

# Short-circuit currents in three-phase a.c. systems —

**Part 1: Factors for the calculation of  
short-circuit currents according to  
IEC 60909-0**

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# National foreword

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The UK participation in its preparation was entrusted to Technical Committee PEL/73, Short circuit currents, which has the responsibility to:

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**Courants de court-circuit dans les réseaux  
triphasés à courant alternatif –**

**Partie 1:  
Facteurs pour le calcul des courants de  
court-circuit conformément à la CEI 60909-0**

**Short-circuit currents in three-phase  
a.c. systems –**

**Part 1:  
Factors for the calculation of short-circuit  
currents according to IEC 60909-0**



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INTERNATIONAL ELECTROTECHNICAL COMMISSION

**SHORT-CIRCUIT CURRENTS IN THREE-PHASE AC SYSTEMS –**

**Part 1: Factors for the calculation of short-circuit currents  
according to IEC 60909-0**

FOREWORD

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Technical reports do not necessarily have to be reviewed until the data they provide are considered to be no longer valid or useful by the maintenance team.

IEC 60909-1, which is a technical report, has been prepared by IEC technical committee 73: Short-circuit currents.

This technical report shall be read in conjunction with IEC 60909-0.

The text of this technical report is based on the following documents:

|               |                  |
|---------------|------------------|
| Enquiry draft | Report on voting |
| 73/120/DTR    | 73/125/RVC       |

Full information on the voting for the approval of this technical report can be found in the report on voting indicated in the above table.

This publication has been drafted in accordance with the ISO/IEC Directives, Part 3.

This document, which is purely informative, is not to be regarded as an International Standard.

The committee has decided that the contents of this publication will remain unchanged until 2010. At this date, the publication will be

- reconfirmed;
- withdrawn;
- replaced by a revised edition, or
- amended.

## SHORT-CIRCUIT CURRENTS IN THREE-PHASE AC SYSTEMS –

### Part 1: Factors for the calculation of short-circuit currents according to IEC 60909-0

#### 1 General

##### 1.1 Scope and object

This part of IEC 60909 is a technical report applicable to short-circuit currents in three-phase a.c. systems. This technical report aims at showing the origin and the application, as far as necessary, of the factors used to meet the demands of technical precision and simplicity when calculating short-circuit currents according to IEC 60909-0.

Thus this technical report is an addition to IEC 60909-0. It does not, however, change the basis for the standardized calculation procedure given in IEC 60909-0.

NOTE References are given in some cases to offer additional help, not to change the procedure laid down in the standard.

##### 1.2 Reference documents

IEC 60038:1983, *IEC standard voltages*

IEC 60909-0:2001, *Short-circuit currents in three-phase a.c. systems – Part 0: Calculation of currents*

IEC/TR 60909-2:1992, *Electrical equipment – Data for short-circuit current calculations in accordance to IEC 60909 (1988)*

IEC/TR 60909-4:2000, *Short-circuit currents in three-phase a.c. systems – Part 4: Examples for the calculation of short-circuit currents*

##### 1.3 Application of the factors

###### 1.3.1 Factor $c$

The voltage factors  $c_{\max}$  and  $c_{\min}$  are used together with the equivalent voltage source at the short-circuit location in order to calculate maximum and minimum initial short-circuit currents (see 2.1).

###### 1.3.2 Factors $K_G$ and $K_S$ or $K_{SO}$

The impedance correction factors  $K_G$  and  $K_S$  or  $K_{SO}$  are introduced when calculating the short-circuit impedances of generators and power station units (with or without on-load tap changer) (see 2.2).

###### 1.3.3 Factors $K_{G,S}$ , $K_{T,S}$ or $K_{G,SO}$ , $K_{T,SO}$

The impedance correction factors  $K_{G,S}$ ,  $K_{T,S}$  or  $K_{G,SO}$ ,  $K_{T,SO}$  are introduced when calculating the partial short-circuit currents in case of a short circuit between generator and unit transformer (with or without on-load tap changer) of a power station unit (see 2.2.3.2 or 2.2.4.2).

###### 1.3.4 Factor $K_T$

The impedance correction factor  $K_T$  is used when calculating the short-circuit impedances of network transformers (see 2.3).

### 1.3.5 Factor $\kappa$

The peak short-circuit current is calculated by using this factor (see 2.4).

### 1.3.6 Factors $\mu$ , $\lambda$ and $q$

Factors used when calculating the decay of the a.c. component of the short-circuit current of a near-to-generator or a near-to-asynchronous-motor short circuit (see 2.5, 2.6 and 2.7).

### 1.3.7 Factors $m$ and $n$

The factors  $m$  and  $n$  are used for the calculation of the Joule integral or the thermal equivalent short-circuit current (see 2.8).

### 1.3.8 Contribution of asynchronous motors to the initial symmetrical short-circuit current

Derivation and validity of relevant equations for checking the contribution of asynchronous motors or groups of asynchronous motors to the initial symmetrical short-circuit current (see 2.9).

## 1.4 Symbols, subscripts and superscripts

The following symbols, subscripts and superscripts are used in addition to those already defined in IEC 60909-0.

### 1.4.1 Symbols

|                |                                                                                                                                                          |
|----------------|----------------------------------------------------------------------------------------------------------------------------------------------------------|
| $E$            | Voltage behind the synchronous direct axis reactance $X_d$ of a synchronous machine                                                                      |
| $E'$           | Voltage behind the transient direct axis reactance $X_d'$ of a synchronous machine                                                                       |
| $E''$          | Voltage behind the subtransient direct axis reactance $X_d''$ of a synchronous machine                                                                   |
| $E_Q''$        | Subtransient voltage behind the impedance of a network feeder connected at Q                                                                             |
| $E_0(I_f)$     | Terminal voltage of a saturated synchronous machine at no-load ( $I_G = 0$ )                                                                             |
| $I^b$          | Branch current (load current) before the short circuit                                                                                                   |
| $I_f$          | Field current of a synchronous machine                                                                                                                   |
| $i_k(t)$       | Time-dependent short-circuit current                                                                                                                     |
| $I_{kUb}''$    | Initial symmetrical short-circuit current caused by the voltage $-U^b$ , when calculating short-circuit currents using the superposition method          |
| $p_G$ or $p_T$ | Relative values to define the region for the variation of terminal voltages, for instance $U_G = U_{rG} (1 \pm p_G)$ or $U_{THV} = U_{rTHV} (1 \pm p_T)$ |
| $T_{AC}$       | AC time constant of an asynchronous motor                                                                                                                |
| $T_N''$        | Mean value of the time constants $T_{dN}''$ and $T_{qN}''$                                                                                               |
| $T_{\mu q}$    | Time constant calculated with the product $\mu q$ (see 2.7.2)                                                                                            |
| $t_p$          | Time duration from the beginning of a short circuit until the peak short-circuit current                                                                 |
| $U^b$          | Voltage at the short-circuit location before the short circuit                                                                                           |
| $X_p$          | Potier reactance                                                                                                                                         |
| $Y$            | Admittance                                                                                                                                               |
| $\gamma$       | Impedance angle                                                                                                                                          |
| $\Delta$       | Deviation                                                                                                                                                |
| $\varphi_U$    | Voltage angle                                                                                                                                            |

### 1.4.2 Subscripts

|     |                                                         |
|-----|---------------------------------------------------------|
| 0   | No load ( $T_{d0}''$ )                                  |
| a   | Approximation                                           |
| ad  | Admissible                                              |
| d   | Direct axis                                             |
| e   | Exact                                                   |
| f   | Field of the synchronous machine                        |
| IEC | according to IEC 60909-0, for example $K_{S(IEC)}$      |
| i   | Internal                                                |
| L   | Load                                                    |
| MAX | Maximum (short-circuit current at worst-case load flow) |
| N   | Network                                                 |
| q   | Quadrature axis                                         |
| S   | Superposition method                                    |
| *   | Per unit quantity                                       |

### 1.4.3 Superscripts

|   |              |
|---|--------------|
| b | Before       |
| ' | Transient    |
| " | Subtransient |

## 2 Factors used in IEC 60909-0

### 2.1 Voltage factor $c$ for the equivalent voltage source at the short-circuit location

#### 2.1.1 General

The magnitude of a short-circuit current in a three-phase a.c. system (maximum or minimum short-circuit current) at any location depends primarily on the network configuration, the generators or power-station units and the motors in operation and secondarily on the operational stage of the network before the short circuit.

The variations during operation in a three-phase a.c. system are very large. Therefore, it is difficult to find the special load flow that leads either to a maximum or to a minimum short-circuit current at the different locations of the network. In a given system, there are as many different short-circuit current magnitudes as there are possible different load-flow conditions for every location. Normally, extreme load-flow cases are not empirically known.

IEC 60909-0 therefore recommends a calculation method with the equivalent voltage source  $cU_n / \sqrt{3}$  at the short-circuit location. This method, described in IEC 60909-0, is an approximation method without special conditions of operation. The aim of this standard is to find the maximum short-circuit currents with sufficient accuracy, mainly taking into account safety aspects and as far as possible economical aspects.

During the planning stage of a network, the different future load-flow conditions are unknown. Therefore, the equivalent voltage source  $cU_n / \sqrt{3}$  is based on the nominal system voltage  $U_n$  and the voltage factor  $c = c_{\max}$  or  $c = c_{\min}$  for the calculation of the maximum or the minimum short-circuit currents. These factors  $c$  are given in table 1 of IEC 60909-0. The introduction of a voltage factor  $c$  is necessary for various reasons (IEC 60909-0, 1.3.15). These are:

- voltage variation depending on time and place;
- changing of transformer taps;

- neglecting loads and capacitances by calculating according to IEC 60909-0 (see 2.3.1);
- the subtransient behaviour of generators, power-station units and motors.

The meaning of the voltage factor  $c$  is illustrated for a simple model of a radial network in 2.1.4. Furthermore, results of extended calculations given in 2.2.5 and 2.3.4 demonstrate the possible deviations of calculations with the equivalent voltage source at the short-circuit location against the worst-case values found with a special procedure using the superposition method.

### 2.1.2 Calculation methods

In principle, there are two methods for the calculation of the initial symmetrical short-circuit current at the short-circuit location (IEC 60909-0, figures 1 and 2):

- the superposition method, derived from Helmholtz's or Thevenin's principle;
- the method using the equivalent voltage source at the short-circuit location (see 2.1.3).

Examples for the superposition method are given in 2.2 and 2.3. There the results of the superposition method are compared with the results found with the method using the equivalent voltage source at the short-circuit location.

If a certain load flow in an existing network is known, then it is possible to calculate the initial symmetrical short-circuit current with the superposition method, but this method gives the short-circuit current only related to the load flow presupposed. Therefore, it does not necessarily lead to the maximum short-circuit current. The reason is that for one short-circuit location there are as many short-circuit currents as load-flow conditions without exceeding the boundary conditions of voltages and currents during normal operation, even if the same operational voltage at the short-circuit location is given.

To overcome this problem and to find the worst-case load flow that leads to the maximum short-circuit current at one short-circuit location, a special method was developed by varying the operation conditions [9], [13], [26]<sup>1)</sup>. Further information is given in 2.2.5 and 2.3.4.

### 2.1.3 Equivalent voltage source at the short-circuit location and voltage factor $c$

The procedure for the calculation of the initial symmetrical short-circuit current using the equivalent voltage source at the short-circuit location is described in IEC 60909-0. This method, which is normally based only on the rated data of electrical equipment, is an essential simplification compared to the superposition method or a transient calculation, because also in this case it is necessary to know the load-flow conditions before the short circuit.

Using this simplified procedure, the equivalent voltage source  $cU_n / \sqrt{3}$  at the short-circuit location is the only active voltage in the positive-sequence system. All network feeders, synchronous machines and asynchronous motors are short-circuited behind their internal (subtransient) reactances (IEC 60909-0, 3.6.1). All the shunt capacitances and the shunt admittances (loads), except those of the motors, are to be omitted in the positive- and the negative-sequence system (IEC 60909-0, 2.3). Capacitances of the zero-sequence system are to be considered in general. The zero-sequence capacitances are to be omitted in low-voltage systems and in high-voltage effectively grounded systems (i.e. earth fault factor  $\delta \leq 1,4$ ). Special considerations are necessary in high-voltage networks with long-distance lines and, of course, in the case of isolated neutral or resonant earthed networks (IEC 60909-0, 1.1). An example for the application of the calculation using the equivalent voltage source at the short-circuit location F is given in IEC 60909-0, figure 4.

<sup>1)</sup> The figures in square brackets refer to the bibliography.

The factor  $c_{\max}$  or  $c_{\min}$  is introduced according to table 1 of IEC 60909-0. Corresponding to  $c_{\max}$  or  $c_{\min}$  special conditions are introduced for the calculation of the maximum and minimum short-circuit currents (see IEC 60909-0, 2.4 and 2.5). The introduction of the voltage factor  $c$  aims at finding a short-circuit current, for instance, a maximum short-circuit current, as near as possible to the real value. Using the impedance correction factors (IEC 60909-0, 3.3.3, 3.6.1, 3.7.1 and 3.7.2) together with the voltage factor  $c$  realistic values even for the partial short-circuit currents shall be obtained, even though compromises are necessary to a certain extent (see 2.2.5).

The following clause deals with the reliability of the method using the equivalent voltage source at the short-circuit location and gives the fundamental relation between the admissible or usual relative voltage drops  $\Delta u$  and the maximum possible deviation  $\Delta i_k''$  and furthermore the dependence of the factor  $c_{\max}$  from the voltage  $U_{Q\max}$ .

#### 2.1.4 A simple model illustrating the meaning of the voltage factor $c$

The following simple model in figure 1 illustrates the fundamental meaning of the voltage factor  $c$  in the case of a non-meshed radial network, for instance, in a distribution network. Complex models and their calculation results used to find the coherence between the relative voltage deviations  $\Delta u$  and the voltage factor  $c$  are given in [10] and [17].

The positive-sequence system of the model in figure 1a is given in figure 1b. It is presumed that the voltage  $U_Q$  at the beginning of the line is constant ( $I_{kQ}'' \Rightarrow \infty$ ). The load is concentrated and simulated by the shunt impedance  $\underline{Z}_A$  at the variable location A between the line impedances  $\alpha \underline{Z}_L$  and  $(1-\alpha) \underline{Z}_L$  with  $0 \leq \alpha \leq 1$ .

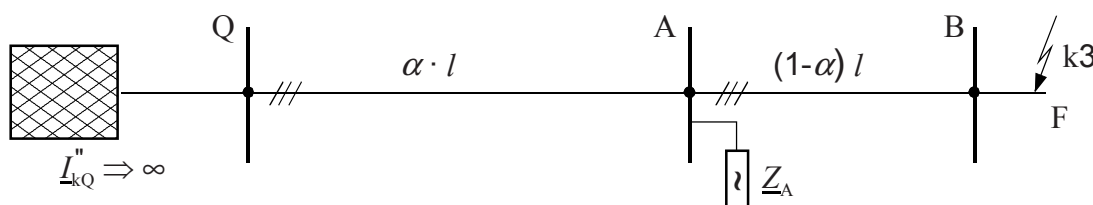


Figure 1a – Three-phase a.c. model (non-meshed radial network)

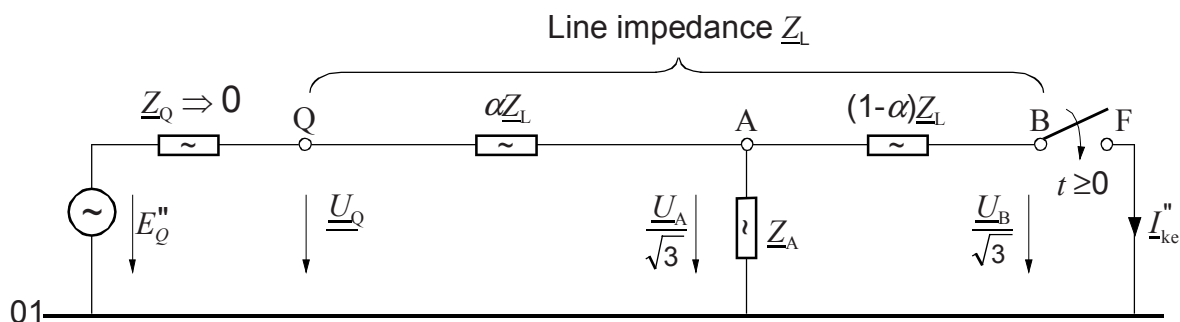


Figure 1b – Equivalent circuit diagram, positive-sequence system, before the short circuit at F

Figure 1 – Model for the calculation of the coherence between the voltage deviation  $\Delta u$  and the short-circuit current deviation  $\Delta i_k''$

It shall be shown that the short-circuit current deviation  $\Delta i_k''$  depends on the voltage deviation  $\Delta u$ . The following definitions are used:

$$\Delta u = \left| \frac{\underline{U}_Q}{\underline{U}_B} \right| - 1 \quad (1)$$

$$\Delta i_k'' = \left| \frac{I_{ka}''}{I_{ke}''} \right| - 1 \quad (2)$$

where

a is the subscript for the approximation of the short-circuit current when  $\underline{Z}_A$  is neglected;

e is the subscript for the exact value of the short-circuit current when  $\underline{Z}_A$  is taken into account.

The following equation, giving the voltage conditions before the short circuit, can be derived from figure 1b if  $\underline{U}_Q$  is taken as a constant value:

$$\underline{U}_Q = \underline{U}_A (1 + \alpha \underline{Z}_L \underline{Y}_A) = \underline{U}_B (1 + \alpha \underline{Z}_L \underline{Y}_A) \quad (3)$$

with  $\underline{U}_A = \underline{U}_B$  (see figure 1b) and  $\underline{Y}_A = 1/\underline{Z}_A$ .

Using equation (3) the voltage deviation can be expressed as follows:

$$\Delta u = \left| \frac{\underline{U}_Q}{\underline{U}_B} \right| - 1 = |1 + \alpha \underline{Z}_L \underline{Y}_A| - 1 \quad (4)$$

The exact value of the initial symmetrical short-circuit current can be calculated with the help of figure 1b:

$$I_{ke}'' = I_Q \cdot \frac{1}{1 + (1 - \alpha) \underline{Z}_L \underline{Y}_A} \quad (5a)$$

with

$$I_Q = \frac{\underline{U}_Q}{\sqrt{3} \underline{Z}_L} \cdot \frac{1}{\alpha + \frac{(1 - \alpha)}{1 + (1 - \alpha) \underline{Z}_L \underline{Y}_A}} \quad (5b)$$

Introducing  $I_Q$  from equation (5b) to equation (5a) leads to

$$I_{ke}'' = \frac{\underline{U}_Q}{\sqrt{3} \underline{Z}_L} \cdot \frac{1}{1 + \alpha (1 - \alpha) \underline{Z}_L \underline{Y}_A} \quad (6)$$

The approximation  $I_{ka}''$  is found from figure 1b with  $\underline{Z}_A = \infty$  (or  $\underline{Y}_A = 0$ ) and the voltage  $\underline{U}_B$  at the prospective short-circuit location, using equation (3):

$$I_{ka}'' = \frac{\underline{U}_B}{\sqrt{3} \underline{Z}_L} = \frac{\underline{U}_Q}{\sqrt{3} \underline{Z}_L} \cdot \frac{1}{1 + \alpha \underline{Z}_L \underline{Y}_A} \quad (7)$$

The current deviation  $\Delta i_k''$  follows from equation (6) and (7):

$$\Delta i_k'' = \left| \frac{I_{ka}''}{I_{ke}''} \right| - 1 = \left| \frac{1 + \alpha(1 - \alpha)Z_L Y_A}{1 + \alpha Z_L Y_A} \right| - 1 \quad (8)$$

The product  $Z_L Y_A$  can be written as:

$$Z_L Y_A = Z_L e^{j\gamma} Y_A e^{-j\varphi} = Z_L Y_A e^{j(\gamma - \varphi)} = Z_L Y_A e^{j\eta} \quad (9)$$

with  $Z_L = R_L + jX_L = Z_L e^{j\gamma}$  and  $Y_A = G_A - jB_A = Y_A e^{-j\varphi}$

The following results can be found from figure 2.

- The largest negative deviation  $\Delta i_k''$  occurs in the case  $\alpha = 1$  and  $\eta = 0$ . That means that the load  $Z_A$  is at the end of the line ( $\alpha = 1$ ) and that the load is inductive ( $\eta = 0$ ).
- The absolute values of the negative deviations  $\Delta i_k''$  are smaller than the voltage deviations  $\Delta u$ :

$$|\Delta i_k''| < \Delta u \quad (10)$$

- In the case of  $\alpha = 1$  and  $\eta = 0$  equation (4) leads to (see figure 2):

$$\Delta u = Z_L Y_A = \Delta u_{\max} \quad (11)$$

- The following relation can be found from equation (8) established for the highest negative deviations  $\Delta i_{k \max}''$  at  $\alpha = 1$  (broken line in figure 2a), depending on the maximum positive voltage deviations  $\Delta u_{\max}$ :

$$\Delta i_{k \max}'' = \frac{1}{1 + \Delta u_{\max}} - 1 \quad (12)$$

- The following conditions are found from equation (12):

$$\Delta u_{\max} = +5 \%: -0,048 \leq \Delta i_{k \max}''$$

$$\Delta u_{\max} = +10 \%: -0,091 \leq \Delta i_{k \max}''$$

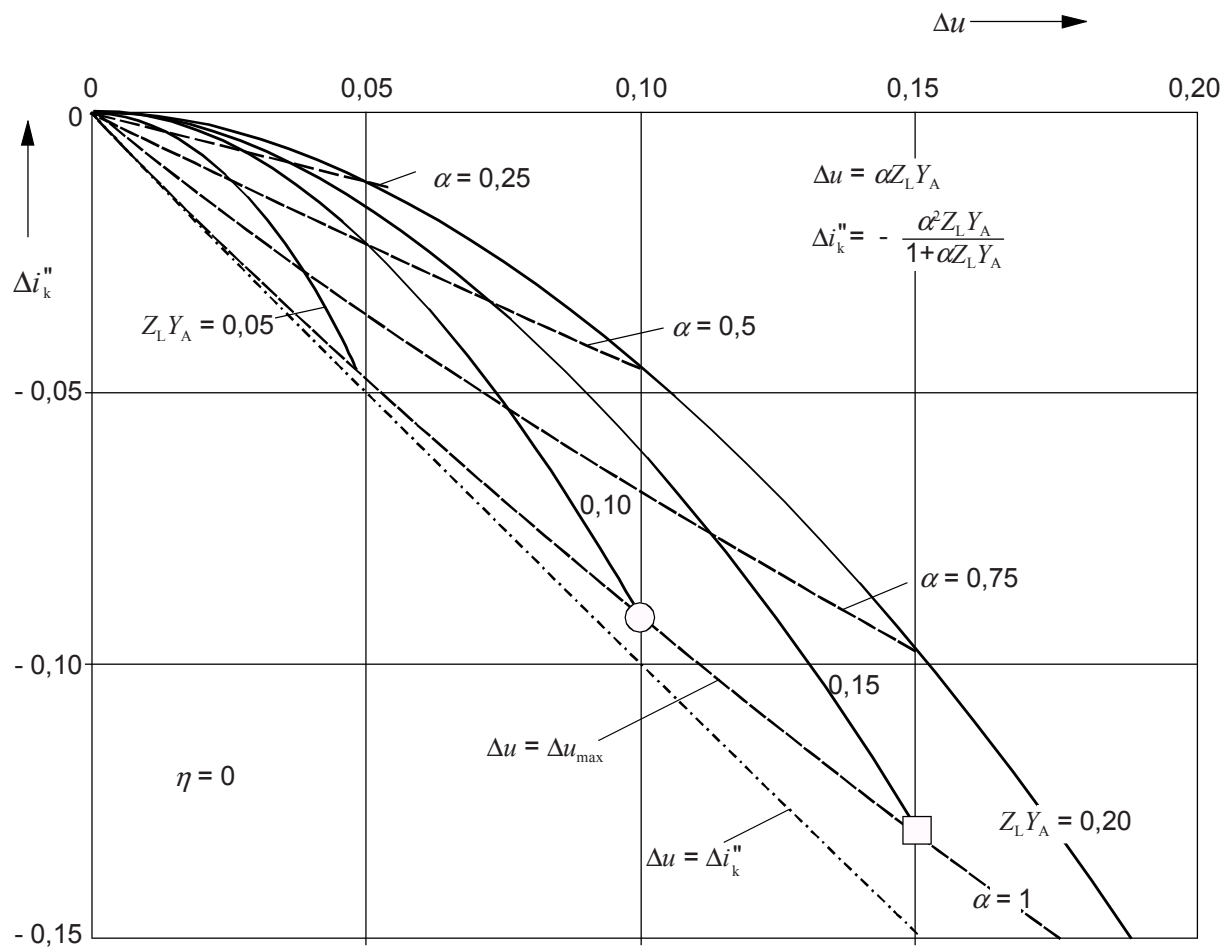
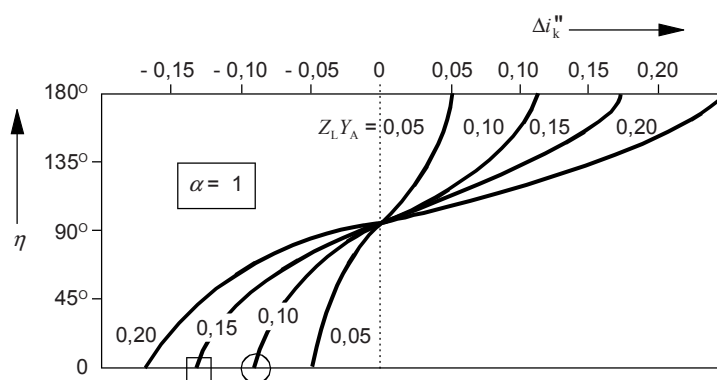
$$\Delta u_{\max} = +15 \%: -0,130 \leq \Delta i_{k \max}''$$

Together with the approximation  $I_{ka}''$  from equation (7) and  $\Delta u_{\max} = Z_L Y_A$  according to equation (11), equation (12) leads to

$$I_{ke \max}'' = I_{ka}'' (1 + \Delta u_{\max}) = \frac{U_Q}{\sqrt{3} Z_L} \quad (13)$$

If the method with the equivalent voltage source  $cU_n / \sqrt{3}$  at the short-circuit location is used (see 2.1.3) to calculate the initial symmetrical short-circuit current  $I_{k(IEC)}''$  and if the result shall be approximately the same as  $I_{ke \max}''$  then the following relation is found with  $I_{ke \max}''$  from equation (13):

$$I_{k(IEC)}'' = \frac{cU_n}{\sqrt{3} Z_L} \approx I_{ke \max}'' \quad (14)$$

Figure 2a –  $\Delta i_k'' = f(\Delta u, \alpha)$  with  $\eta = 0$ Figure 2b –  $\Delta i_k'' = f(\eta, Z_L Y_A)$  with  $\alpha = 1$ Figure 2 – Calculation of  $\Delta i_k''$  according to equation (8) for different parameters

This leads, if the maximum short-circuit current  $\underline{I}_{k(IEC)\max}''$  shall be calculated, to the maximum of factor  $c$  [17]:

$$c_{\max} \approx \frac{U_{Q\max}}{U_n} \quad (15)$$

Due to the relation given in equation (15), even if it is only found for the simple model with  $Z_Q \Rightarrow 0$  in figure 1, the maximum voltage  $U_{Q\max}$  at the feeding point is the relevant voltage for the calculation of the maximum short-circuit current.

However caution is necessary if voltages higher than  $c_{\max}U_n$  (or  $c_{\max}U_n/\sqrt{3}$  in the positive-sequence system) exist in a network. One example is the internal voltage  $E''$  behind the subtransient reactance  $X_d''$  of a synchronous machine (figures 4 and 6).

It can be shown [10] that this is also the most unfavourable case, even in comparison with results of meshed networks and long-distance transmissions up to about 400 km.

The factor  $c = c_{\max}$  (IEC 60909-0, 2.3.1 and table 1) takes into account these results ( $c_{\max} = 1,1$  for medium- and high-voltage networks and  $c_{\max} = 1,05$  or  $1,10$  for low-voltage networks depending on the tolerance for the voltage during operation), considering that the highest voltage in a normal system does not differ, on average, by more than +5 % (LV) or by +10 % (HV) approximately from the nominal system voltage  $U_n$  (IEC 60038, table III, note 2). In a normal system of Series I (50 Hz or 60 Hz systems), the highest and the lowest voltage do not differ by more than approximately  $\pm 10$  % from the nominal voltage of the system. In a normal system of Series II (60 Hz systems – North American practice), the highest voltage does not differ by more than +5 % and the lowest voltage by more than –10 % from the nominal voltage of the system. If in a network this assumption for a normal system is not fulfilled, and the highest voltage during operation does differ more than above, then a higher factor  $c_{\max}$  may be necessary, see equation (15).

Special conditions occur in the case of generators and power-station units with high values of  $x_d''$  and  $u_k$  which lead to voltage deviations higher than 10 %. Therefore, impedance correction factors are introduced for the calculation of the impedances of this electrical equipment (IEC 60909-0, 3.6 and 3.7).

The short-circuit voltage of network transformers may in special cases reach values up to 35 %; the rated voltages of these transformers (two-winding or three-winding transformers) may be considerably different from the nominal voltages of the connected networks and in many cases the transformers are equipped with on-load tap changers. Therefore, impedance correction factors are introduced for the calculation of the impedances of network transformers (IEC 60909-0, 3.3.3).

NOTE The note given in 8.3.2.2 of IEC 60909:1988 [28], did not give any help for the user, when carrying out practical calculations with network transformers, if one of the conditions given there is valid. Therefore, it became necessary to develop an impedance correction factor for network transformers (see 2.3).

## 2.2 Impedance-correction factors when calculating the short-circuit impedances of generators, unit transformers and power-station units

### 2.2.1 General

One of the main criteria for the rating of electrical equipment is the maximum short-circuit current and, in many cases, also the maximum partial short-circuit current. It is necessary to introduce impedance-correction factors  $K_G$  (see 2.2.2) for generators and impedance-correction factors  $K_S$  for power-station units with (see 2.2.3) and  $K_{SO}$  without (see 2.2.4) on-load tap changer of the unit transformer in addition to the voltage factor  $c_{\max}$ , especially if the subtransient reactances  $x_d''$  of the generators are high and the transformation ratio of the unit transformers (with or without on-load tap changer) is different from the ratio of the system voltages during operation on both sides of the transformer. The correction factors for generators and power-station units are given in IEC 60909-0, 3.6 and 3.7.

Special considerations and impedance-correction factors are necessary for the calculation of the partial short-circuit currents in the case of a short circuit between generator and unit transformer or auxiliary transformer of a power-station unit (see IEC 60909-0, 4.2.1.3 and 4.2.1.4). These calculations are normally carried out only once during the construction of the power-station unit.

The impedance-correction factors given in IEC 60909-0, 3.6 and 3.7 are derived for the maximum partial short-circuit currents ( $c = c_{\max}$ ). The factor  $c_{\max}$  shall be taken from IEC 60909-0, table 1 in accordance with the voltage  $U_{rG}$  when using IEC 60909-0, equation (18) and in accordance with the voltage  $U_{nQ}$  at the high-voltage side of the unit transformer when using IEC 60909-0, equations (22) and (24). Additional investigations in meshed networks have shown that these correction factors are also adequate when calculating short-circuit currents at different locations of the network (see 2.2.5).

Special considerations are necessary for the correction factors when calculating minimum short-circuit currents, because the special boundary conditions for the different power-station units must be known. These conditions, for instance, are given by the maximum extent of underexcited operation, the minimum active power of thermal power stations during long-term operation or the maximum reactive power (overexcited or underexcited) of units in hydro-pumping stations as well as by special devices for the limitation of the torque angle. Furthermore, attention shall be given to the fact that even during low load conditions in a network, the number of power-station units operating with partial load within the underexcited region is usually minimized. Therefore, a rough estimation for minimum short-circuit currents may be found using the instructions given in IEC 60909-0, 2.5 and given impedance correction factors, even though these are based on operation at rated conditions before the short circuit (IEC 60909-0, 3.7.1).

## 2.2.2 Correction factor $K_G$

The impedance correction factor  $K_G$  is used for the impedance  $\underline{Z}_G = R_G + j X_d''$  of a generator directly connected to a low- or a medium-voltage network (without unit transformer) as shown in figure 3 (IEC 60909-0, figure 11b).

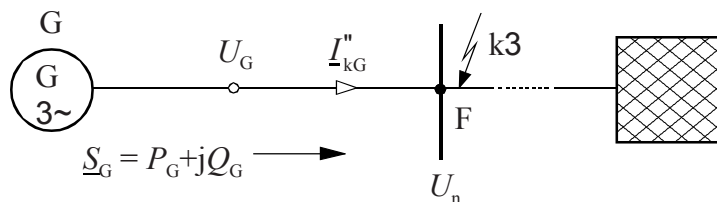


**Figure 3 – Partial short-circuit current  $I''_{kG(S)}$  of a generator directly connected to a network**

The impedance correction factor  $K_G$  is derived from a phasor diagram for normal overexcited operation of the generator taking into account the subtransient reactance  $X_d''$  and the subtransient internal voltage  $E''$ .

Figure 4a gives the equivalent circuit diagram (positive-sequence system) of a generator. The terminal voltage  $U_G$  of the generator is controlled and therefore constant during operation before the short circuit. Normally  $U_G = U_{rG} = 1,05 U_n$  is valid. In special cases the setpoint may vary:  $U_G = U_{rG} (1 \pm p_G)$ .

Figure 4 describes the procedure for the calculation of the partial short-circuit current  $I_{-kG(S)}''$  with the superposition method.

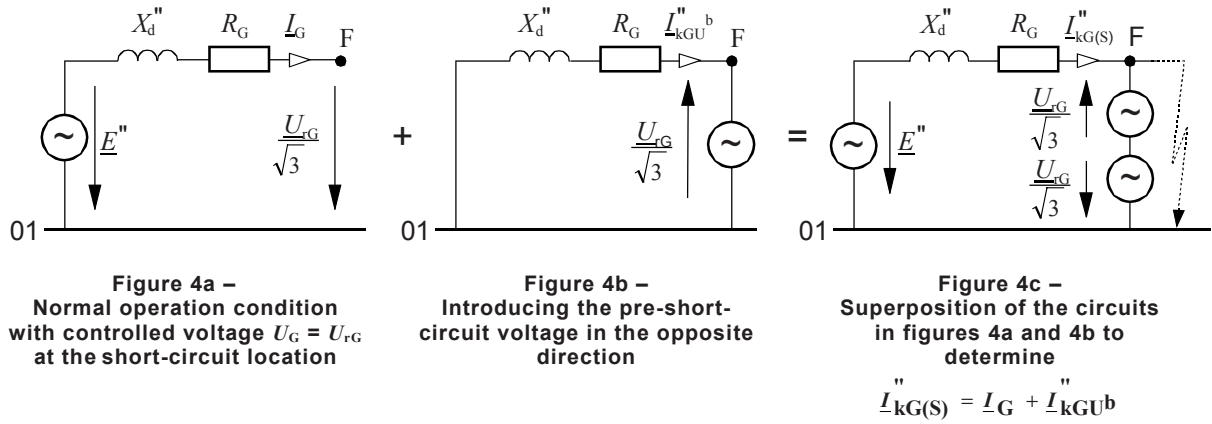


**Figure 4 – Calculation of  $I_{-kG(S)}''$  with the superposition method**

The currents  $I_G$  and  $I_{-kGU^b}''$  are derived from figures 4a and 4b at  $U_G = U_{rG}$  as follows:

$$I_G = \frac{E'' - U_{rG} / \sqrt{3}}{R_G + jX_d''} \quad (16)$$

$$I_{-kGU^b}'' = \frac{U_{rG} / \sqrt{3}}{R_G + jX_d''} \quad (17)$$

The index  $U^b$  indicates that the current  $I_{-kGU^b}''$  is found when the voltage  $U_{rG} / \sqrt{3}$  before the short circuit is introduced in the opposite direction (figure 4b).

The superposition according to figure 4c leads to the partial short-circuit current  $I_{-kG(S)}''$ :

$$I_{-kG(S)}'' = I_G + I_{-kGU^b}'' = \frac{E'' - U_{rG} / \sqrt{3}}{R_G + jX_d''} + \frac{U_{rG} / \sqrt{3}}{R_G + jX_d''} = \frac{E''}{R_G + jX_d''} \quad (18)$$

On the other hand, when applying the method with the equivalent voltage source  $cU_n / \sqrt{3}$  at the short-circuit location, the following equation for the calculation of the short-circuit current  $I_{-kG}''$  is found:

$$I_{-kG}'' = \frac{E''}{R_G + jX_d''} = \frac{cU_n}{\sqrt{3}(R_G + jX_d'')K_G} \quad (19)$$

Taking  $E'' = U_{rG} / \sqrt{3} + I_G Z_G = U_{rG} / \sqrt{3} + I_G (\cos \varphi_G - j \sin \varphi_G)(R_G + jX_d'')$ , the impedance correction factor  $K_G$  is found:

$$K_G = \frac{U_n}{U_{rG}} \cdot \frac{c}{1 + \frac{\sqrt{3}I_G}{U_{rG}}(R_G \cos \varphi_G + X_d'' \sin \varphi_G) + j \frac{\sqrt{3}I_G}{U_{rG}}(X_d'' \cos \varphi_G - R_G \sin \varphi_G)} \quad (20)$$

If  $R_G$  is very small compared to  $X_d''$  ( $R_G \ll X_d''$ ) the following approximation can be applied:

$$K_G \approx \frac{U_n}{U_{rG}} \cdot \frac{c}{1 + (I_G / I_{rG}) x_d'' \sin \varphi_G} \quad (21)$$

The per unit (p.u.) value of  $X_d''$  is introduced with  $x_d'' = X_d'' / Z_{rG}$  and  $Z_{rG} = U_{rG}^2 / S_{rG}$  (IEC 60909-0, 3.6.1).

The maximum short-circuit current  $I_{kG}''$  is found if the denominator of the second part of the right side of equation (21) reaches the maximum. Normally this will be the case at the point of rated operation ( $S_{rG}$ ,  $U_{rG}$ ,  $\cos \varphi_{rG}$ ) or in its vicinity if the extreme overexcited operation with  $Q > Q_r$  is excluded. Thus, it seems acceptable to choose  $I_G = I_{rG}$  and  $\sin \varphi_G = \sin \varphi_{rG}$ .

By introducing  $c = c_{\max}$  the approximation of equation (21) then assumes the following form:

$$K_G = \frac{U_n}{U_{rG}} \cdot \frac{c_{\max}}{1 + x_d'' \sin \varphi_{rG}} \quad (22)$$

*Example:*

$$S_{rG} = 10 \text{ MVA}$$

$$U_{rG} = 10,5 \text{ kV}$$

$$\cos \varphi_{rG} = 0,8$$

$$x_d'' = 0,12$$

The generator feeds a network with the nominal voltage  $U_n = 10 \text{ kV}$  (see figure 3).

A calculation of the maximum partial short-circuit current according to the right side of equation (19) with  $K_G = 0,977$ , found from equation (22) with  $c_{\max} = 1,1$  (IEC 60909-0, table 1), leads to  $I_{kG}'' = 4,900 \text{ kA}$ .

From a calculation with the superposition method (index (S)) according to equation (18) the short-circuit current  $I_{-kG(S)}'' = (0,759 - j4,889) \text{ kA}$ ;  $I_{kG(S)}'' = 4,948 \text{ kA}$  is found. The approximation value  $I_{kG}''$  is about 1 % smaller than the value  $I_{kG(S)}''$ .

If the terminal voltage of the generator is different from  $U_{rG}$ , then it may be necessary to introduce  $U_G = U_{rG}(1 \pm p_G)$  instead of  $U_{rG}$  to the equations (20), (21) and (22). Then the maximum short-circuit current is found with the voltage  $U_G$  at the upper limit  $U_G = U_{rG}(1 + p_G)$  [17].

## 2.2.3 Correction factors for power station units with on-load tap changer

### 2.2.3.1 Impedance correction factor $K_S$

The determination of the impedance correction factor  $K_S$  (IEC 60909-0, equation (22)) for power-station units with on-load tap-changer according to figure 5 is based on the representation given in figure 6a with the transformation ratio  $t$  of the unit transformer  $t \neq t_r = U_{rTHV} / U_{rTLV}$ .

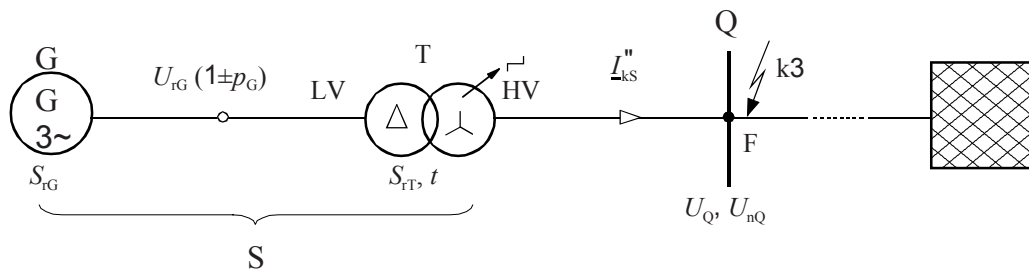


**Figure 5 – Partial symmetrical short-circuit current  $I''_{kS}$  of a power-station unit S, at the high-voltage side of a unit transformer with on-load tap-changer**

The rated transformation ratio of the unit transformer may be higher than the quotient of  $U_{nQ}$  divided by  $U_{rG}$ :  $t_r \geq U_{nQ} / U_{rG}$ .

Using the superposition method (similar to figure 4), both the currents  $I_S$  (figure 6a) and  $I''_{kSU^b}$  are derived as follows.

$$I_S = \frac{1}{t} \cdot I_G = \frac{1}{t} \cdot \frac{\underline{E}'' - \underline{U}_{Ti} / \sqrt{3}}{\underline{Z}_G + \underline{Z}_{TLV}} \quad (23)$$

The current  $I''_{kSU^b}$  is found by the introduction of  $\underline{U}_Q / \sqrt{3}$  in the opposite direction at the short-circuit location F at  $\underline{E}'' = 0$ .

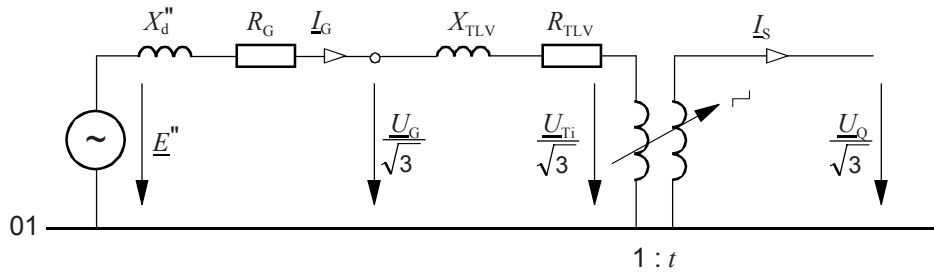
$$I''_{kSU^b} = \frac{\underline{U}_Q / \sqrt{3}}{t^2 (\underline{Z}_G + \underline{Z}_{TLV})} \quad (24)$$

with the transformation ratio  $t = \underline{U}_Q / \underline{U}_{Ti} = U_Q / U_{Ti}$  (figure 6a) and the impedance  $\underline{Z}_{TLV}$  depending on the transformation ratio  $t$ .

The partial short-circuit current  $I''_{kS(S)}$  at the high-voltage side of the unit transformer is found with the superposition method (S) as follows:

$$I''_{kS(S)} = I_S + I''_{kSU^b} = \frac{t(\underline{E}'' - \underline{U}_{Ti} / \sqrt{3})}{t^2 (\underline{Z}_G + \underline{Z}_{TLV})} + \frac{t \underline{U}_{Ti} / \sqrt{3}}{t^2 (\underline{Z}_G + \underline{Z}_{TLV})} = \frac{1}{t} \cdot \frac{t_r^2 \underline{E}''}{t_r^2 \underline{Z}_G + \underline{Z}_{THV}} \quad (25)$$

with  $\underline{Z}_{THV} = t_r^2 \underline{Z}_{TLV}$ .



$$t \neq t_r = U_{rTHV} / U_{rTLV}$$

$$\underline{U}_Q = t \underline{U}_{Ti}$$

$$\underline{I}_S = (1/t) \underline{I}_G$$

Figure 6a – Equivalent circuit diagram in the positive-sequence system with  $\underline{Z}_G = R_G + jX_d''$

and  $\underline{Z}_{TLV} = R_{TLV} + jX_{TLV}$

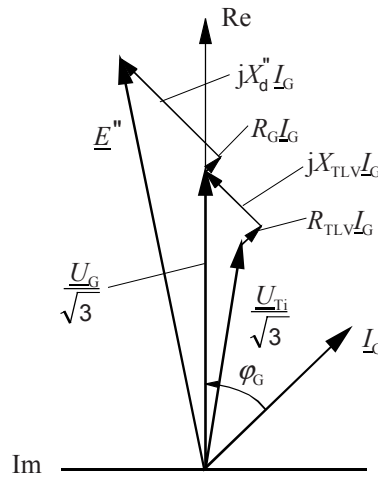


Figure 6b – Phasor diagram for overexcited operation with  $U_G$ ,  $I_G$ ,  $\varphi_G$

### Figure 6 – Simulation of a power-station unit with on-load tap-changer

Without knowing the load flow in the network, neither the voltage  $U_Q$  nor the transformation ratio  $t = U_Q / U_{Ti}$  of the unit transformer ( $t \neq t_r = U_{rTHV} / U_{rTLV}$ ) can be known.

The internal voltage  $\underline{E}''$  of the generator is found from figure 6b, depending on  $\underline{U}_G / \sqrt{3} = U_G / \sqrt{3}$  and  $\underline{I}_G = I_G (\cos \varphi_G - j \sin \varphi_G)$  before the short circuit at the high-voltage side of the unit transformer (figure 5):

$$\underline{E}'' = \frac{\underline{U}_G}{\sqrt{3}} + \underline{I}_G \underline{Z}_G = \frac{\underline{U}_G}{\sqrt{3}} \left[ 1 + \frac{\sqrt{3} I_G}{U_G} (R_G \cos \varphi_G + X_d'' \sin \varphi_G) + j \frac{\sqrt{3} I_G}{U_G} (X_d'' \cos \varphi_G - R_G \sin \varphi_G) \right] \quad (26)$$

The transformation ratio can be substituted by  $t = \underline{U}_Q / \underline{U}_{Ti}$  with  $\underline{U}_{Ti} / \sqrt{3}$  found from the phasor diagram in figure 6b.

$$\begin{aligned} \frac{\underline{U}_{Ti}}{\sqrt{3}} &= \frac{\underline{U}_G}{\sqrt{3}} - \underline{I}_G \underline{Z}_{TLV} \\ &= \frac{\underline{U}_G}{\sqrt{3}} \left[ 1 - \frac{\sqrt{3} I_G}{U_G} (R_{TLV} \cos \varphi_G + X_{TLV} \sin \varphi_G) - j \frac{\sqrt{3} I_G}{U_G} (X_{TLV} \cos \varphi_G - R_{TLV} \sin \varphi_G) \right] \quad (27) \end{aligned}$$

Introducing  $\underline{E}''$  from equation (26),  $\underline{U}_{Ti} / \sqrt{3}$  from equation (27) and the equivalent voltage source  $cU_{nQ} / \sqrt{3}$  at the short-circuit location F (equal to the connection point Q in figure 5), the following equation can be found:

$$\underline{I}_{kS(S)}'' = \frac{cU_{nQ}}{\sqrt{3}(t_r^2 \underline{Z}_G + \underline{Z}_{THV})\underline{K}_S} \quad (28)$$

with  $t_r = U_{rTHV} / U_{rTLV}$

$$\underline{Z}_G = R_G + jX_d''$$

$$\underline{Z}_{THV} = t_r^2 \underline{Z}_{TLV}$$

(without impedance correction factor  $K_T$ ) and

$$\underline{K}_S = \frac{U_{nQ}U_Q}{U_G^2} \cdot \frac{U_{rTLV}^2}{U_{rTHV}^2} \cdot \frac{c}{1 + \frac{\sqrt{3}I_G}{U_G}(R_G \cos \varphi_G + X_d'' \sin \varphi_G) + j \frac{\sqrt{3}I_G}{U_G}(X_d'' \cos \varphi_G - R_G \sin \varphi_G)} \cdot \frac{1}{1 - \frac{\sqrt{3}I_G}{U_G}(R_{TLV} \cos \varphi_G + X_{TLV} \sin \varphi_G) - j \frac{\sqrt{3}I_G}{U_G}(X_{TLV} \cos \varphi_G - R_{TLV} \sin \varphi_G)} \quad (29)$$

It can be assumed that  $R_G \ll X_d''$  and  $R_{TLV} \ll X_{TLV}$ . Equation (29) then leads to the following approximation if  $U_G = U_{rG}$  is valid:

$$K_S \approx \frac{U_{nQ}U_Q}{U_{rG}^2} \cdot \frac{U_{rTLV}^2}{U_{rTHV}^2} \cdot \frac{c_{\max}}{\sqrt{1 + 2x_d'' \left( \frac{I_G}{I_{rG}} \right) \sin \varphi_G + x_d''^2 \left( \frac{I_G}{I_{rG}} \right)^2}} \cdot \frac{1}{\sqrt{1 - 2x_T \left( \frac{I_G}{I_{rG}} \right) \sin \varphi_G + x_T^2 \left( \frac{I_G}{I_{rG}} \right)^2}} \quad (30)$$

with  $x_d'' = X_d'' / Z_{rG}$

$x_T = X_T / Z_{rT}$  and

$Z_{rG} = Z_{rT} = U_{rG}^2 / S_{rG}$  at  $U_{rG} = U_{rTLV}$  and  $S_{rG} = S_{rT}$ .

The investigations for a large number of power-station units with on-load tap-changer have shown that, similar to the case of generators directly connected to the network, the short-circuit current  $I_{kS(S)}''$  reaches its maximum in many cases if the power-station unit is operated at its rated point before the short circuit [7], [11], [16], [17]. Details are given in [22]. 24 power-station units out of the 47 under consideration with  $S_{rG} = 32 \text{ MVA} \dots 1\,640 \text{ MVA}$  have their maximum partial short-circuit currents if they are operated at their rated point  $\underline{S}_{rG}$  before the short circuit. Further 16 power-station units if they are operated at  $Q > Q_{rG}$  in the over-excited region. Only in the remaining seven cases the maximum short-circuit current is to be expected after underexcited operation. In six of these seven cases,  $x_T > x_d''$  is valid ( $S_{rG} = 32 \text{ MVA} \dots 147 \text{ MVA}$ ).

Figure 7 gives one example from these investigations with maximum short-circuit current from the generator after operation at rated conditions before the short circuit. The maximum short-circuit current  $I_{kS(S)}''$  is reached for the lowest value  $U_Q$  at the high-voltage side of the unit transformer with on-load tap-changer. It was assumed that it is sufficient to take  $U_{nQ}$  as the lowest value during normal operation.

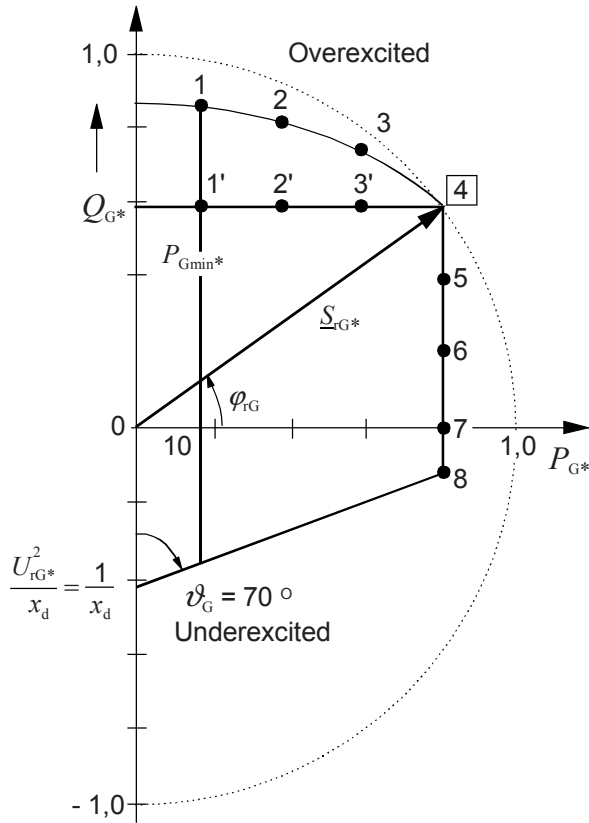


Figure 7a – Power chart of a turbine generator with limits for over- and underexcited operation

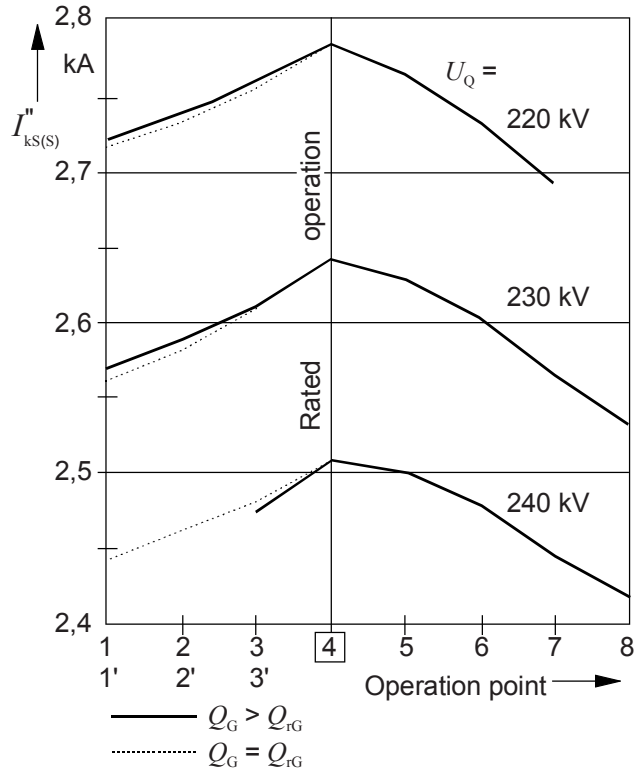


Figure 7b – Partial short-circuit currents found with the superposition method (S) from equation (28) together with  $K_s$  from equation (30)

Example:

$S_{rG} = S_{rT} = 395 \text{ MVA}$

$U_{rG} = 21 \text{ kV}$

$\cos \varphi_{rG} = 0,8$

$x_d' = 0,25$

$x_d = 2,38$

$P_{G \min} = 0,2 P_{rG}$

$U_{rTHV} = 245 \text{ kV}$

$U_{rTLV} = 21 \text{ kV}$

$t = U_{rTHV} (1 \pm 0,112) / U_{rTLV}$

$u_{kr} = 15 \% ; u_{k+} = 15,8 \% ; u_{k-} = 14,5 \% ; U_{nQ} = 220 \text{ kV}$

Figure 7 – Partial short-circuit current of a power station unit found with the superposition method

A further simplification of equation (30) leads to

$$K_S = \frac{U_{nQ}^2}{U_{rG}^2} \cdot \frac{U_{rTLV}^2}{U_{rTHV}^2} \cdot \frac{c_{\max}}{1 + |x_d'' - x_T| \sin \varphi_{rG}} \quad (31)$$

because  $U_Q = U_{nQ}$  can be presumed to give the highest partial short-circuit current  $I''_{ks(S)}$  (see figure 7 and other examples given in [7], [11], [16], [17] and [22]).

Because the pre-short-circuit voltage  $U_Q$  and the actual position of the on-load tap-changer are not known, IEC 60909-0 proposes the use of the following equation for the calculation of the partial short-circuit current:

$$I''_{ks} = \frac{c U_{nQ}}{\sqrt{3} (t_r^2 Z_G + Z_{THV}) K_S} \quad (32)$$

with  $K_S$  from equation (31) and  $\underline{Z}_{THV}$  in equation (32) as the impedance of the unit transformer, calculated from  $u_{kr}$ , see IEC 60909-0, 3.3.1. Only if the minimum operating voltage  $U_{Q\min} > U_{nQ}$  at the high-voltage side of the unit transformer is well known from long-term operating experience, then the use of the product  $U_{nQ}U_{Q\min}$  instead of  $U_{nQ}^2$  in equation (31) is allowed, see IEC 60909-0, 3.7.1.

It is assumed that the operating voltage at the terminals of the generator is equal to  $U_{rG}$ . If the voltage  $U_G$  is permanently higher than  $U_{rG}$ , then  $U_{G\max} = U_{rG}(1 + p_G)$  should be introduced instead of  $U_{rG}$ , with, for instance,  $p_G = 0,05$  [17].

In order to demonstrate the efficiency of the derived impedance correction factor  $K_S$  in equation (31), figure 8 gives the cumulative frequency  $H$  of the deviations  $\Delta_S$ , found with the simplified calculations in accordance to IEC 60909-0 in comparison to the values found with the superposition method, for 47 power-station units with on-load tap-changer of the unit transformer [22] and [23].

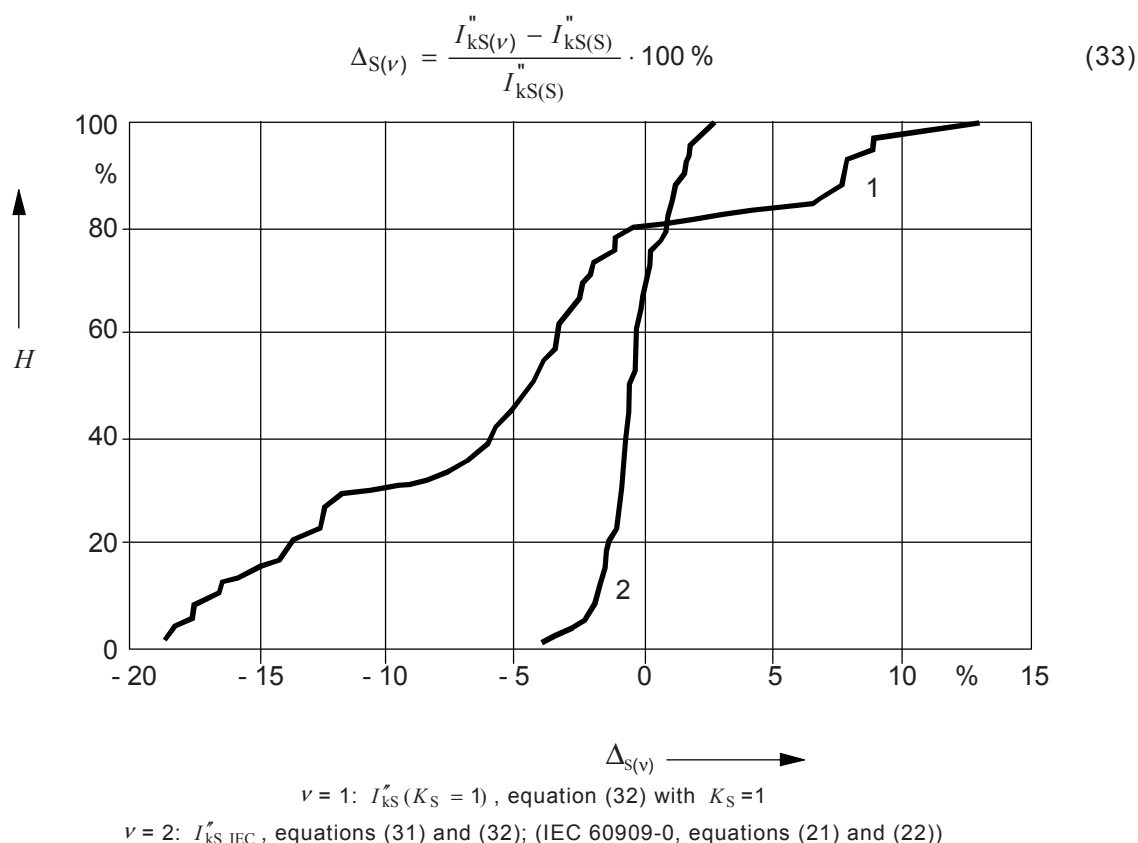


**Figure 8 – Cumulative frequency  $H$  of the deviations calculated with equation (33) [22] and [23]**

Curve 1 of figure 8 demonstrates the necessity for the introduction of an impedance correction factor for the impedance of power-station units together with the equivalent voltage source, because otherwise approximately 50 % of the cases would lead to results on the non-conservative (unsafe) side (deviations more than  $-5\%$ ).

The simplified impedance correction factor in equation (31) leads to a sufficient approximation for the maximum partial short-circuit current  $I''_{kS,IEC}$  (curve 2 in figure 8). All the results are within the region  $\Delta_S = \pm 5\%$ . Safety and economical aspects are sufficiently met, if  $K_S$  is used.