-circuit current effects





$$F = B \cdot l \cdot I$$

2 parallel conductors → force perpendicular to the conductor axis

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

Short-circuit current effects

Thermal strength

I_{th} (I_{ke}) – thermal equivalent short-circuit current – the rms value of a non-decaying current, having the same thermal effect and duration as the actual current

$$Q_k \approx \int_0^{t_k} i_k^{\,2} dt \qquad Q_{ke} \approx I_{ke}^2 \cdot t_k \qquad I_{ke}^2 t_k = \int_0^{t_k} i_k^2(t)dt \qquad I_{ke} = \sqrt{\frac{1}{t_k}\int_0^{t_k} i_k^2(t)dt}$$

$$I_{th} = I_k'' \cdot \sqrt{m+n} \qquad m = \frac{1}{2 f t_k ln\,(\kappa-1)}\left[e^{4 f T_k ln(\kappa-1)} - 1\right]$$

m – thermal effect of the DC aperiodic component
n – thermal effect of the AC component, for far-from-generator faults and t_k > 0,5 s n=1

Short-circuit dimensioning

Mechanical strength $I_{dyn} \geq i_p$

I_{dyn} - dynamic short-circuit current given by manufacturer of electric equipment

Thermal strength $I_{kn1} \geq I_{ke1}$

I_{kn} - short-time withstand current given by manufacturer of electric equipment

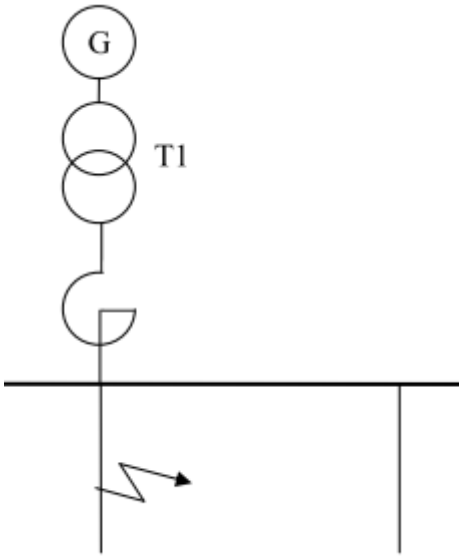
$$Q = I_{ke}^2 \cdot t_k = I_{ke2}^2 \cdot 2 \qquad \Rightarrow \qquad I_{ke2} = I_{ke} \cdot \sqrt{\frac{t_k}{2}}$$

conductor cross-section $$S \geq \frac{I_{ke} \cdot \sqrt{t_k}}{K}$$

Short-circuit limitation

$$I_k^{''} = \frac{U_{výp}}{Z_k} = \frac{c \cdot U_n}{\sqrt{3} \cdot Z_k}$$

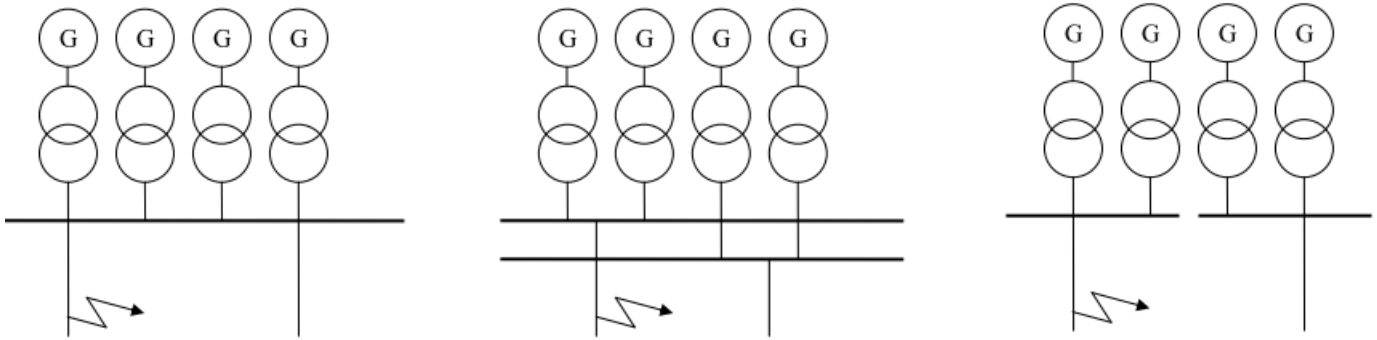
- to increase short-circuit impence
  - transformers with higher impedance
  - line reactors



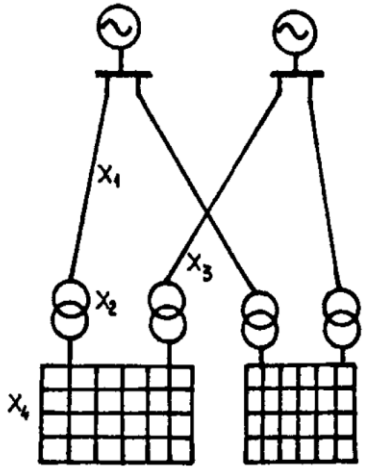


Short-circuit limitation

- to decrease source power
  - split substation bus

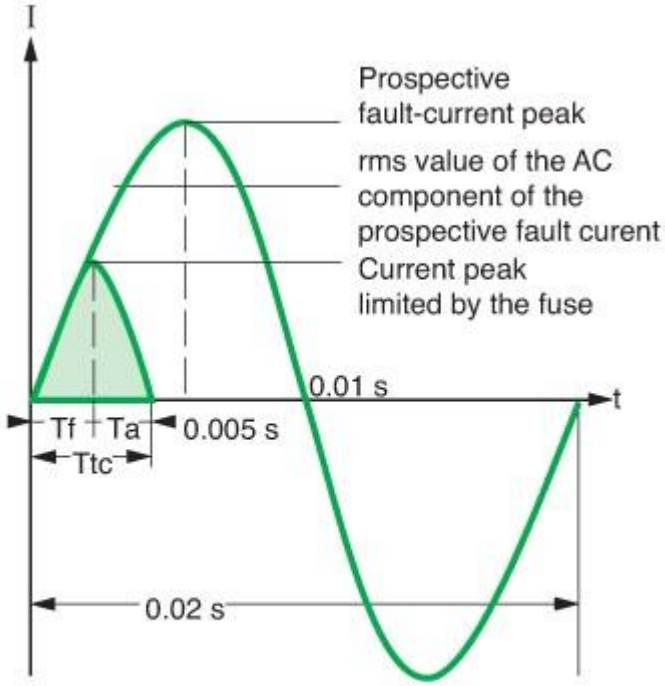


  - separate operation of feeders

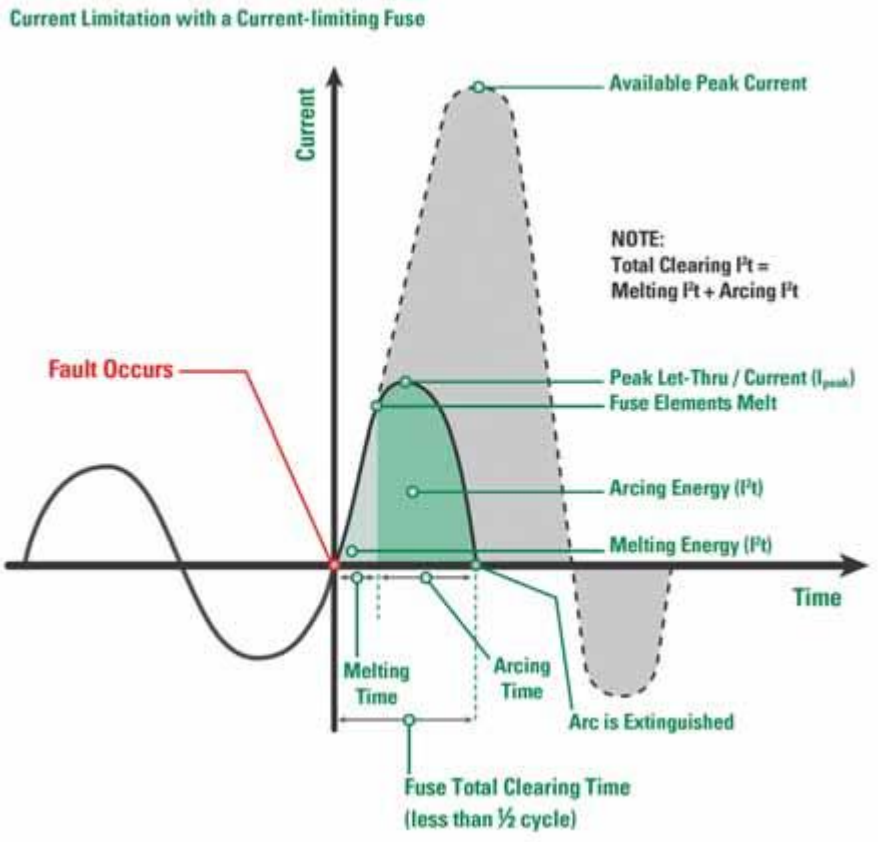


Short-circuit limitation

- to assure fast circuit opening – current and heat effect (I^2t) limitation
  - fuses (LV, MV), rapid circuit-breakers

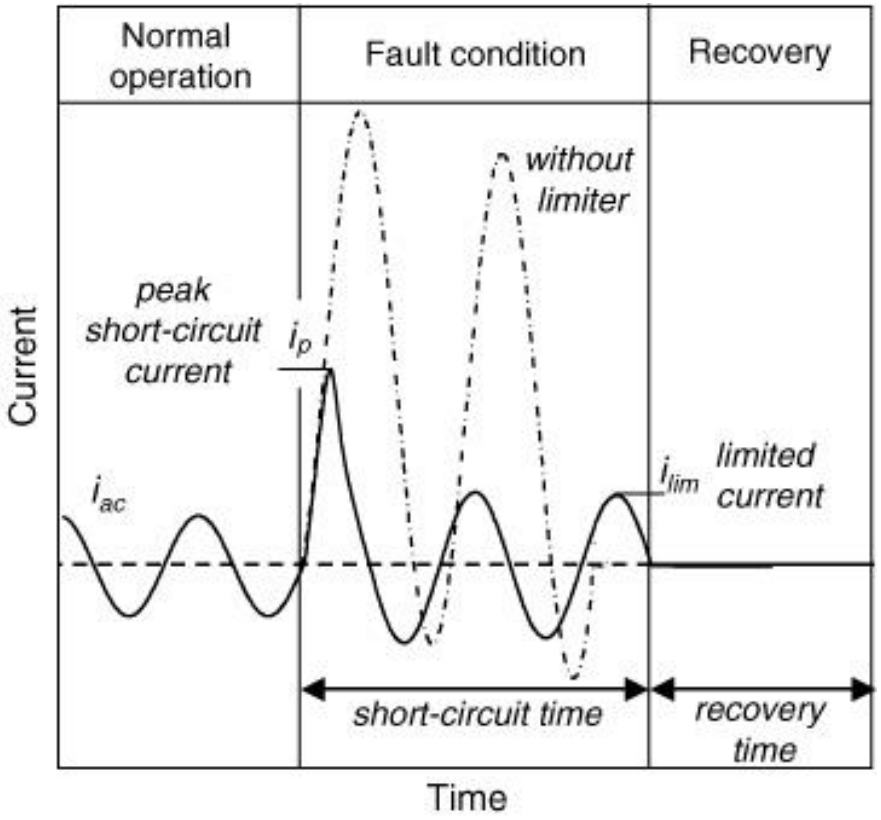


Tf: Fuse pre-arc fusing time
Ta: Arcing time
Ttc: Total fault-clearance time



Short-circuit limitation

- fault current limiters
  - with current limitation and interruption
  - with current limitation only



Short-circuit limitation

- short-circuit current limiter - ABB

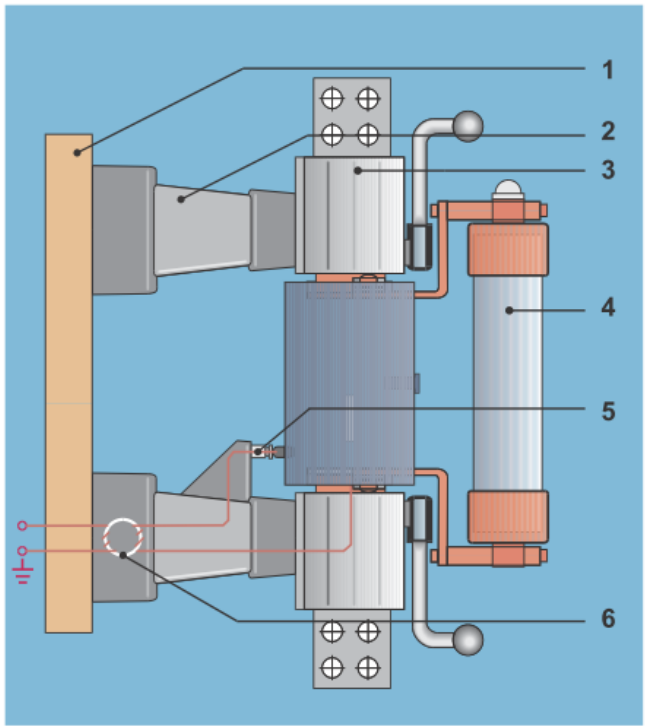


Figure 1: I_S*-limiter insert holder with insert for 12 kV, 2000 A*

1 Base plate
2 Insulator
3 Pole head with clamping device
4 Fuse
5 Telescopic contact
6 Insulator with pulse transformer

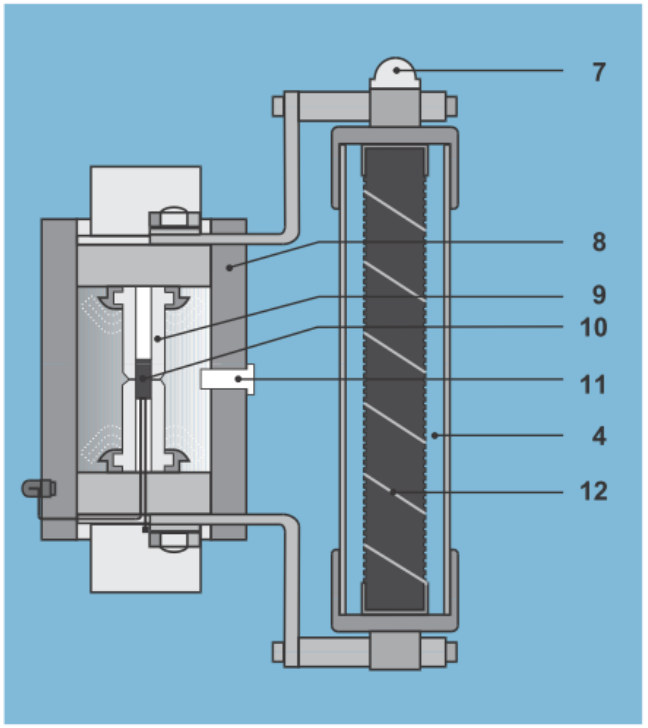


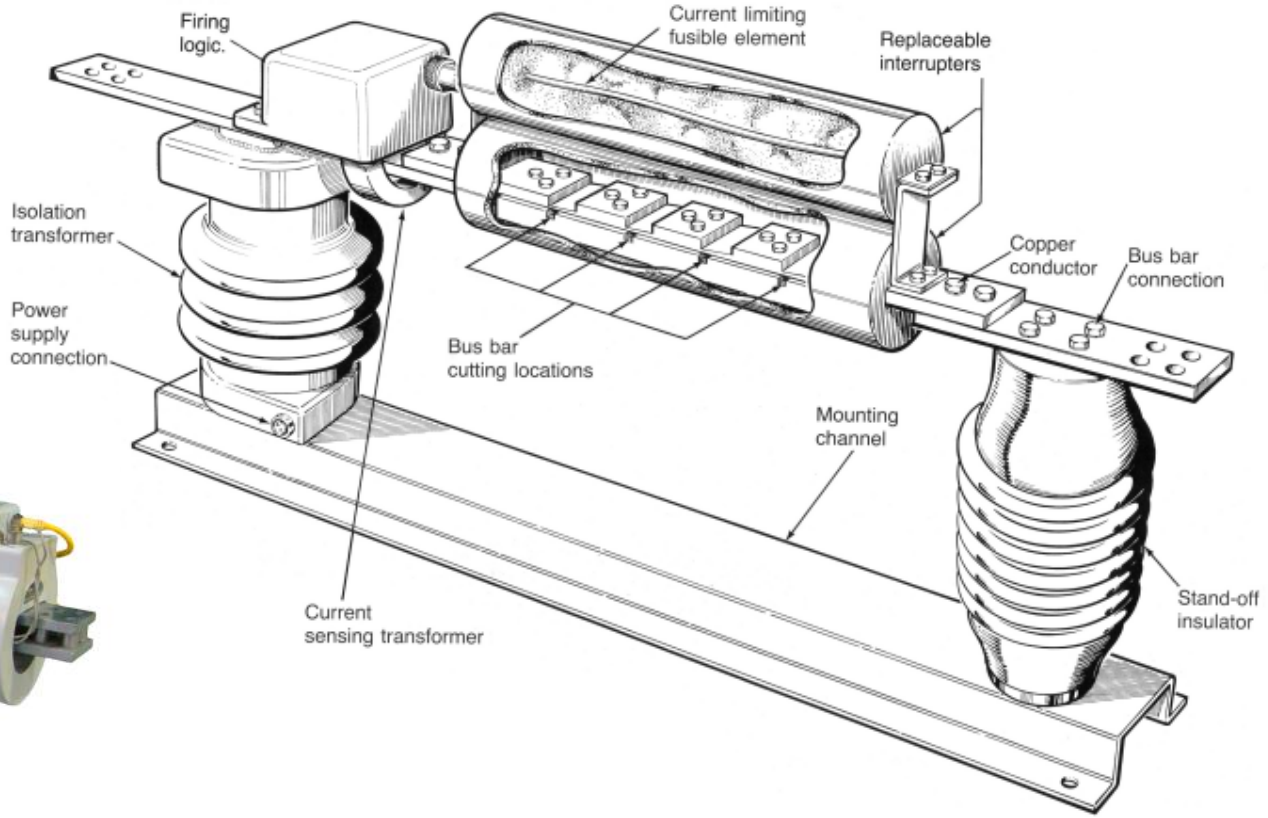
Figure 2: I_S*-limiter insert*

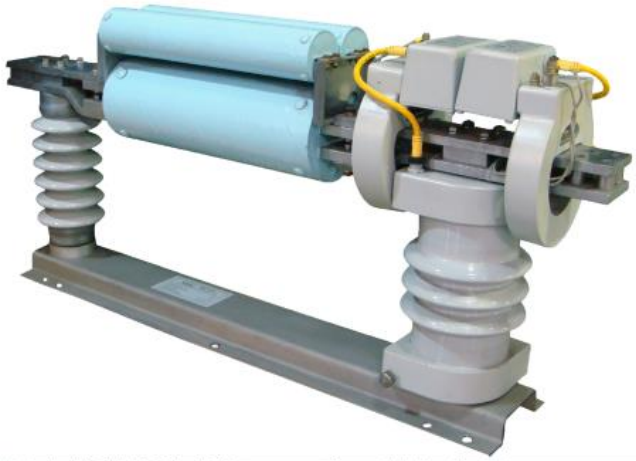
4 Fuse
7 Fuse indicator
8 Insulating tube
9 Bursting bridge
10 Charge
11 Main conductor indicator
12 Fuse element

12 kV	$\Rightarrow$	210 kA_{RMS}
17.5 kV	$\Rightarrow$	210 kA_{RMS}
24 kV	$\Rightarrow$	140 kA_{RMS}
36/40.5 kV	$\Rightarrow$	140 kA_{RMS}

Short-circuit limitation

- short-circuit current limiter – G&W

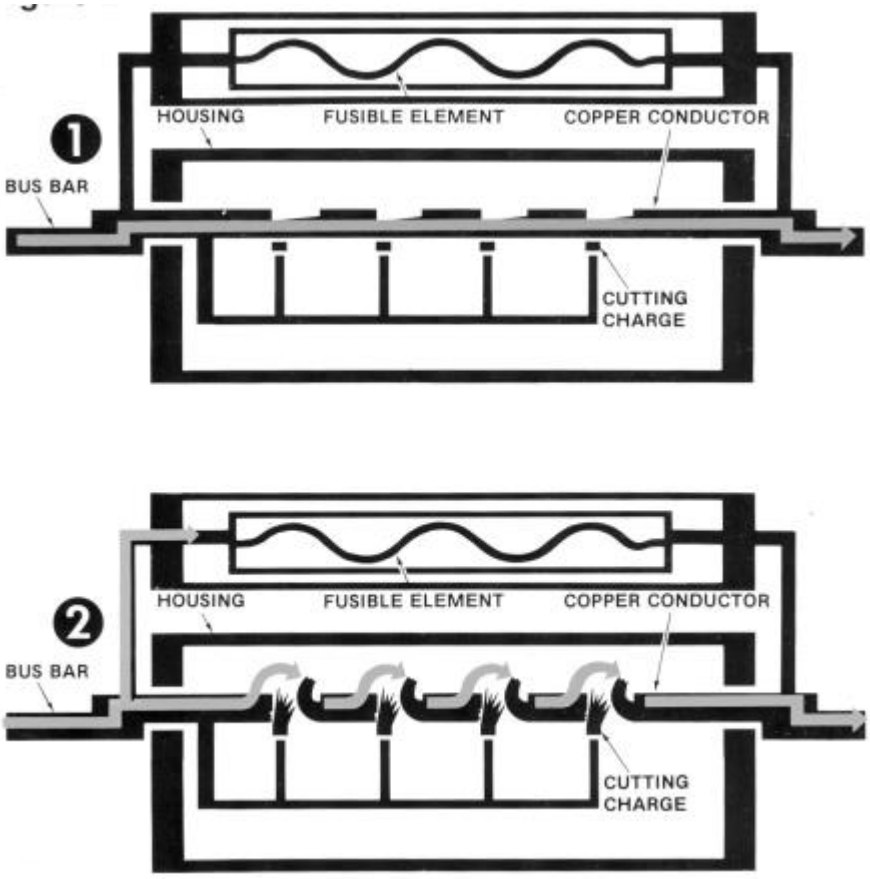




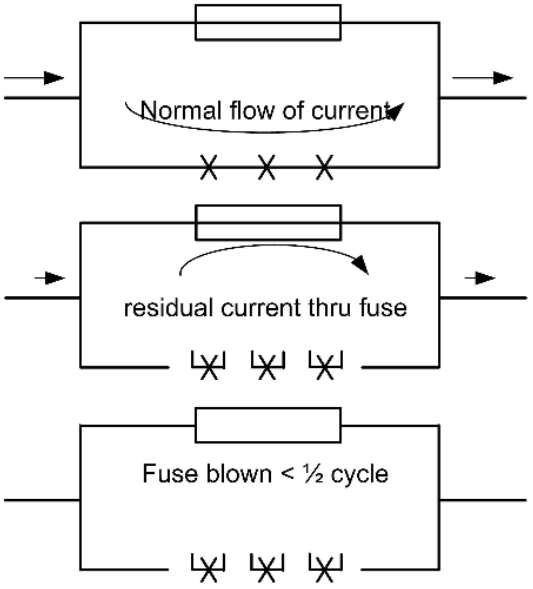
▲ Typical 15.5kV, 3000A, 120kA rms, sym, Current Limiting Protector.

Short-circuit limitation

- short-circuit current limiter – G&W

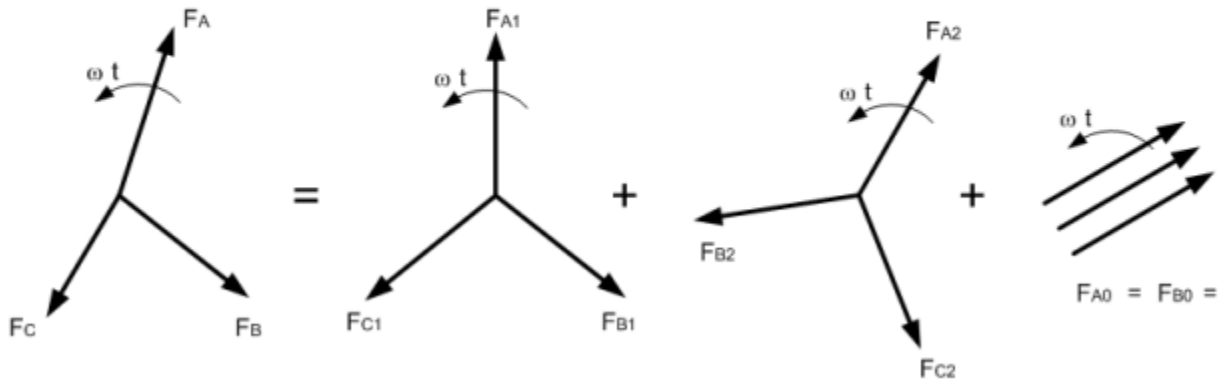






Method of symmetrical components

$$\mathbf{U}_A = \mathbf{U}_{A1} + \mathbf{U}_{A2} + \mathbf{U}_{A0}$$
$$\mathbf{U}_B = \mathbf{U}_{B1} + \mathbf{U}_{B2} + \mathbf{U}_{B0}$$
$$\mathbf{U}_C = \mathbf{U}_{C1} + \mathbf{U}_{C2} + \mathbf{U}_{C0}$$



Pokud zvolíme referenční fázi A, můžeme soustavu přepsat na soustavu

$$\mathbf{U}_A = \mathbf{U}_1 + \mathbf{U}_2 + \mathbf{U}_0$$
$$\mathbf{U}_B = \mathbf{a}^2\mathbf{U}_1 + \mathbf{a}\,\mathbf{U}_2 + \mathbf{U}_0$$
$$\mathbf{U}_C = \mathbf{a}\,\mathbf{U}_1 + \mathbf{a}^2\,\mathbf{U}_2 + \mathbf{U}_0$$

kde **a** je:

$$\mathbf{a} = e^{j120^\circ} = -\frac{1}{2} + j\frac{\sqrt{3}}{2},\ \mathbf{a}^2 = e^{-j120^\circ} = -\frac{1}{2} - j\frac{\sqrt{3}}{2}$$

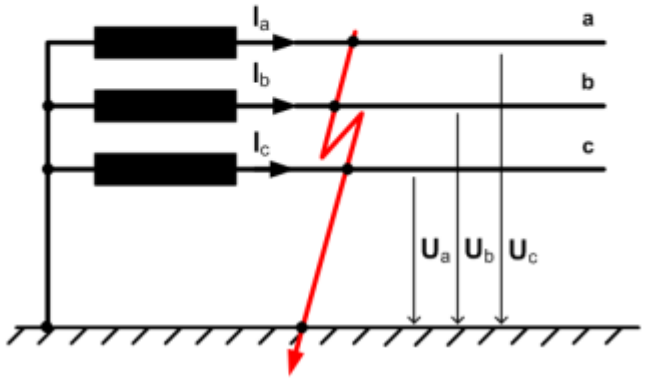
a pro proudy můžeme přepsat stejně jako napětí:

$$\mathbf{I}_A = \mathbf{I}_1 + \mathbf{I}_2 + \mathbf{I}_0$$
$$\mathbf{I}_B = \mathbf{a}^2\mathbf{I}_1 + \mathbf{a}\,\mathbf{I}_2 + \mathbf{I}_0$$
$$\mathbf{I}_C = \mathbf{a}\,\mathbf{I}_1 + \mathbf{a}^2\,\mathbf{I}_2 + \mathbf{I}_0$$

Method of symmetrical components

Three-phase (to-ground) short-circuit

$\mathbf{U}_A = 0, \mathbf{U}_B = 0, \mathbf{U}_C = 0$

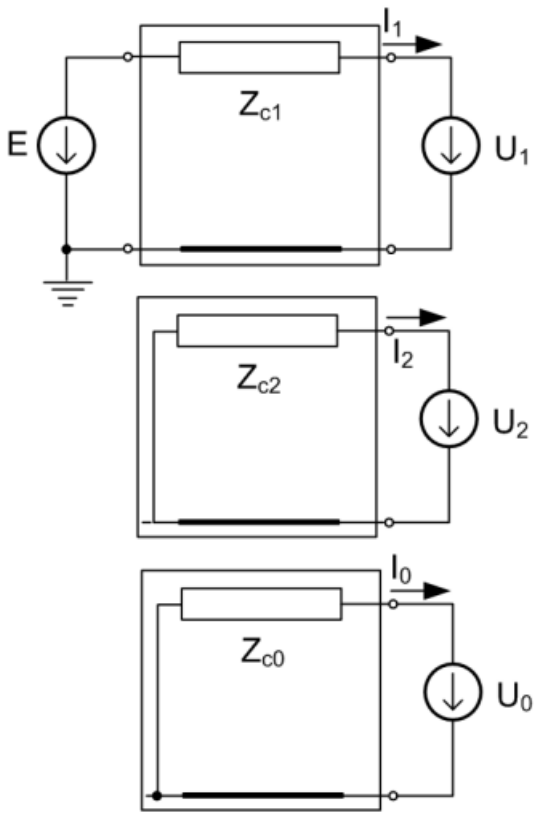


$$\hat{I}_A = \frac{\hat{U}_i}{\hat{Z}_1};\ \hat{I}_B = \hat{a}^2 \frac{\hat{U}_i}{\hat{Z}_1};\ \hat{I}_C = \hat{a} \frac{\hat{U}_i}{\hat{Z}_1}$$

Only the positive-sequence component included.

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

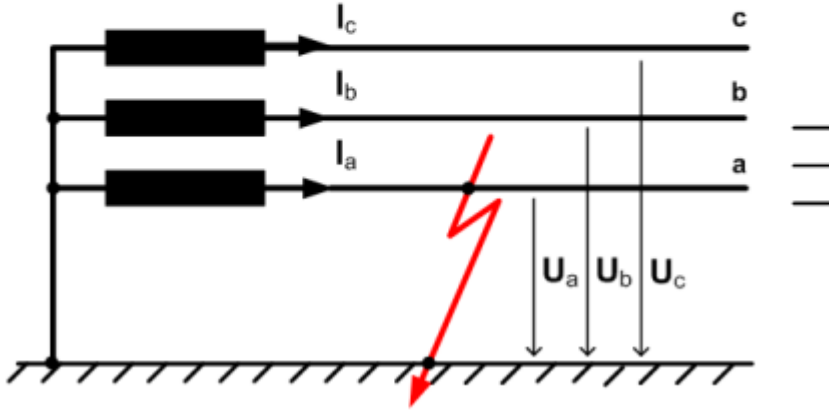
$$\hat{I}_1 = \frac{\hat{U}_i}{\hat{Z}_1};\ \hat{I}_2 = 0;\ \hat{I}_0 = 0$$



Method of symmetrical components

Single-phase-to-ground short-circuit

$$\mathbf{U}_A = 0,\ \mathbf{I}_B = 0,\ \mathbf{I}_C = 0$$



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

All three components are in series.

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

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

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

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

