

Short-circuit current calculation in three-phase a.c. systems

**Part 1. Factors for the calculation of
short-circuit currents in three-phase a.c.
systems according to BS 7639**

Committees responsible for this Published Document

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National foreword

This Part of PD 7639 has been prepared under the direction of the Power Electrical Engineering Standards Policy Committee. It is identical with IEC 909-1 : 1991 *Short-circuit current calculation in three-phase a.c. systems Part 1: Factors for the calculation of short-circuit currents in three-phase a.c. systems according to IEC 909*, published by the International Electrotechnical Commission (IEC). The IEC document has been published as a type 2 Technical Report. It is not to be regarded as an international standard. A review of the Technical Report will be carried out by the IEC not later than 3 years after its publication with the options of extension for a further period of 3 years, conversion to an international standard or withdrawal.

Cross-references

International standard	Corresponding British Standard
IEC 50	BS 4727 <i>Glossary of electrotechnical, power, telecommunication, electronics, lighting and colour terms</i>
IEC 781 : 1989	BS 7638 : 1993 <i>Application guide for calculation of short-circuit currents in low-voltage radial systems</i> (Identical)
IEC 909 : 1988	BS 7639 : 1993 <i>Short-circuit current calculation in three-phase a.c. systems</i> (Technically equivalent)

Compliance with a British Standard does not of itself confer immunity from legal obligations.

SHORT-CIRCUIT CURRENT CALCULATION IN THREE-PHASE A.C. SYSTEMS

Part 1: Factors for the calculation of short-circuit currents in three-phase a.c. systems according to IEC 909

Section 1: General

1.1 Scope and object

This IEC Technical Report aims to show 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 909.

Thus this technical report is an addition to IEC 909. It does not, however, change the basis for standardized calculation procedure given in that publication.

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

1.2 Normative references

The following standards contain provisions which, through reference in this text, constitute provisions of this part of IEC 909. At the time of publication, the editions indicated were valid. All standards are subject to revision, and parties to agreement based on this part of IEC 909 are encouraged to investigate the possibility of applying the most recent editions of the standards indicated below. Members of IEC and ISO maintain registers of currently valid International Standards.

IEC 38: 1983, *IEC standard voltages*.

IEC 865: 1986, *Calculation of the effects of short-circuit currents*.

IEC 909: 1988, *Short-circuit current calculation in three-phase a.c. systems*.

1.3 Application of the factors

1.3.1 Factors c

The 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. (clause 2.1)

1.3.2 Factors K

The impedance correction factors K_G and K_{PSU} are introduced when calculating the short-circuit impedances of generators and power-station units (clause 2.2).

1.3.3 Factor κ

The peak short-circuit current is calculated by using this factor (clause 2.3).

1.3.4 Factors μ , λ and q

Factors used when calculating the decay of the a.c. component of the short-circuit current of a near-to generator short-circuit (clauses 2.4, 2.5 and 2.6).

1.3.5 Contribution of asynchronous motors to the initial short-circuit current

Derivation and validity of relevant equations for checking the contribution of asynchronous motors or groups of asynchronous motors to the short-circuit current (clause 2.7).

1.4 Symbols, subscripts and superscripts

The following symbols, subscripts and superscripts are used in addition to those already defined in IEC 909.

1.4.1 Symbols

E	Voltage behind synchronous direct axis reactance of a synchronous machine, see figure 16
E	Error
E'	Voltage behind transient direct axis reactance of a synchronous machine, see figure 16
E''_Q	Subtransient voltage behind impedance of a network feeder connected at Q
$E_0(I_f)$	Terminal voltage of a saturated synchronous machine at no-load ($I_G = 0$) as a function of I_f
I^b	Branch current (load current) before the short circuit
I_f	Field current of a synchronous machine
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 constant T''_{dN} and T''_{qN}

$T_{\mu q}$	Time constant calculated with the product $\mu \cdot q$ (2.6.2)
t_p	Time from the beginning of a short circuit until the peak short-circuit current i_p
U^b	Voltage at the short-circuit location before the short circuit
X_p	Potier reactance
Y	Admittance
γ	Impedance angle
Δ	Deviation
φ_U	Voltage angle

1.4.2 *Subscripts*

0	No load (T''_{d0})
A.C.	Alternating current
ad	Admissible
D.C.	Direct current
d	Direct axis (see q)
IEC	According to IEC 909, for example $K_{PSU(IEC)}$
i	Internal
L	Load
N	Network
q	Quadrature axis (see d)
S	Superposition method ($\mathcal{S}$)
t_r	Constant transformation ratio ($t = t_r = \text{const}$; e.g. $K_{PSU(t_r)}$)
t	Transformation ratio ($t \neq t_r$).

1.4.3 *Superscripts*

b	Before
'	Transient

Section 2: Factors used in IEC 909

2.1 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 currents) 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 state of the network before the short circuit occurs.

The variations during operation in a three-phase a.c. system are very large. Therefore it is difficult to find the special load flow condition that leads either to a maximum or to a minimum short-circuit current at the different locations of the system. 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 909 therefore recommends a calculation method with the equivalent voltage source $cU_n/\sqrt{3}$ at the short-circuit location. This method, described in clause 6 of IEC 909, is an approximation method without special conditions of operation. The aim of this method 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 factor $c = c_{\max}$ or $c = c_{\min}$ for the calculation of the maximum or the minimum short-circuit currents. These factors are given in table I of IEC 909. The introduction of the factor c is necessary for various reasons (IEC 909, 3.16):

- voltage variation depending on time and place;
- changing of transformer taps;
- omitting loads and capacitances by calculations according to clause 6 of IEC 909, (2.1.3);
- the subtransient behaviour of generators, power-station units (clause 2.2) and motors.

The meaning of the factor c is illustrated for a simple model of a radial network in 2.1.4. Furthermore results of extended calculations given in 2.2.6 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 909, figures 1 and 2):

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

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.

The superposition method gives the short-circuit current only related to the one load flow presupposed. Therefore this method 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 [8]. Further information is given in 2.2.6.

2.1.3 *Equivalent voltage source at the short-circuit location and 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 clause 6 of IEC 909. This method, which is normally based only on the rated data of the electrical equipment, is an essential simplification compared to the superposition method.

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 909, 11.5.3). All the shunt capacitances and the shunt admittances (loads), except those of the motors, are to be omitted in the positive and negative-sequence system (IEC 909, 8.3.2.5, 11.5.3.5 and clause 13). 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 grounded networks (IEC 909, 8.3.1 and 11.4). An example for the application of the calculation using the equivalent voltage source at the short-circuit location F is given in figure 3 of IEC 909.

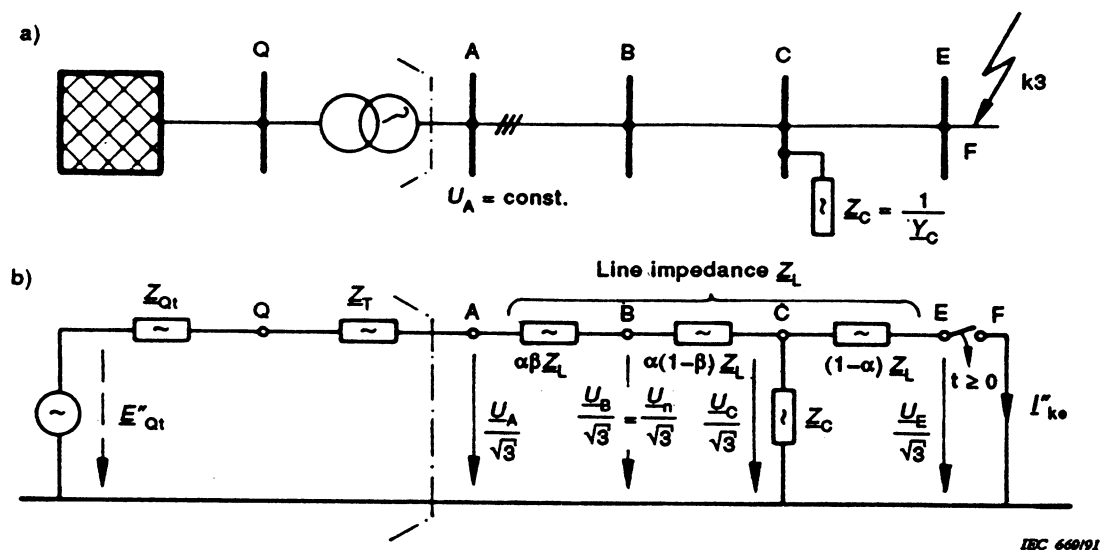
The factor $c_{\max}$ or $c_{\min}$ is introduced according to table I of IEC 909. Corresponding to $c_{\max}$ or $c_{\min}$, the maximum or the minimum short-circuit current $I''_{kQ\max}$ or $I''_{kQ\min}$, must be introduced for the network feeders (IEC 909, clause 2 and subclause 12.2.3.1). Special conditions are to be considered when calculating $I''_{k\min}$ (IEC 909, 9.3). The introduction of the factor c aims to find 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 909, 11.5.3.6, 11.5.3.7 and 11.5.3.8) realistic values for the partial short-circuit currents are also obtained, even though compromises are necessary to a certain extent, see 2.2.6.

The following subclause 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 voltage drops Δu and the maximum possible deviations $\Delta i''_k$, see equation (13).

2.1.4 A simple model illustrating the meaning of factor c

The following simple model in figure 1 illustrates the fundamental meaning of the 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 drops Δu and the factor c are given in [9,14]. Further comments on the relation between the impedance correction factors of generators and power-station units and the factor c in meshed networks are described in 2.2.6.

The positive-sequence system of the model network of figure 1a) is given in figure 1b). It is presumed that the voltage U_A at the beginning of the line is constant. The consumer load is concentrated and simulated through the shunt impedance Z_C at the variable location C between the line impedances αZ_L and $(1-\alpha)Z_L$ with $0 \leq \alpha \leq 1$.



- a) Three phase a.c. model (radial non-meshed network)
- b) Equivalent circuit diagram, positive sequence system, before and after the short circuit at F

Figure 1 - Model for the calculation of the coherence between the voltage drop Δu and the short-circuit current deviation $\Delta i''_k$

It is assumed that at the variable location B ($0 \leq \beta \leq 1$) the voltage U_B is equal to the nominal system voltage U_n .

The following relations shall be used:

$$\left. \begin{aligned} \Delta u_A &= \left| \frac{U_A}{U_B} \right| - 1 \\ \Delta u_E &= \left| \frac{U_E}{U_B} \right| - 1 \end{aligned} \right\} \Rightarrow \Delta u = \text{Max} \{ \Delta u_A, \Delta u_E \} \quad (1a)$$

$$(1b)$$

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

where

a is the index for the approximation of the short-circuit current;

e is the index for the exact value of the short-circuit current.

The following equations can be derived giving the voltage condition before the short circuit, taking $U_A/\sqrt{3}$ as a constant value:

$$U_A = U_B \frac{\alpha Z_L + Z_C}{\alpha (1 - \beta) Z_L + Z_C} \quad (3)$$

$$U_C = U_B \frac{Z_C}{\alpha (1 - \beta) Z_L + Z_C} \quad (4)$$

With $U_E/\sqrt{3} = U_C/\sqrt{3}$ before the short-circuit ($t < 0$) and $U_B/\sqrt{3} = U_n/\sqrt{3}$, the relative voltage drops of equation (1) can be expressed as follows:

$$\Delta u_A = \left| \frac{U_A}{U_B} \right| - 1 = \left| \frac{1 + \alpha Z_L Y_C}{1 + \alpha (1 - \beta) Z_L Y_C} \right| - 1 \quad (5)$$

$$\Delta u_E = \left| \frac{U_E}{U_B} \right| - 1 = \left| \frac{1}{1 + \alpha (1 - \beta) Z_L Y_C} \right| - 1 \quad (6)$$

The exact value of the initial symmetrical short-circuit current is calculated as follows:

$$I_{ke}'' = I_A \frac{Z_C}{(1 - \alpha) Z_L + Z_C} \quad (7)$$

$$\text{with } I_A = \frac{U_A}{\sqrt{3}} \frac{1}{\alpha Z_L + \frac{(1 - \alpha) Z_L Z_C}{(1 - \alpha) Z_L + Z_C}} \quad (8)$$

Introducing I_A from equation (8) to equation (7) and using $Z_C=1/Y_C$:

$$I''_{ke} = \frac{U_A}{\sqrt{3} Z_L} \cdot \frac{1}{1 + \alpha (1 - \alpha) Z_L Y_C} \quad (9)$$

The approximation I''_{ka} with $Z_C = \infty$ (or $Y_C = 0$) and $U_n = U_B$ is found as follows from figure 1b) using equation (3), but without factor c :

$$I''_{ka} = \frac{U_B}{\sqrt{3} Z_L} = \frac{U_A}{\sqrt{3} Z_L} \cdot \frac{1 + \alpha (1 - \beta) Z_L Y_C}{1 + \alpha Z_L Y_C} \quad (10)$$

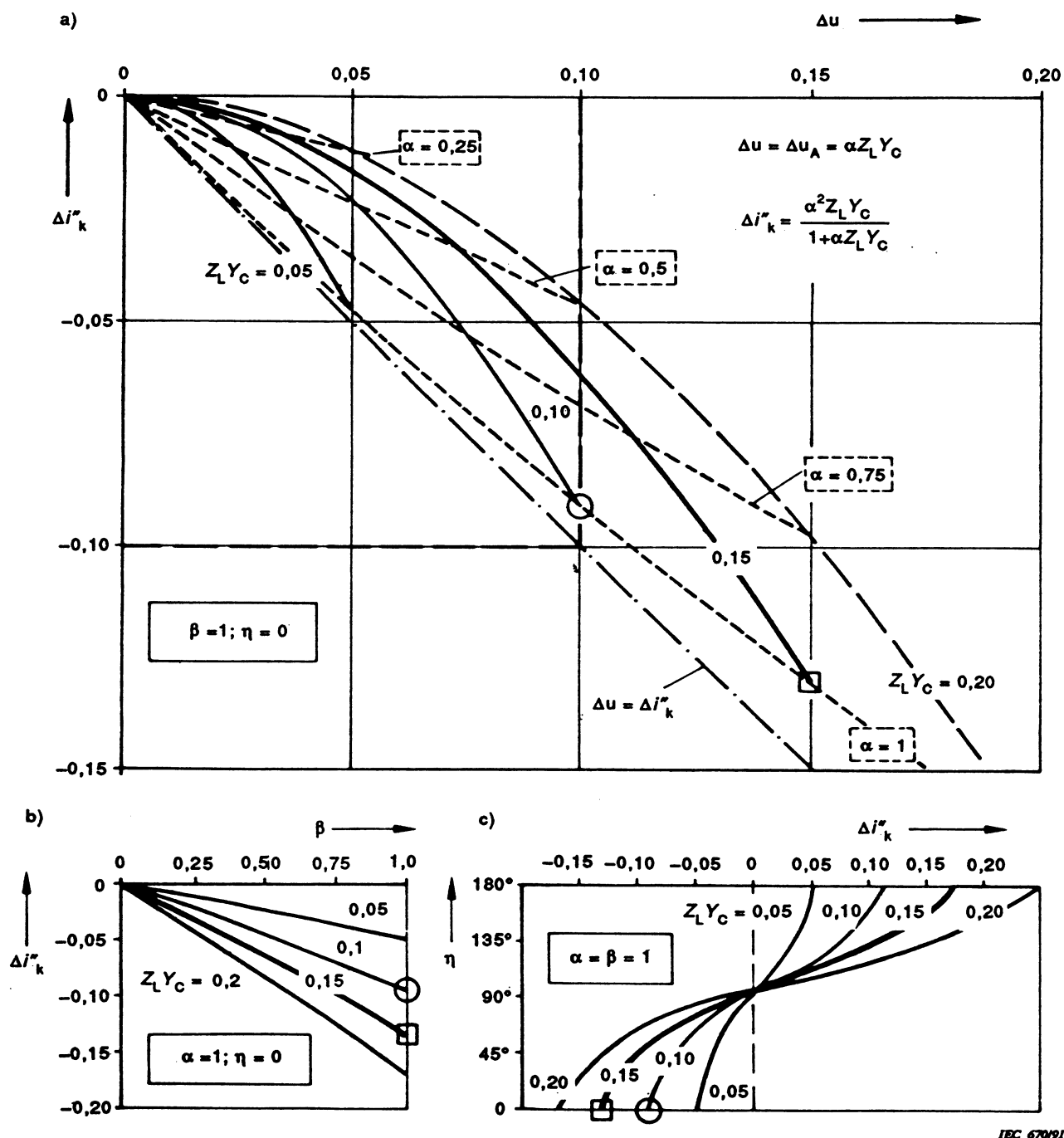
and therefore:

$$\Delta i''_k = \left| \frac{I''_{ka}}{I''_{ke}} \right| - 1 = \left| \frac{[1 + \alpha(1 - \beta) Z_L Y_C] [1 + \alpha(1 - \alpha) Z_L Y_C]}{1 + \alpha Z_L Y_C} \right| - 1 \quad (11)$$

The product $Z_L Y_C$ can be written as:

$$Z_L Y_C = Z_L e^{j\gamma} Y_C e^{-j\varphi} = Z_L Y_C e^{j(\gamma - \varphi)} = Z_L Y_C e^{j\eta} \quad (12)$$

$$\text{with } Z_L = R_L + j X_L = Z_L e^{j\gamma} \quad \text{and} \quad Y_C = G - jB = Y_C e^{-j\varphi}$$



a) $\Delta i''_k = f(\Delta u, \alpha)$ with $\Delta u = \Delta u_A$ and $\beta = 1, \eta = 0$

b) $\Delta i''_k = f(\beta, Z_L Y_C)$ with $\alpha = 1, \eta = 0$

c) $\Delta i''_k = f(\eta, Z_L Y_C)$ with $\alpha = \beta = 1$

Figure 2 - Calculation of $\Delta i''_k$ according to equation (11) for different parameters

The following results can be derived from figure 2:

- The largest negative deviations $\Delta i_k''$ from equation (11) occur in the case $\alpha = \beta = 1$ and $\eta = 0$. The consumer load $Z_C = 1/Y_C$ is at the end of the line ($\alpha = 1$). The voltage at the consumer load is equal to U_n ($\beta = 1$; $\Delta u_E = 0$). The angle of the complex product $Z_L Y_C$ is equal to zero ($\eta = 0$), i.e. the consumer is inductive.
- The absolute values of the negative deviations $\Delta i_k''$ are smaller than the relative voltage drops $\Delta u = \Delta u_A$:

$$|\Delta i_k''| < \Delta u \quad (13)$$

- The following equation can be established for the largest possible negative deviations $\Delta i_{kmax}''$ at $\alpha = 1$ (see figure 2), depending on the admissible voltage drop $\Delta u_{ad} = \Delta u_A$ (see equation (5)):

$$\Delta i_{kmax}'' = \frac{1}{1 + \Delta u_{ad}} - 1 \quad (14)$$

The broken line ($\alpha = 1$) in figure 2a) corresponds to this equation.

Furthermore, the following relation between Δu_{ad} and the product $Z_L Y_C$ ($\eta = 0$) can be derived from figure 2a):

$$Z_L Y_C \leq \Delta u_{ad} \quad (15)$$

Equation (14) is valid for positive values Δu as well as for negative values, consequently the following conditions are found:

$$\Delta u_{ad} = \pm 5 \% : -0,048 \leq \Delta i_{kmax}'' \leq 0,053$$

$$\Delta u_{ad} = \pm 10 \% : -0,091 \leq \Delta i_{kmax}'' \leq 0,111$$

$$\Delta u_{ad} = \pm 15 \% : -0,130 \leq \Delta i_{kmax}'' \leq 0,176$$

It can be shown [9] 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 909, clause 6 and table I) takes into account these results ($c_{max} = 1,1$ for medium and high-voltage networks and $c_{max} = 1,05$ for low-voltage networks), considering that the highest voltage in a normal system does not differ, on average, by more than +5 % (LV) or +10 % (HV) approximately from the nominal voltage U_n (IEC 38, table III note 2). In a normal system of Series I (50 Hz or 60 Hz systems), the highest voltage and the lowest voltage do not differ by more than approximately ± 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.)

Special conditions may occur in the case of generators and power-station units with high values of x''_d and u_k which lead to voltage drops greater than 10 %. Therefore impedance correction factors (see clause 2.2) are given for the calculation of the short-circuit impedances of this electrical equipment (IEC 909, 11.5.3.6, 11.5.3.7 and 11.5.3.8).

The relative voltage drop of network transformers is normally smaller than 10 %, even if the short-circuit voltage u_{kr} reaches values up to 20 %. Therefore it is in general sufficient also for transformers with tap-changer to determine the short-circuit impedance Z_T for the main position (IEC 909, 8.3.2.2, note).

2.2 Impedance correction factors K (K_G , K_{PSU}) when calculating the short-circuit impedances of generators 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 the maximum partial short-circuit current, too. It is necessary to introduce impedance-correction factors K_G (2.2.2) for generators and K_{PSU} (2.2.3) for power-station units in addition to the factor c_{max} , especially if the subtransient reactances x''_d of generators are high and the transformation ratio of the unit transformers (with or without a tap changer) is different from the ratio of the system voltages during operation on both sides of the transformer. The correction factors K_G and K_{PSU} are given in IEC 909, 11.5.3.6 and 11.5.3.8. In the case of K_{PSU} an additional note is given which draws attention to the special conditions applying (2.2.3).

Special considerations and impedance-correction factors are necessary for the calculation of the short-circuit current and the partial short-circuit current in the case of a short circuit between generator and transformer of a power station unit. Normally these calculations are made only once during the construction of the power station.

The impedance correction factors given in 11.5.3.6 and 11.5.3.8 of IEC 909 are derived for the maximum partial short-circuit currents ($c = c_{max}$). The factors c_{max} should be taken from table I of IEC 909 in accordance with the voltages U_{rG} when using equation (22), in accordance with the voltage U_{nQ} at the high-voltage side of the unit transformer when using the equations (32) and (36). Additional calculations in meshed networks have shown that these correction factors are also adequate when calculating short-circuit currents at different locations (2.2.6).

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 or within the underexcited

region is usually minimised. Therefore a rough estimation for minimum short-circuit currents may be found using the instructions given in 9.3 and 12.4 of IEC 909 and using the given impedance-correction factors for generators and power-station units, even though these are found from calculations for the case of rated operation.

2.2.2 Correction factor K_G

The impedance correction factor K_G is used for the impedance $Z_G = R_G + jX_d''$ of a generator directly connected to a low or a medium-voltage network (without unit transformer) as shown in figure 3 (IEC 909, 11.5.3.6 and 12.4).

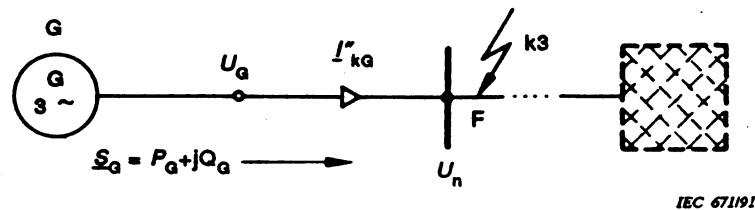
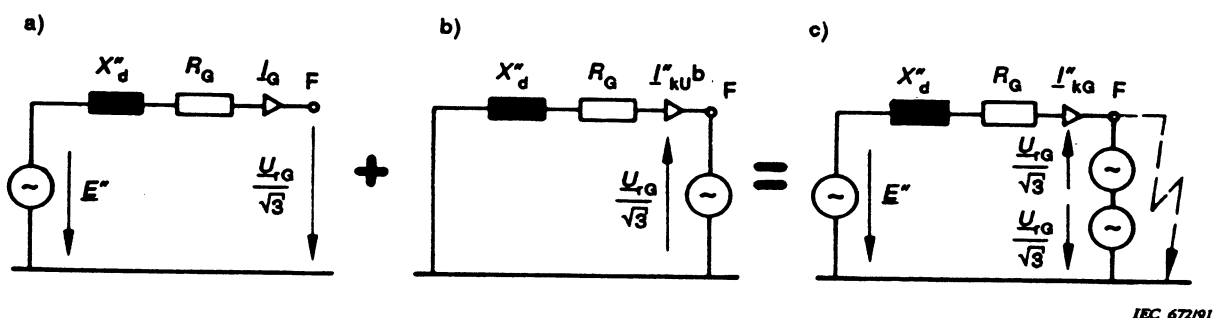


Figure 3 - Partial short-circuit current I''_{kG} of a generator directly connected to a network

The impedance correction factor K_G is derived from a phasor diagram for normal over-excited 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 turbine 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} using the superposition method.



- Normal operation conditions with controlled voltage $U_G = U_{rG}$
- Introducing the pre short-circuit voltage $U_{rG}/\sqrt{3}$ in the opposite direction at the short-circuit location
- Superposition of the circuit in the figures a) and b) to determine $I''_{kG} = I_G + I''_{kUb}$

Figure 4 - Calculation of I''_{kG} using the superposition method

The currents I_G and I''_{kUb} are derived from figures 4a) and 4b) at $U_G = U_{rG}$ as follows:

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

$$I''_{kUb} = \frac{U_{rG}/\sqrt{3}}{R_G + jX''_d} \quad (17)$$

The index U^b indicates that the current I''_{kUb} is found when introducing the voltage $U_{rG}/\sqrt{3}$ before the short circuit in the opposite direction.

The superposition according to figure 4c) leads to the partial short-circuit current I''_{kG} :

$$I''_{kG} = I_G + I''_{kUb} = \frac{E'' - U_{rG}/\sqrt{3}}{R_G + jX''_d} + \frac{U_{rG}/\sqrt{3}}{R_G + jX''_d} = \frac{E''}{R_G + jX''_d} \quad (18)$$

On the other hand, when applying the method using 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 $E'' = U_{rG}/\sqrt{3} + I_G Z_G = U_{rG}/\sqrt{3} + I_G (\cos \varphi_G - j \sin \varphi_G) \cdot (R_G + jX''_d)$, 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 p.u. value of the subtransient reactance is introduced with $x''_d = X''_d / Z_{rG}$ and $Z_{rG} = U_{rG}^2 / S_{rG}$ (IEC 909, 3.22, note).

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 $c = c_{\max}$ (IEC 909, table I) the approximation of equation (21) then assumes the following form (IEC 909, equation (36)):

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

Example: $S_{rG} = 10$ MVA; $U_{rG} = 10,5$ kV; $\cos \varphi_{rG} = 0,8$; $x''_d = 0,12$

The generator feeds a system with the nominal voltage $U_n = 10$ kV (see figure 3).

The calculation of the maximum partial short-circuit current according to equation (19) with K_G found from equation (22) and $c = c_{\max} = 1,1$ (IEC 909, table I) leads to $I''_{kG} = 4,900$ kA.

The value calculated with the superposition method is $I''_{kG(S)} = (0,759 - j 4,889)$ kA; $I''_{kG(S)} = 4,948$ kA. The approximation for 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 I''_{kG} is found, when the voltage U_G reaches the upper limit $U_G = U_{rG}(1 + p_G)$.

2.2.3 Correction factor K_{PSU}

The determination of the impedance correction factor K_{PSU} (IEC 909, 11.5.3.8) for power-station units according to figure 5 requires special considerations where:

- The unit transformer, depending on national conditions or network configurations, is equipped either with a tap changer or with a correspondingly higher transformation ratio $t_r = U_{rTHV}/U_{rTLV} > U_{nQ}/U_{rG}$. In some cases even a combination of these two measures is used in order to deliver active and reactive power of the power-station unit via a long transmission line to the network.
- The rated voltages of the generator and the low-voltage side of the unit transformer may be different ($U_{rG} \neq U_{rTLV}$) and the rated apparent powers of generator and transformer may also differ ($S_{rG} \neq S_{rT}$).

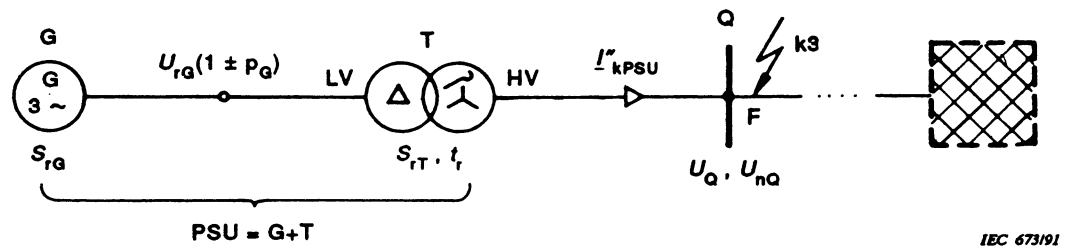
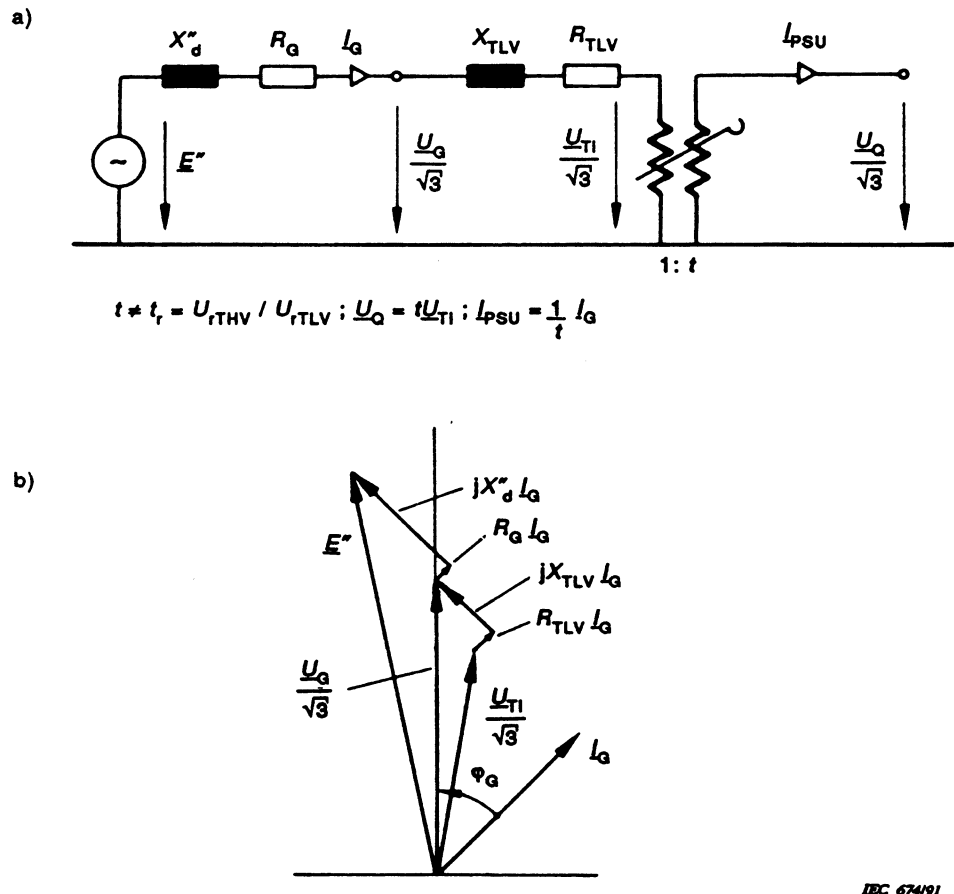


Figure 5 - Partial symmetrical short-circuit current I''_{kPSU} at the high voltage side of the unit transformer of a power-station unit (PSU)

Based on the simulation of a power station unit, as shown in figure 6, the correction factor K_{PSU} will first be derived for the case of a tap changer in the unit transformer. Special consideration is given in 2.2.5 to the case where the unit transformer has no on-load tap changer.



- a) Equivalent circuit diagram with E'' , $Z_G = R_G + jX''_d$ and $Z_{TLV} = R_{TLV} + jX_{TLV}$ in the positive sequence system
 b) Phasor diagram for overexcited operation

Figure 6 - Simulation of a power station unit (PSU)

Using the superposition method (similar to figure 4), both the current I_{PSU} (figure 6) and $I''_{\text{kPSU,U}^b}$ can be found. $I''_{\text{kPSU,U}^b}$ is found by the introduction of $\underline{U}_Q/\sqrt{3}$ in the opposite direction at the short-circuit location and $\underline{E}'' = 0$.

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

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

with $t = \underline{U}_Q/\underline{U}_{\text{Ti}} = U_Q/U_{\text{Ti}}$.

The partial short-circuit current I''_{kPSU} at the high voltage side of the unit transformer is found as follows:

$$I''_{\text{kPSU}} = I_{\text{PSU}} + I''_{\text{kPSU,U}^b} = \frac{1}{t} \cdot \frac{\underline{E}''}{\underline{Z}_G + \underline{Z}_{\text{TLV}}} = \frac{1}{t} \cdot \frac{t_r^2 \underline{E}''}{t_r^2 \underline{Z}_G + \underline{Z}_T} \quad (25)$$

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

Without knowing the load flow in the network, neither the voltage U_Q nor the transformation ratio $t = U_Q/U_{\text{Ti}}$ of the unit transformer with tap changer ($t \neq t_r = U_{\text{rTHV}}/U_{\text{rTLV}}$) can be known. The internal voltage $\underline{E}''$ is found from figure 6b) depending on U_G ($\underline{U}_G/\sqrt{3} = U_G/\sqrt{3}$) and the current $I_G = I_G(\cos \varphi_G - j \sin \varphi_G)$ before the short circuit:

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

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

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

Introducing $\underline{E''}$ from equation (26) and using $\underline{U}_{Ti}/\sqrt{3}$ from equation (27) and the equivalent voltage source $cU_n/\sqrt{3} = cU_{nQ}/\sqrt{3}$ at the short-circuit location F, the following equation can be found:

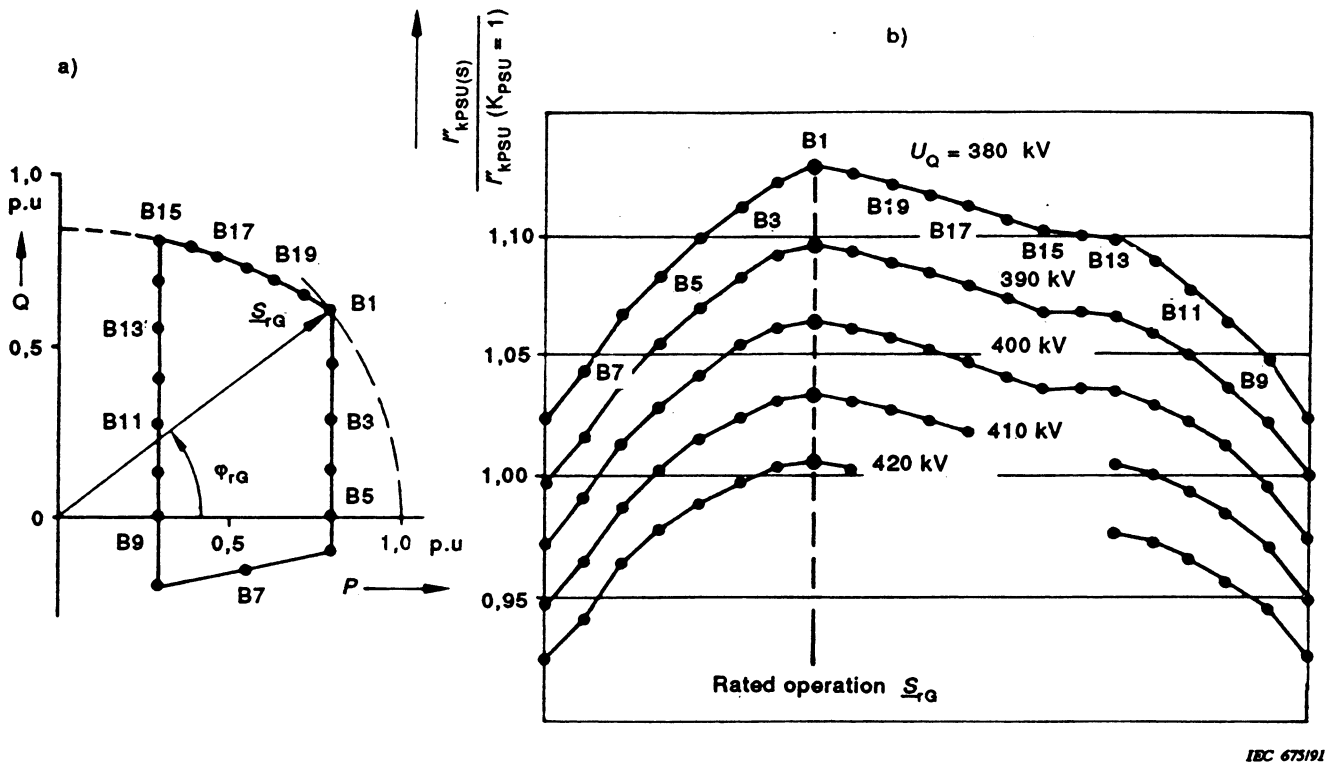
$$I''_{kPSU} = \frac{cU_{nQ}}{\sqrt{3} (\epsilon_r^2 Z_G + Z_T) K_{PSU}} \quad (28)$$

with $\epsilon_r = U_{rTHV}/U_{rTLV}$, $Z_T = Z_{THV} = \epsilon_r^2 Z_{TLV}$ and

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

For a large number of power-station units, investigations of the correction factor K_{PSU} , which depends on U_Q , I_G and $\cos \varphi_G$, have shown that similar to the case of generators directly connected to the network, the factor K_{PSU} reaches its minimum and therefore I''_{kPSU} its maximum if the power-station unit is operated at its rated point ($I_G = I_{rG}$; $\cos \varphi_G = \cos \varphi_{rG}$ and correspondingly $S_G = S_{rG}$) [6,10,14]*. Figure 7 gives an example from these investigations. The maximum short-circuit current is reached for the lowest value U_Q at the high voltage side of the unit transformer with tap changer when the voltage $U_G = U_{rG}$ is constant.

* Numbers in brackets refer to annex A: Bibliography.



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- a) Power chart of the turbine generator with limits of over and underexcited operation;
 $P_{Gmin} = 0,4 P_{rG}$
- b) The relation of $I''_{kPSU(S)}$, according to equation (28) found with the superposition method (S), to the first approximation with $K_{PSU} = 1$

$$I''_{kPSU} (K_{PSU} = 1) = \frac{c U_{nQ}}{\sqrt{3} |r_r^2 Z_G + Z_T|}$$

therefore $I''_{kPSU(S)} / I''_{kPSU} (K_{PSU} = 1) = 1 / K_{PSU}$ (29)

Figure 7 - Partial short-circuit currents of a power-station unit with tap changer
 (Example: $S_{rG} = S_{rT} = 1\,070$ MVA; $U_G = U_{rG} = U_{rTLV}$)

Considering $R_G \ll X''_d$ and $R_T \ll X_T$ and introducing the following relations:

$$I_G = \frac{S_G}{\sqrt{3} U_G} ; x''_d = X''_d \frac{S_{rG}}{U_{rG}^2} ; x_T = X_T \frac{S_{rT}}{U_{rTLV}^2}$$