Short circuit calculations
Purpose of Short-Circuit Calculations

- Dimensioning of switching devices
- Dynamic dimensioning of switchgear
- Thermal rating of electrical devices (e.g. cables)
- Protection coordination
- Fault diagnostic
- Input data for
  - Earthing studies
  - Interference calculations
  - EMC planning
  - .....
Short-Circuit Calculation Standards

- IEC 60909: Short-Circuit Current Calculation in Three-Phase A.C. Systems

  - European Standard EN 60909
    » German National Standard DIN VDE 0102
    » further National Standards

  - Engineering Recommendation G74 (UK)
    Procedure to Meet the Requirements of IEC 60909 for the Calculation of Short-Circuit Currents in Three-Phase AC Power Systems

- ANSI IEEE Std. C37.5 (US)
Short-Circuit Calculations
Scope of IEC 60909

- three-phase a.c. systems
- low voltage and high voltage systems up to 500 kV
- nominal frequency of 50 Hz and 60 Hz
- balanced and unbalanced short circuits
  - three phase short circuits
  - two phase short circuits (with and without earth connection)
  - single phase line-to-earth short circuits in systems with solidly earthed or impedance earthed neutral
  - two separate simultaneous single-phase line-to-earth short circuits in a systems with isolated neutral or a resonance earthed neutral (IEC 60909-3)
- maximum short circuit currents
- minimum short circuit currents
Short-Circuit Calculations
Types of Short Circuits

3-phase

2-phase

1-phase
Variation of short circuit current shapes

- Fault located in the network: fault at voltage peak
- Fault located near generator: fault at voltage zero crossing
Short-Circuit Calculations
Far-from-generator short circuit

- $I_k$: Initial symmetrical short-circuit current
- $I_p$: Peak short-circuit current
- $I_k$: Steady-state short-circuit current
- $A$: Initial value of the d.c component

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**Diagram Description**: The diagram illustrates a waveform representing the short-circuit current over time. The waveform is characterized by its oscillatory nature, with peaks and troughs indicating the transient behavior of the current. Key points include:

- The initial symmetrical short-circuit current ($I_k$) is shown as the initial value of the d.c component.
- The peak short-circuit current ($I_p$) is depicted as the maximum value of the waveform.
- The steady-state short-circuit current ($I_k$) stabilizes at a lower level.
- The d.c component ($i_{dc}$) of the short-circuit current is highlighted, showing the constant component of the waveform.

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**Mathematical Representation**: The waveform can be mathematically represented by the equation $2\sqrt{2}I_k$, which indicates the peak value of the waveform in relation to the initial value of the d.c component ($A$) and the steady-state value ($2\sqrt{2}I_k$).
Short-Circuit Calculations
Definitions according IEC 60909 (I)

- **initial symmetrical short-circuit current** \( I_k \)
- r.m.s. value of the a.c. symmetrical component of a prospective (available) short-circuit current, applicable at the instant of short circuit if the impedance remains at zero-time value

- **initial symmetrical short-circuit power** \( S_k \)
- fictitious value determined as a product of the initial symmetrical short-circuit current \( I_k \), the nominal system voltage \( U_n \) and the factor \( \sqrt{3} \):

\[
S_k = \sqrt{3} U_n I_k
\]

- NOTE: \( S_k \) is often used to calculate the internal impedance of a network feeder at the connection point. In this case the definition given should be used in the following form:

\[
Z = \frac{c \cdot U_n}{S_k''}
\]
Short-Circuit Calculations
Definitions according IEC 60909 (II)

• decaying (aperiodic) component \( i_{\text{d.c.}} \) of short-circuit current
• mean value between the top and bottom envelope of a short-circuit current decaying from an initial value to zero

• peak short-circuit current \( i_p \)
• maximum possible instantaneous value of the prospective (available) short-circuit current

• NOTE: The magnitude of the peak short-circuit current varies in accordance with the moment at which the short circuit occurs.
Short-Circuit Calculations
Near-to-generator short circuit

- $I_k$" Initial symmetrical short-circuit current
- $i_p$ Peak short-circuit current
- $I_k$ Steady-state short-circuit current
- $A$ Initial value of the d.c component
- $I_B$ Symmetrical short-circuit breaking current
Short-Circuit Calculations
Definitions according IEC 60909 (III)

- steady-state short-circuit current $I_k$
- r.m.s. value of the short-circuit current which remains after the decay of the transient phenomena

- symmetrical short-circuit breaking current $I_b$
- r.m.s. value of an integral cycle of the symmetrical a.c. component of the prospective short-circuit current at the instant of contact separation of the first pole to open of a switching device
## Short-Circuit Calculations
### Purpose of Short-Circuit Values

<table>
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<th>Physical Effect</th>
<th>Relevant short-circuit current</th>
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</thead>
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<tr>
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<td>Thermal stress to arcing chamber; arc extinction</td>
<td>Symmetrical short-circuit breaking current $I_b$</td>
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<tr>
<td>Mechanical stress to equipment</td>
<td>Forces to electrical devices (e.g. bus bars, cables…)</td>
<td>Peak short-circuit current $i_p$</td>
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<tr>
<td>Thermal stress to equipment</td>
<td>Temperature rise of electrical devices (e.g. cables)</td>
<td>Initial symmetrical short-circuit current $I_k$” Fault duration</td>
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<td>Potential rise; Magnetic fields</td>
<td>Maximum initial symmetrical short-circuit current $I_k$”</td>
</tr>
</tbody>
</table>
Equivalent Voltage Source
Short-circuit
Equivalent voltage source at the short-circuit location

Operational data and the passive load of consumers are neglected
Tap-changer position of transformers is dispensable
Excitation of generators is dispensable
Load flow (local and time) is dispensable
Short circuit in meshed grid
Equivalent voltage source at the short-circuit location

- real network

![Equivalent circuit diagram]

Motor or an equivalent motor of a motor group
Voltage Factor $c$

$c$ is a safety factor to consider the following effects:

- voltage variations depending on time and place,
- changing of transformer taps,
- neglecting loads and capacitances by calculations,
- the subtransient behaviour of generators and motors.

<table>
<thead>
<tr>
<th>Nominal voltage</th>
<th>Voltage factor $c$ for calculation of maximum short circuit currents</th>
<th>Voltage factor $c$ for calculation of minimum short circuit currents</th>
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<tbody>
<tr>
<td>Low voltage 100 V – 1000 V</td>
<td></td>
<td></td>
</tr>
<tr>
<td>- systems with a tolerance of 6%</td>
<td>1.05</td>
<td>0.95</td>
</tr>
<tr>
<td>- systems with a tolerance of 10%</td>
<td>1.10</td>
<td>0.95</td>
</tr>
<tr>
<td>Medium voltage &gt;1 kV – 35 kV</td>
<td>1.10</td>
<td>1.00</td>
</tr>
<tr>
<td>High voltage &gt;35 kV</td>
<td>1.10</td>
<td>1.00</td>
</tr>
</tbody>
</table>
Short Circuit Impedances and Correction Factors
Short Circuit Impedances

• For network feeders, transformer, overhead lines, cable etc.
  • impedance of positive sequence system = impedance of negative sequence system
  • impedance of zero sequence system usually different
  • topology can be different for zero sequence system

• Correction factors for
  – generators,
  – generator blocks,
  – network transformer

• factors are valid in zero, positive, negative sequence system
At a feeder connection point usually one of the following values is given:
- the initial symmetrical short circuit current $I_k$
- the initial short-circuit power $S_k$

If $R/X$ of the network feeder is unknown, one of the following values can be used:
- $R/X = 0.1$
- $R/X = 0.0$ for high voltage systems $>35$ kV fed by overhead lines

$$Z_N = \frac{c \cdot U_n}{\sqrt{3} \cdot I_k} = \frac{c \cdot U_n^2}{S_k}$$

$$X_N = \frac{Z_N}{\sqrt{1 + (R/X)^2}}$$
Network transformer
Correction of Impedance

\[ Z_{TK} = Z_T \cdot K_T \]

– general

\[ K_T = 0.95 \cdot \frac{c_{max}}{1 + 0.6 \cdot x_T} \]

– at known conditions of operation

\[ K_T = \frac{U_n}{U^b} \cdot \frac{c_{max}}{1 + x_T \left( \frac{l^b_{r}}{l^b_{T}} \right) \sin \phi_T^b} \]

no correction for impedances between star point and ground
Network transformer

Impact of Correction Factor

- The Correction factor is $K_T < 1.0$ for transformers with $x_T > 7.5\%$.

→ Reduction of transformer impedance
→ Increase of short-circuit currents
Generator with direct Connection to Network
Correction of Impedance

\[ Z_{GK} = Z_G K_G \]

- general

\[ K_G = \frac{U_n}{U_{rG}} \cdot \frac{c_{max}}{1 + x_d'' \cdot \sin \phi_{rG}} \]

- for continuous operation above rated voltage:

\[ U_{rG} (1+p_G) \text{ instead of } U_{rG} \]

- turbine generator: \( X_{(2)} = X_{(1)} \)
- salient pole generator: \( X_{(2)} = 1/2 (X_d'' + X_q'') \)
Generator Block (Power Station)
Correction of Impedance

\[ Z_{S(O)} = (t_r^2 \ Z_G + Z_{THV}) \ K_{S(O)} \]

- power station with on-load tap changer:

\[
K_S = \frac{U_{nQ}^2 \cdot U_{rTLV}^2}{U_{rG}^2 \cdot U_{rTHV}^2} \cdot \frac{c_{max}}{1 + \left| x_d'' - x_T \right| \cdot \sin \phi_{rG}}
\]

- power station without on-load tap changers:

\[
K_{SO} = \frac{U_{nQ}}{U_{rG} (1 + p_G)} \cdot \frac{U_{rTLV} (1 + p_t)}{U_{rTHV}} \cdot \frac{c_{max}}{1 + x_d'' \cdot \sin \phi_{rG}}
\]
Asynchronous Motors

- Motors contribute to the short circuit currents and have to be considered for calculation of maximum short circuit currents.

\[
Z_M = \frac{1}{I_{LR}/I_{rM}} \cdot \frac{U_{rM}^2}{S_{rM}}
\]

\[
X_M = \frac{Z_M}{\sqrt{1 + (R_M / X_M)^2}}
\]

- If R/X is unknown, the following values can be used:
  - R/X = 0.1  medium voltage motors (power per pole pair > 1 MW)
  - R/X = 0.15 medium voltage motors (power per pole pair ≤ 1 MW)
  - R/X = 0.42 low voltage motors (including connection cables)
Special Regulations for low Voltage Motors

- low voltage motors can be neglected if $\sum I_r M \leq I_k$
- groups of motors can be combined to an equivalent motor
- $I_{LR}/I_{rM} = 5$ can be used
Calculation of initial short circuit current
Calculation of initial short circuit current

Procedure

– Set up equivalent circuit in symmetrical components

– Consider fault conditions
  – in 3-phase system
  – transformation into symmetrical components

– Calculation of fault currents
  – in symmetrical components
  – transformation into 3-phase system
Calculation of initial short circuit current

Equivalent circuit in symmetrical components

a)\[\begin{align*}
G1 & \quad T1 \quad SS1 \quad SK1 \quad SS2 \\
G2 & \quad T2 \quad SK2 \quad S1 \quad Netz
\end{align*}\]

b)\[\begin{align*}
E''_{G1} & \quad Z''_{(1)R1} \quad Z''_{(1)R2} \quad Z''_{(1)R3} \\
E''_{G2} & \quad Z''_{(2)R1} \quad Z''_{(2)R2} \quad Z''_{(2)R3} \\
U_0 & \quad \sqrt{3}
\end{align*}\]

- **positive sequence system**
- **negative sequence system**
- **zero sequence system**
Calculation of initial short circuit current

3-phase short circuit

\[ U_{L1} = -U_f \]
\[ U_{L2} = a^2 (-U_f) \]
\[ U_{L3} = a (-U_f) \]

\[ I_{sc3}'' = \frac{c \cdot U_r}{\sqrt{3} \cdot Z_{(1)}} \]
Calculation of 2-phase initial short circuit current

L1-L2-L3-system

\[ I_{L1} = 0 \]
\[ I_{L2} = -I_{L3} \]
\[ U_{L3} - U_{L2} = -U_i \]

012-system

\[ I_{(0)} = 0 \]
\[ I_{(1)} = -I_{(2)} \]

\[ I''_{sc2} = \frac{c \cdot U_r}{2 \left| Z_1 \right|} \Rightarrow \frac{I''_{sc2}}{I''_{sc3}} = \frac{\sqrt{3}}{2} \]

\[ I''_{sc2} = \frac{c \cdot U_r}{2 \left| Z_1 \right|} \Rightarrow \frac{I''_{sc2}}{I''_{sc3}} = \frac{\sqrt{3}}{2} \]
Calculation of 2-phase initial short circuit current with ground connection

L1-L2-L3-system

\[ I_{L1} = 0 \]
\[ U_{L2} = -a^2 \cdot c \cdot \frac{U_n}{\sqrt{3}} \]
\[ U_{L3} = -a \cdot c \cdot \frac{U_n}{\sqrt{3}} \]

\[ I''_{scE2E} = \frac{\sqrt{3} \cdot c \cdot U_r}{|Z_{(1)} + 2Z_{(0)}|} \]

012-system

\[ Z_{(1)l} \]
\[ \sim \]
\[ Z_{(2)l} \]
\[ \sim \]
\[ Z_{(0)l} \]
\[ \sim \]
\[ \sim \]
\[ Z_{(1)r} \]
\[ \sim \]
\[ Z_{(2)r} \]
\[ \sim \]
\[ Z_{(0)r} \]
\[ \sim \]

network left of fault location

fault location

network right of fault location

\[ U_{(1)} - U_{(2)} = -c \cdot \frac{U_n}{\sqrt{3}} = U_{(1)} - U_{(0)} \]
\[ I_{(0)} = I_{(1)} = I_{(2)} \]
Calculation of 1-phase initial short circuit current

L1-L2-L3-System

\[ I_{\text{sc1}} = \frac{\sqrt{3} \cdot c \cdot U_r}{Z_{(1)} + Z_{(2)} + Z_{(0)}} \]

\[ U_{L1} = -c \cdot \frac{U_n}{\sqrt{3}} \]

\[ I_{L2} = 0 \]

\[ I_{L3} = 0 \]
Short Circuit Calculation Results

Faults at all Buses

Infeed
\( I_k^* = 17.29 \text{ kA} \)
\( I_a = 16.34 \text{ kA} \)
\( I_p = 46.03 \text{ kA} \)

Station 1
\( I_k^* = 17.42 \text{ kA} \)
\( I_a = 16.41 \text{ kA} \)
\( I_p = 44.05 \text{ kA} \)

Station 2
\( I_k^* = 17.42 \text{ kA} \)
\( I_a = 16.41 \text{ kA} \)
\( I_p = 44.05 \text{ kA} \)

Station 20-2
\( I_k^* = 16.15 \text{ kA} \)
\( I_a = 15.36 \text{ kA} \)
\( I_p = 37.64 \text{ kA} \)

Station 20-1
\( I_k^* = 16.15 \text{ kA} \)
\( I_a = 15.36 \text{ kA} \)
\( I_p = 37.64 \text{ kA} \)
Short Circuit Calculation Results
Contribution for one Fault Location

Station 1
I^* = 17.39 kA
I_a = 16.39 kA
I_p = 44.01 kA
Example
Data of sample calculation

Network feeder:
- 110 kV
- 3 GVA
- R/X = 0.1

Transformer:
- 110 / 20 kV
- 40 MVA
- u_k = 15 %
- P_{krT} = 100 kVA

Overhead line:
- 20 kV
- 10 km
- R_1' = 0.3 Ω / km
- X_1' = 0.4 Ω / km
Impedance of Network feeder

\[ Z_l = \frac{c \cdot U_n^2}{S_k} \]

\[ Z_l = \frac{1.1 \cdot (20\text{kV})^2}{3\text{GVA}} \]

\[ Z_l = 0.1467 \Omega \quad R_l = 0.0146 \Omega \quad X_l = 0.1460 \Omega \]
Impedance of Transformer

\[ Z_T = u_k \cdot \frac{U_n^2}{S_n} \]

\[ Z_T = 0.15 \cdot \frac{(20\,\text{kV})^2}{40\,\text{MVA}} \]

\[ Z_T = 1.5000 \, \Omega \]

\[ R_T = P_{krT} \cdot \frac{U_n^2}{S_n^2} \]

\[ R_T = 100\,\text{kVA} \cdot \frac{(20\,\text{kV})^2}{(40\,\text{MVA})^2} \]

\[ R_T = 0.0250 \, \Omega \]

\[ X_T = 1.4998 \, \Omega \]
Impedance of Transformer Correction Factor

\[ K_T = 0.95 \cdot \frac{c_{\text{max}}}{1 + 0.6 \cdot x_T} \]

\[ K_T = 0.95 \cdot \frac{1.1}{1 + 0.6 \cdot 0.14998} \]

\[ K_T = 0.95873 \]

\[ Z_{TK} = 1.4381 \Omega \]

\[ R_{TK} = 0.0240 \Omega \]

\[ X_{TK} = 1.4379 \Omega \]
Impedance of Overhead Line

\[ R_L = R' \cdot \ell \]
\[ R_L = 0.3 \Omega / \text{km} \cdot 10 \text{km} \]
\[ R_L = 3.0000 \Omega \]

\[ X_L = X' \cdot \ell \]
\[ X_L = 0.4 \Omega / \text{km} \cdot 10 \text{km} \]
\[ X_L = 4.0000 \Omega \]
**Initial Short-Circuit Current – Fault location 1**

\[ R = R_i + R_{TK} \]

\[ R = 0.0146 \Omega + 0.0240 \Omega \]

\[ R = 0.0386 \Omega \]

\[ X = X_i + X_{TK} \]

\[ X = 0.1460 \Omega + 1.4379 \Omega \]

\[ X = 1.5839 \Omega \]

\[ I_k' = \frac{c \cdot U_n}{\sqrt{3} \cdot (R_1 + j \cdot X_1)} \]

\[ I_k'' = \frac{1.1 \cdot 20 \text{kV}}{\sqrt{3} \cdot \sqrt{(0.0386 \Omega)^2 + (1.5839 \Omega)^2}} \]

\[ I_k'' = 8.0 \text{kA} \]
Initial Short-Circuit Current – Fault location 2

\[ R = R_1 + R_{TK} + R_L \]
\[ R = 0.0146\Omega + 0.0240\Omega + 3.0000\Omega \]
\[ R = 3.0386\Omega \]

\[ X = X_1 + X_{TK} + X_L \]
\[ X = 0.1460\Omega + 1.4379\Omega + 4.0000\Omega \]
\[ X = 5.5839\Omega \]

\[ I_k'' = \frac{c \cdot U_n}{\sqrt{3} \cdot (R_1 + j \cdot X_1)} \]
\[ I_k'' = \frac{1.1 \cdot 20kV}{\sqrt{3} \cdot \sqrt{(3.0386\Omega)^2 + (5.5839\Omega)^2}} \]
\[ I_k'' = 2.0kA \]
Peak current
Peak Short-Circuit Current Calculation acc. IEC 60909

maximum possible instantaneous value of expected short circuit current

\[ i_p = \kappa \cdot \sqrt{2} \cdot I''_k \]

\[ \kappa = 1.02 + 0.98 \cdot e^{-3R/X} \]
Peak Short-Circuit Current Calculation in non-meshed Networks

- The peak short-circuit current $i_p$ at a short-circuit location, fed from sources which are not meshed with one another is the sum of the partial short-circuit currents:

$$i_p = i_{p1} + i_{p2} + i_{p3} + i_{p4}$$
Peak Short-Circuit Current Calculation in meshed Networks

- **Method A**: uniform ratio $R/X$
  - smallest value of all network branches
  - quite inexact

- **Method B**: ratio $R/X$ at the fault location
  - factor $\kappa_b$ from relation $R/X$ at the fault location (equation or diagram)
  - $\kappa = 1.15 \kappa_b$

- **Method C**: procedure with substitute frequency
  - factor $\kappa$ from relation $R_c/X_c$ with substitute frequency $f_c = 20$ Hz
  
  $\frac{R}{X} = \frac{R_c}{X_c} \cdot \frac{f_c}{f}$

  - best results for meshed networks
Peak Short-Circuit Current  
Fictitious Resistance of Generator

- \( R_{Gf} = 0.05 \, X_d" \) for generators with \( U_{rG} > 1 \, \text{kV} \) and \( S_{rG} \geq 100 \, \text{MVA} \)

- \( R_{Gf} = 0.07 \, X_d" \) for generators with \( U_{rG} > 1 \, \text{kV} \) and \( S_{rG} < 100 \, \text{MVA} \)

- \( R_{Gf} = 0.15 \, X_d" \) for generators with \( U_{rG} \leq 1000 \, \text{V} \)

NOTE: Only for calculation of peak short circuit current
Peak Short-Circuit Current – Fault location 1

\[ I_k'' = 8.0 \text{kA} \]
\[ R = 0.0386 \Omega \quad X = 1.5839 \Omega \]
\[ \frac{R}{X} = 0.0244 \]
\[ \kappa = 1.02 + 0.98 \cdot e^{-3 \frac{R}{X}} \]
\[ \kappa = 1.93 \]
\[ i_p = \kappa \cdot \sqrt{2} \cdot I_k'' \]
\[ i_p = 21.8 \text{kA} \]
Peak Short-Circuit Current – Fault location 2

\[ I''_k = 2.0 \text{kA} \]
\[ R = 3.0386 \Omega \quad X = 5.5839 \Omega \]
\[ R/X = 0.5442 \]
\[ \kappa = 1.02 + 0.98 \cdot e^{-3R/X} \]
\[ \kappa = 1.21 \]
\[ i_p = \kappa \cdot 2 \cdot I''_k \]
\[ i_p = 3.4 \text{kA} \]
Breaking Current
Breaking Current Differentiation

• Differentiation between short circuits "near" or "far" from generator

• Definition short circuit "near" to generator

  • for at least one synchronous machine is: $I_k^\prime > 2 \cdot I_{r,\text{Generator}}$
  or
  • $I_k^\prime$ with motor $> 1.05 \cdot I_k^\prime$ without motor

• Breaking current $I_b$ for short circuit "far" from generator

  $I_b = I_k^\prime$
Breaking Current Calculation in non-meshed Networks

- The breaking current \( I_B \) at a short-circuit location, fed from sources which are not meshed is the sum of the partial short-circuit currents:

\[
I_B = I_{B1} + I_{B2} + I_{B3} + I_{B4}
\]

\[
I_{B1} = \mu \cdot I''_k
\]

\[
I_{B2} = I''_k
\]

\[
I_{B3} = \mu \cdot q \cdot I''_k
\]

\[
I_{B4} = \mu \cdot q \cdot I''_k
\]
Breaking current

Decay of Current fed from Generators

\[ I_B = \mu \cdot I_k \]

Factor \( \mu \) to consider the decay of short circuit current fed from generators.
Breaking current

Decay of Current fed from Asynchronous Motors

\[ I_B = \mu \cdot q \cdot I_k \]

Factor \( q \) to consider the decay of short circuit current fed from asynchronous motors.
Breaking Current Calculation in meshed Networks

- Simplified calculation:
  \[ I_b = I_k'' \]

- For increased accuracy can be used:
  \[
  I_b = I_k'' + \sum_i \frac{\Delta U''_{Gi}}{c \cdot U_n / \sqrt{3}} \cdot (1 - \mu_i) \cdot I''_{kGi} - \sum_j \frac{\Delta U''_{Mj}}{c \cdot U_n / \sqrt{3}} \cdot (1 - \mu_j q_j) \cdot I''_{kMj}
  \]

  \[
  \Delta U''_{Gi} = j X''_{diK} \cdot I''_{kGi} \]

  \[
  \Delta U''_{Mj} = j X''_{Mj} \cdot I''_{kMj}
  \]

- \( X''_{diK} \): subtransient reactance of the synchronous machine (i)
- \( X''_{Mj} \): reactance of the asynchronous motors (j)
- \( I''_{kGi}, I''_{kMj} \): contribution to initial symmetrical short-circuit current from the synchronous machines (i) and the asynchronous motors (j) as measured at the machine terminals
Continuous short circuit current

Continuous short circuit current $I_k$

- r.m.s. value of short circuit current after decay of all transient effects
- depending on type and excitation of generators
- statement in standard only for single fed short circuit
- calculation by factors (similar to breaking current)

Continuous short circuit current is normally not calculated by network calculation programs.

For short circuits far from generator and as worst case estimation

$$I_k = I''_k$$