

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

(Implementation of HD 533 S1)

UDC 621.3.02.001

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National foreword

This British Standard has been prepared under the direction of the Power Electrical Engineering Standards Policy Committee PEL/-. It implements Harmonization Document HD 533 S1:1991 which was published by the European Committee for Electrotechnical Standardization (CENELEC). It was derived by CENELEC from IEC 909:1988 *Short circuit current calculations in three phase a.c. systems*, published by the International Electrotechnical Commission (IEC).

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Summary of pages

This document comprises a front cover, an inside front cover, pages i and ii, the HD title page, pages 2 to 86, an inside back cover and a back cover.

This standard has been updated (see copyright date) and may have had amendments incorporated. This will be indicated in the amendment table on the inside front cover.

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Descriptors: Calculation, short-circuit current, three-phase systems

English version

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

(IEC 909:1988, modified)

Calcul des courants de court-circuit dans les
réseaux triphasés à courant alternatif
(CEI 909:1988, modifiée)

Berechnung von Kurzschlußströmen in
Drehstromnetzen
(IEC 909, modifiziert)

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Up-to-date lists and bibliographical references concerning such national implementation may be obtained on application to the Central Secretariat or to any CENELEC member.

This Harmonization Document exists in three official versions (English, French, German).

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European Committee for Electrotechnical Standardization
Comité Européen de Normalisation Electrotechnique
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Foreword

The CENELEC questionnaire procedure, performed for finding out whether or not the International Standard IEC 909:1988 could be accepted without textual changes, has shown that some CENELEC common modifications were necessary for the acceptance as Harmonization Document.

The reference document, together with the common modifications prepared by the CENELEC Reporting Secretariat SR 73, was submitted to the CENELEC members for formal vote.

The text of the draft was approved by all CENELEC members, with the exception of Austria, Finland and Norway, as HD 533 S1 on 5 March 1990.

The following dates were fixed:

- latest date of announcement of the HD at national level (doa) 1990-09-01
- latest date of publication of a new harmonized national standard (dop) 1991-11-01
- latest date of withdrawal of conflicting national standards (dow) 1991-11-01

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1 Scope

This standard is applicable to the calculation of short-circuit currents:

- in low-voltage three-phase a.c. systems,
- in high-voltage three-phase a.c. systems with nominal voltages up to 380 kV operating at nominal frequency (50 Hz or 60 Hz).

This standardized procedure is given in such a form as to facilitate as far as possible its use by non-specialist engineers.

2 Object

The object of this standard is to establish a general, practicable and concise procedure leading to conservative results with sufficient accuracy. For this purpose, an equivalent voltage source at the short-circuit location is considered, as described under Clause 6. This does not exclude the use of special methods, for example the superposition method, adjusted to particular circumstances, if they give at least the same precision.

Short-circuit currents and short-circuit impedances may also be determined by system tests, by measurement on a network analyzer, or with a digital computer. In existing low-voltage systems it is possible to determine the short-circuit impedance on the basis of measurements at the location of the prospective short circuit considered.

The calculation of the short-circuit impedance, based on the rated data of the electrical equipment and the topological arrangement of the system has the advantage of being possible both for existing systems and for systems at the planning stage.

There are two different short-circuit currents to be calculated which differ in their magnitude:

- the maximum short-circuit current which determines the capacity or rating of electrical equipment;
- the minimum short-circuit current which can be a basis, for example, for the selection of fuses and for the setting of protective devices and for checking the run-up of motors.

One has to distinguish between

- systems with short-circuit currents having no a.c. component decay (far-from-generator short circuit), treated in Section 1,
- systems with short-circuit currents having decaying a.c. components (near-to-generator short circuit), treated in Section 2. This section also includes the influence of motors.

This standard does not cover short-circuit currents deliberately created under controlled conditions (short-circuit testing stations).

This standard does not deal with installations on board ships and areoplanes.

For the calculation of the thermal equivalent short-circuit currents see Section 2 of IEC Publication 865.

An application guide, dealing with non-meshed low-voltage three-phase a.c. systems and a technical report on the derivation of the parameters and various calculation factors of this standard are under consideration.

3 Definitions

For the purpose of this standard, the following definitions apply. Reference is made to the International Electrotechnical Vocabulary (IEV) [IEC Publication 50] when applicable.

3.1

short circuit

the accidental or intentional connection, by a relatively low resistance or impedance, of two or more points in a circuit which are normally at different voltages (IEV 151-03-41)

3.2

short-circuit current

an over-current resulting from a short circuit due to a fault or an incorrect connection in an electric circuit (IEV 441-11-07)

NOTE It is necessary to distinguish between the short-circuit current at the short-circuit location and in the network branches.

3.3**prospective (available) short-circuit current**

the current that would flow if the short circuit were replaced by an ideal connection of negligible impedance without any change of the supply

NOTE The current in a three-phase short circuit is assumed to be made simultaneously in all poles. Investigations of non-simultaneous short circuits, which can lead to higher aperiodic components of short-circuit current, are beyond the scope of this standard.

3.4**symmetrical short-circuit current**

the r.m.s. value of the a.c. symmetrical component of a prospective (available) short-circuit current (see Sub-clause 3.3), the aperiodic component of current, if any, being neglected

3.5**initial symmetrical short-circuit current I_k''**

the r.m.s. value of the a.c. symmetrical component of a prospective (available) short-circuit current (see Sub-clause 3.3) applicable at the instant of short circuit if the impedance remains at zero-time value (see Figure 1 and Figure 12, pages 11 and 31)

3.6**initial symmetrical short-circuit (apparent) power S_k''**

the fictive value determined as a product of the initial symmetrical short-circuit current I_k'' (see Sub-clause 3.5), the nominal system voltage U_n (see Sub-clause 3.14), and the factor $\sqrt{3}$:

$$S_k'' = \sqrt{3} U_n I_k''$$

3.7**D.C. (aperiodic) component i_{DC} of short-circuit current**

the mean value between the top and bottom envelope of a short-circuit current decaying from an initial value to zero according to Figure 1 and Figure 12

3.8**peak short-circuit current i_p**

the maximum possible instantaneous value of the prospective (available) short-circuit current (see Figure 1 and Figure 12)

NOTE The magnitude of the peak short-circuit current varies in accordance with the moment at which the short circuit occurs. The calculation of the peak three-phase short-circuit current i_p applies for the phase conductor and moment at which the greatest possible short-circuit current exists. Sequential faults are not considered. For three-phase short circuits it is assumed that the short circuit occurs simultaneously in all phase conductors.

3.9**symmetrical short-circuit breaking current I_b**

the 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 of a switching device

3.10**steady-state short-circuit current I_k**

The r.m.s. value of the short-circuit current which remains after the decay of the transient phenomena (see Figure 1 and Figure 12, pages 11 and 31)

3.11**symmetrical locked-rotor current I_{LR}**

The highest symmetrical r.m.s. current of an asynchronous motor with locked rotor fed with rated voltage U_{FM} at rated frequency

3.12**equivalent electric circuit**

a model to describe the behaviour of a circuit by means of a network of ideal elements (IEV 131-01-33)

3.13**(independent) voltage source**

an active element which can be represented by an ideal voltage source independent of all currents and voltages in the circuit, in series with a passive circuit element (IEV 131-01-37)

3.14**nominal system voltage U_n**

voltage (line-to-line) by which a system is designated and to which certain operating characteristics are referred. Values are given in IEC Publication 38

3.15**equivalent voltage source $cU_n/\sqrt{3}$**

the voltage of an ideal source applied at the short-circuit location in the positive-sequence system for calculating the short-circuit current according to Clause 6. This is the only active voltage of the network

3.16**voltage factor c**

the ratio between the equivalent voltage source and the nominal system voltage U_n divided by $\sqrt{3}$. The values are given in Table I

NOTE The introduction of a voltage factor c is necessary for various reasons. These are:

- voltage variations depending on time and place,
- changing of transformer taps,
- neglecting loads and capacitances by calculations according to Clause 6,
- the subtransient behaviour of generators and motors.

3.17**subtransient voltage E'' : of a synchronous machine**

the r.m.s. value of the symmetrical internal voltage of a synchronous machine which is active behind the subtransient reactance X_d'' at the moment of short circuit

3.18**far-from-generator short circuit**

a short circuit during which the magnitude of the symmetrical a.c. component of prospective (available) short-circuit current remains essentially constant (see Clause 7)

3.19**near-to-generator short circuit**

a short circuit to which at least one synchronous machine contributes a prospective initial symmetrical short-circuit current which is more than twice the generator's rated current, or a short circuit to which synchronous and asynchronous motors contribute more than 5 % of the initial symmetrical short-circuit current I_k'' without motors (see Clause 10)

3.20 Short-circuit impedances at the short-circuit location F **3.20.1****positive-sequence short-circuit impedance $Z_{(1)}$ of a three-phase a.c. system**

the impedance of the positive-sequence system as viewed from the short-circuit location [see Sub-clause 8.3.1 and Figure 4 a), page 15]

3.20.2**negative-sequence short-circuit impedance $Z_{(2)}$ of a three-phase a.c. system**

the impedance of the negative-sequence system as viewed from the short-circuit location [see Sub-clause 8.3.1 and Figure 4 b), page 15]

3.20.3**zero-sequence short-circuit impedance $Z_{(0)}$ of a three-phase a.c. system**

the impedance of the zero-sequence system as viewed from the short-circuit location [see Sub-clause 8.3.1 and Figure 4 c), page 15]. It includes three times the neutral-to-earth impedance $3 Z_{NE}$

3.20.4**short-circuit impedance $\underline{Z}_k$ of a three-phase a.c. system**

abbreviated expression for the positive-sequence short-circuit impedance $\underline{Z}_{(1)}$ according to Sub-clause 3.20.1 for the calculation of three-phase short-circuit currents

3.21 Short-circuit impedances of electrical equipment**3.21.1****positive-sequence short-circuit impedance $\underline{Z}_{(1)}$ of electrical equipment**

the ratio of the line-to-neutral voltage to the short-circuit current of the corresponding phase of electrical equipment when fed by a symmetrical positive-sequence system of voltages (see Sub-clause 8.3.2)

NOTE Index of symbol $\underline{Z}_{(1)}$ may be omitted if there is no possibility of confusion with the negative-sequence and the zero-sequence short-circuit impedances.

3.21.2**negative-sequence short-circuit impedance $\underline{Z}_{(2)}$ of electrical equipment**

the ratio of the line-to-neutral voltage to the short-circuit current of the corresponding phase of electrical equipment when fed by a symmetrical negative-sequence system of voltages (see Sub-clause 8.3.2)

3.21.3**zero-sequence short-circuit impedance $\underline{Z}_{(0)}$ of electrical equipment**

the ratio of the line-to-earth voltage to the short-circuit current of one phase of electrical equipment when fed by an a.c. voltage source, if the three parallel phase conductors are used for the outgoing current and a fourth line and/or earth is joint return (see Sub-clause 8.3.2)

3.22**subtransient reactance X_d'' of a synchronous machine**

the effective reactance at the moment of short circuit. For the calculation of short-circuit currents the saturated value of X_d'' is taken

NOTE When the reactance X_d'' in ohms is divided by the rated impedance $Z_{rG} = U_{rG}^2 / S_{rG}$ of the synchronous machine, the result in per unit is represented by a small letter $x_d'' = X_d'' / Z_{rG}$.

3.23**minimum time delay $t_{\min}$ of a circuit breaker**

the shortest time between the beginning of the short-circuit current and the first contact separation of one pole of the switching device

NOTE The time $t_{\min}$ is the sum of the shortest possible operating time of an instantaneous relay and the shortest opening time of a circuit breaker. It does not take into account adjustable time delays of tripping devices.

4 Symbols, subscripts and superscripts

Symbols of complex quantities are underlined, for example: $\underline{Z} = R + jX$.

All equations are written without specifying units. The symbols represent quantities possessing both numerical values and dimensions that are independent of units, provided a coherent unit system is chosen, for example, the International System of Units (SI).

4.1 Symbols

A	Initial value of aperiodic component
c	Voltage factor
$cU_n/\sqrt{3}$	Equivalent voltage source (r.m.s.)
E^w	Subtransient voltage of a synchronous machine
f	Frequency (50 Hz or 60 Hz)
I_b	Symmetrical short-circuit breaking current (r.m.s.)
I_k	Steady-state short-circuit current (r.m.s.)
I_{kP}	Steady-state short-circuit current at the terminals (poles) of a generator with compound excitation

I''_k or I''_{k3}	Initial symmetrical short-circuit current (r.m.s.)
I_{LR}	Locked-rotor current of an asynchronous motor
i_{DC}	Decaying aperiodic component of short-circuit current
i_p	Peak short-circuit current
K	Correction factor for impedances
P_{kvT}	Total loss in transformer windings at rated current
q	Factor for the calculation of breaking currents of asynchronous motors
q_n	Nominal cross section
R resp. r	Resistance, absolute respectively relative value
R_G	Fictitious resistance of a synchronous machine when calculating I''_k and i_p
S''_k	Initial symmetrical short-circuit power (apparent power)
S_r	Rated apparent power of electrical equipment
t_f	Fictitious transformation ratio
t_{min}	Minimum time delay
t_r	Rated transformation ratio (tap changer in main position); $t_r \geq 1$
U_n	Nominal system voltage, line-to-line (r.m.s.)
U_r	Rated voltage, line-to-line (r.m.s.)
u_{ks}	Rated short-circuit voltage in percent
u_{Rr}	Rated ohmic voltage in percent
$U_{(1)}, U_{(2)}, U_{(0)}$	Positive-, negative-, zero-sequence voltage
X resp. x	Reactance, absolute respectively relative value
X_d resp. X_q	Synchronous reactance, direct axis respectively quadrature axis
X_{dP}	Fictitious reactance of a generator with compound excitation in the case of steady-state short circuit at the terminals (poles) if the excitation is taken into account
X''_d resp. X''_q	Subtransient reactance of a synchronous machine (saturated value), direct axis respectively quadrature axis
$X_{d\ est}$	Reciprocal of the short-circuit ratio
Z resp. z	Impedance, absolute respectively relative value
Z_k	Short-circuit impedance of a three-phase a.c. system
$Z_{(1)}$	Positive-sequence short-circuit impedance
$Z_{(2)}$	Negative-sequence short-circuit impedance
$Z_{(0)}$	Zero-sequence short-circuit impedance
η	Efficiency of asynchronous motors
x	Factor for the calculation of the peak short-circuit current
λ	Factor for the calculation of the steady-state short-circuit current
μ	Factor for the calculation of the symmetrical short-circuit breaking current
μ_0	Absolute permeability of vacuum, $\mu_0 = 4\pi/10^{-7}$ H/m
ϱ	Resistivity
φ	Phase angle

4.2 Subscripts

(1)	Positive-sequence component
-----	-----------------------------

(2)	Negative-sequence component
(0)	Zero-sequence component
f	Fictitious
k or k3	Three-phase short circuit
k1	Line-to-earth short circuit, line-to-neutral short circuit
k2	Line-to-line short circuit without earth connection
k2E resp. kE2E	Line-to-line short circuit with earth connection, line current respectively earth current
max	Maximum
min	Minimum
n	Nominal value (IEV 151-04-01)
r	Rated value (IEV 151-04-03)
rsl	Resulting
t	Transformed value
AT	Auxiliary transformer
B	Busbar
E	Earth
F	Fault, short-circuit location
G	Generator
HV	High-voltage, high-voltage winding of a transformer
LV	Low-voltage, low-voltage winding of a transformer
L	Line
LR	Locked rotor
L1, L2, L3	Line 1, 2, 3 of a three-phase system
M	Asynchronous motor or group of asynchronous motors
$\overline{M}$	Without motor
MV	Medium-voltage, medium-voltage winding of a transformer
N	Neutral of a three-phase a.c. system
P	Terminal, pole
PSU	Power-station unit (generator and transformer)
Q	Feeder connection point
T	Transformer

4.3 Superscripts

"	Initial (subtransient) value
'	Resistance or reactance per unit length



In meshed networks according to Sub-clause 9.1.3.2 — Method A — the right hand side of equation (1) should be multiplied by 1.15. According to Sub-clause 9.1.3.2 — Method B — the equivalent frequency should be selected as follows:

$\frac{2\pi ft}{f_c f}$	$< 2\pi$	$< 5\pi$	$< 10\pi$	$< 25\pi$
	0.27	0.15	0.092	0.055

where $f = 50$ Hz or 60 Hz.

Furthermore, the calculation of maximum and minimum short-circuit currents is based on the following simplifications:

- 1) For the duration of the short circuit there is no change in the number of circuits involved, that is, a three-phase short-circuit remains three phase and a line-to-earth short circuit remains line-to-earth during the time of short circuit.
- 2) Tap changers of the transformers are assumed to be in main position.
- 3) Arc resistances are not taken into account.

While these assumptions are not strictly true for the power systems considered, the recommended short-circuit calculations have acceptable accuracy.

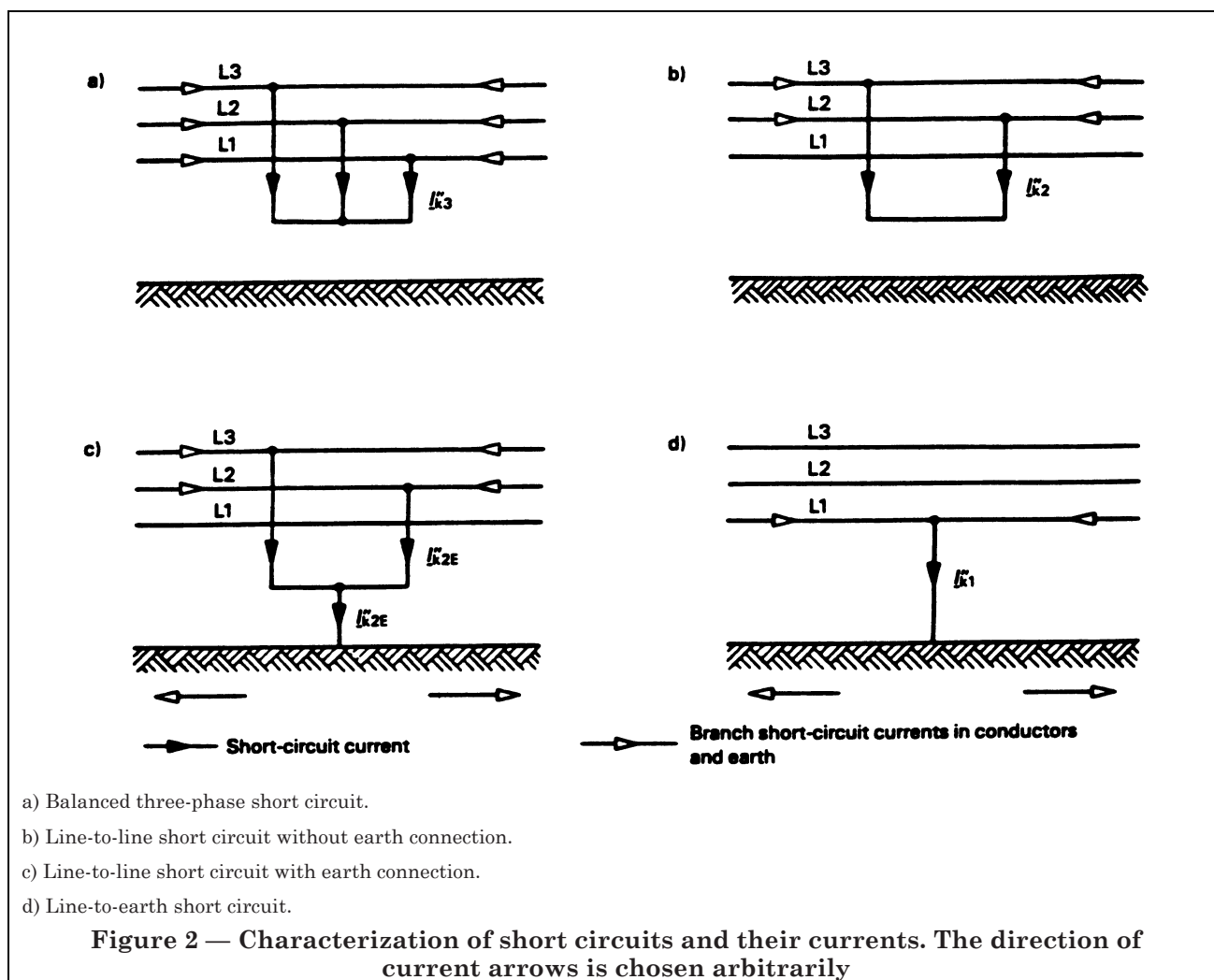
For balanced and unbalanced short circuits as shown in Figure 2, page 13, it is useful to calculate the short-circuit currents by the method of symmetrical components (see Sub-clause 8.2).

6 Equivalent voltage source at the short-circuit location

In all cases in Sections 1 and 2 it is possible to determine the short-circuit current at the short-circuit location F with the help of an equivalent voltage source. Operational data on the static load of consumers, tap changer position of transformers, excitation of generators and so on are dispensable; additional calculations about all the different possible load flows at the moment of short circuit are superfluous.

The equivalent voltage source is the only active voltage of the system. All network feeders, synchronous and asynchronous machines are replaced by their internal impedances (see Sub-clause 8.3.1).

Furthermore, with this method all line capacitances and parallel admittances of non-rotating loads, except those of the zero-sequence system (see Sub-clauses 8.3.1 and 11.4), shall be neglected.

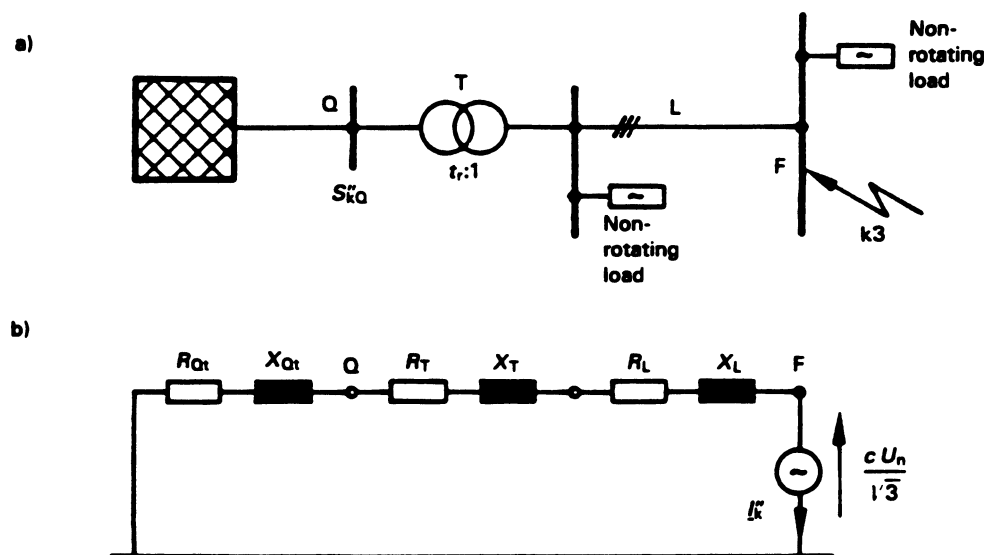


Finally high-voltage transformers in many cases are equipped with regulators and tap changers operating under load flow conditions, whereas transformers feeding low-voltage systems have normally only a few taps, for example + 2.5 % or + 4 %. The actual regulator or tap changer position of transformers in the case of far-from-generator short circuits may be disregarded without unacceptable loss of accuracy by use of this method.

The modelling of the system equipment by means of impedances according to Sub-clauses 8.3.2 and 11.5.3 applies in conjunction with the equivalent voltage source at the short-circuit location irrespective of whether a far-from-generator short-circuit according to Section 1 or a near-to-generator short-circuit according to Section 2 is involved.

Figure 3, page 14, shows an example of the equivalent voltage source at the short-circuit location F as the sole active voltage of the system in the case of a low-voltage system fed by a single transformer. All other active voltages in the system are assumed to be zero. Thus the network feeder in Figure 3 a), page 14, is represented only by its internal impedance Z_Q (see Sub-clause 8.3.2.1). Parallel admittances (e.g. line capacitances and passive loads) are not to be considered when calculating short-circuit currents in accordance with Figure 3 b), page 14.

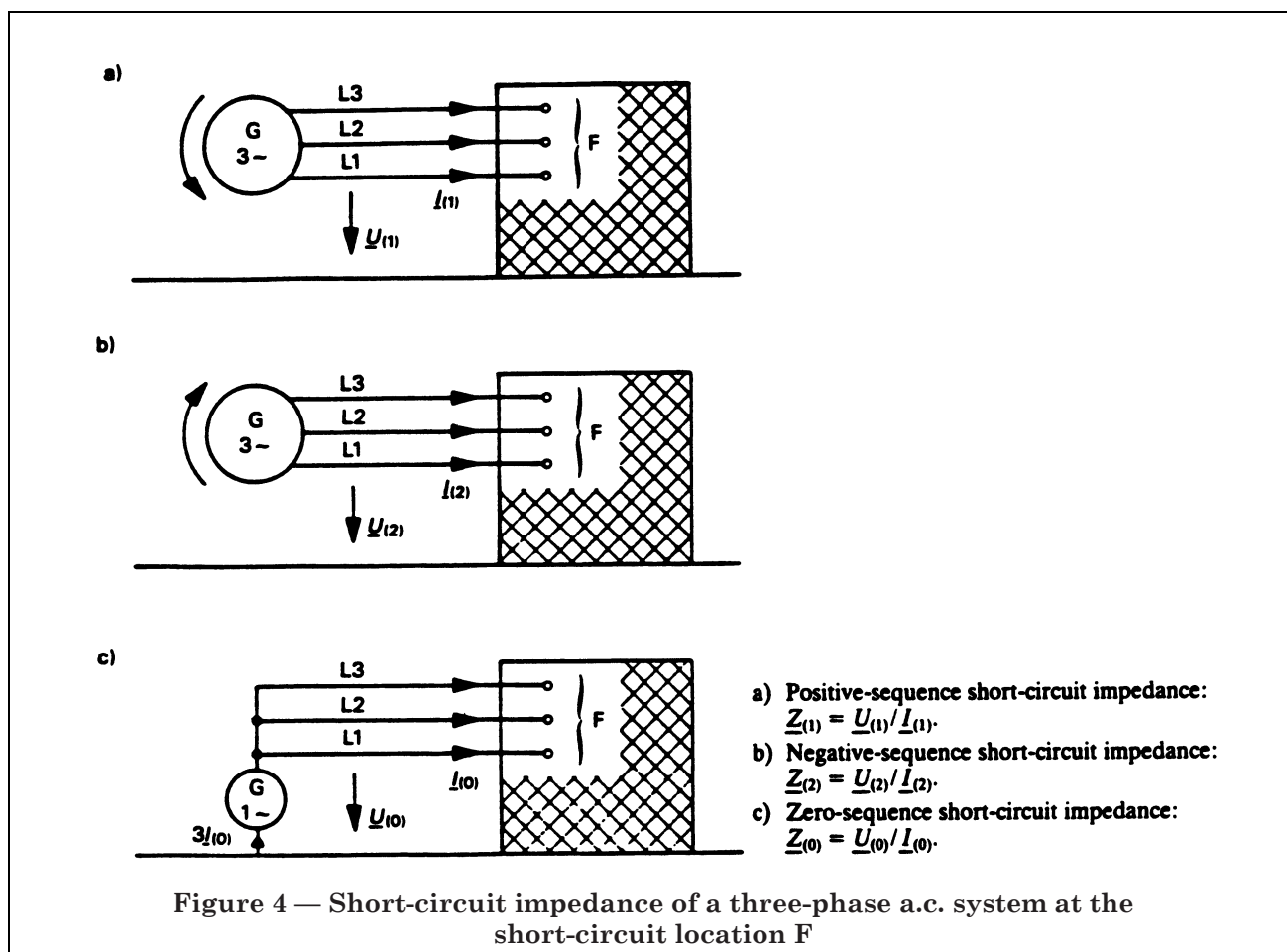
The equivalent voltage source $cU_n/\sqrt{3}$ (see Sub-clause 3.15) at the short-circuit location F is composed of the voltage factor c , the nominal system voltage U_n , and $\sqrt{3}$. The voltage factor c is different for the calculation of maximum or minimum short-circuit currents. If there are no national standards, it seems adequate to choose a voltage factor c according to Table I, 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.



a) System diagram.

b) Equivalent circuit diagram (positive-sequence system).

Figure 3 — Illustration for calculating the initial symmetrical short-circuit current I_k'' in compliance with the procedure for the equivalent voltage source

Table I — Voltage factor c

Nominal voltage U_n	Voltage factor c for the calculation of	
	maximum short-circuit current $c_{\max}$	minimum short-circuit current $c_{\min}$
<i>Low voltage</i> 100 V to 1 000 V (IEC Publication 38, Table I) a) 230 V/400 V b) Other voltages	1.00 1.05	0.95 1.00
<i>Medium voltage</i> > 1 kV to 35 kV (IEC Publication 38, Table A.III)	1.10	1.00
<i>High voltage</i> > 35 kV to 380 kV (IEC Publication 38, Table A.IV)	1.10	1.00

NOTE cU_n should not exceed the highest voltage U_m for equipment of power systems.

In this way the equivalent voltage source for the calculation of the maximum short-circuit current can be established, according to Table I, by:

$$cU_n/\sqrt{3} = 1.00 U_n/\sqrt{3} \text{ in low-voltage systems 230 V/400 V, 50 Hz} \quad (2a)$$

$$cU_n/\sqrt{3} = 1.05 U_n/\sqrt{3} \text{ in other low-voltage systems} \quad (2b)$$

$$cU_n/\sqrt{3} = 1.10 U_n/\sqrt{3} \text{ in medium and high-voltage systems.} \quad (2c)$$

Section 1. Systems with short-circuit currents having no a.c. component decay (far-from-generator short circuits)

7 General

This section refers to short circuits where there is no change for the duration of the short circuit in the voltage or voltages that caused the short-circuit current to develop (i.e. a quasi-stationary voltage condition), nor any significant change in the impedance of the circuit (i.e. constant and linear impedances). Therefore, the prospective (available) short-circuit current can be considered as the sum of the following two components:

- the a.c. component with constant amplitude during the whole short circuit,
- the aperiodic component beginning with an initial value A and decaying to zero.

Figure 1, page 11, gives schematically the general course of the short-circuit current in the case of a far-from-generator short circuit. The symmetrical a.c. components I''_k and I_k are r.m.s. values and are nearly equal in magnitude.

This assumption is generally satisfied in power systems fed from extended high-voltage systems through transformers, that is in the case of a far-from-generator short circuit.

Single-fed short-circuits supplied by a transformer according to Figure 3, page 14, may a priori be regarded as far-from-generator short circuits if $X_{TLV} \geq 2 X_{Qt}$ with X_{Qt} to be calculated in accordance with Sub-clause 8.3.2.1 and X_{TLV} in accordance with Sub-clause 8.3.2.2.

8 Short-circuit parameters

8.1 Balanced short circuit

The balanced three-phase short circuit of a three-phase a.c. system in accordance with Figure 2 a), page 13, is of special interest, because this kind of fault often leads to the highest values of prospective (available) short-circuit current and the calculation becomes particularly simple on account of the balanced nature of the short circuit.

In calculating the short-circuit current, it is sufficient to take into account only the positive-sequence short-circuit impedance $Z_{(1)} = Z_k$ as seen from the fault location (see Sub-clause 8.3.1).

Details of calculation are given in Clause 9.

8.2 Unbalanced short circuit

The following types of unbalanced (asymmetrical) short circuits are treated in this standard:

- line-to-line short circuit without earth connection [see Figure 2 b), page 13],
- line-to-line short circuit with earth connection [see Figure 2 c), page 13],
- line-to-earth short circuit [see Figure 2 d), page 13].

As a rule, the three-phase short-circuit current is the largest. In the event of a short circuit near to a transformer with neutral earthing or a neutral-earthing transformer, the line-to-earth short-circuit current may be greater than the three-phase short-circuit current. This applies in particular to transformer of vector group Yz, Dy and Dz when earthing the y- or z-winding on the low voltage side of the transformer.

In three-phase systems the calculation of the current values resulting from unbalanced short circuits is simplified by the use of the method of symmetrical components which requires the calculation of three independent system components, avoiding any coupling of mutual impedances.

Using this method, the currents in each line are found by superposing the currents of three symmetrical component systems:

- positive-sequence current $I_{(1)}$,
- negative-sequence current $I_{(2)}$,
- zero-sequence current $I_{(0)}$.

Taking the line L1 as reference, the currents I_{L1} , I_{L2} and I_{L3} are given by:

$$\underline{I}_{L1} = \underline{I}_{(1)} + \underline{I}_{(2)} + \underline{I}_{(0)} \quad (3a)$$

$$\underline{I}_{L2} = \underline{a}^2 \underline{I}_{(1)} + \underline{a} \underline{I}_{(2)} + \underline{I}_{(0)} \quad (3b)$$

$$\underline{I}_{L3} = \underline{a} \underline{I}_{(1)} + \underline{a}^2 \underline{I}_{(2)} + \underline{I}_{(0)} \quad (3c)$$

$$\underline{a} = -\frac{1}{2} + j\frac{1}{2}\sqrt{3}; \quad \underline{a}^2 = -\frac{1}{2} - j\frac{1}{2}\sqrt{3} \quad (4)$$

Each of the three symmetrical component systems has its own impedance (see Sub-clause 8.3).

The method of the symmetrical components postulates that the system impedances are balanced, for example in the case of transposed lines. The results of the short-circuit calculation have an acceptable accuracy also in the case of untransposed lines.

8.3 Short-circuit impedances

For the purpose of this standard, one has to make a distinction between short-circuit impedances at the short-circuit location F and short-circuit impedances of individual electrical equipment. According to the calculation with symmetrical components positive-sequence, negative-sequence and zero-sequence short-circuit impedances shall be considered.

8.3.1 Short-circuit impedances at the short-circuit location F

The positive-sequence short-circuit impedance $Z_{(1)}$ at the short-circuit location F is obtained according to Figure 4 a), page 15, when a symmetrical system of voltages of positive-sequence phase order is applied to the short-circuit location F and all synchronous and asynchronous machines are replaced by their internal impedances. When calculating short-circuit currents in accordance with Clause 9, all line capacitances and parallel admittances of non-rotating loads are neglected.

For the calculation of balanced three-phase short circuits, the positive-sequence impedance is the only relevant impedance. In this case $Z_k = Z_{(1)}$ (see Sub-clauses 3.20.1 and 3.20.4).

The negative-sequence short-circuit impedance $Z_{(2)}$ at the short-circuit location F is obtained according to Figure 4 b), page 15, when a symmetrical system of voltages of negative-sequence phase order is applied to the short-circuit location F. When calculating short-circuit currents in accordance with Clause 9, all line capacitances and parallel admittances of non-rotating loads are neglected.

The values of positive-sequence and negative-sequence impedances can differ from each other only in the case of rotating machines. In this section, where far-from-generator short circuits are calculated, it is generally allowed to take $Z_{(2)} = Z_{(1)}$.

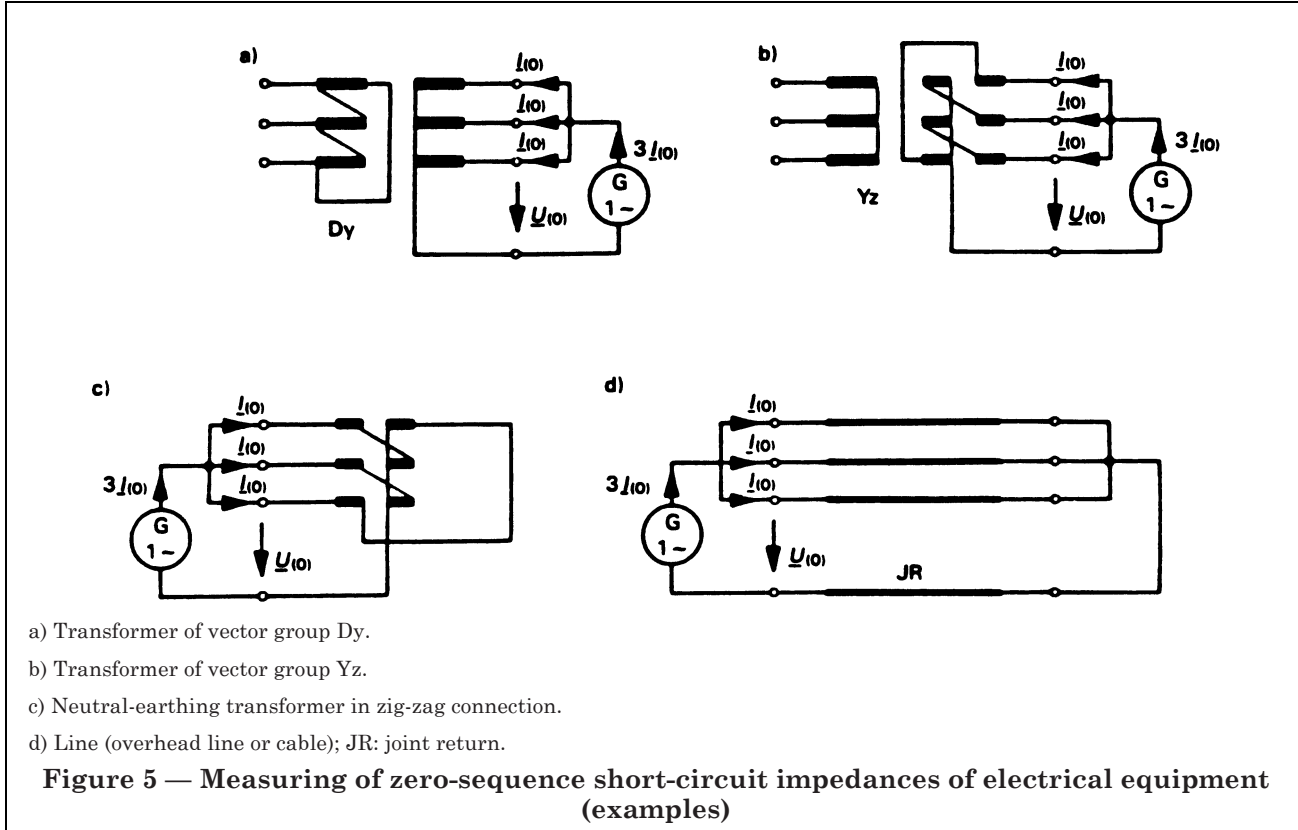
The zero-sequence short-circuit impedance $Z_{(0)}$ at the short-circuit location F is obtained according to Figure 4 c), page 15, if an a.c. voltage is applied between the short-circuited lines and the common returns (e.g. earth system, neutral conductor, earth wires, cable sheaths, cable armouring).

When calculating unbalanced short-circuit currents in medium or high-voltage systems and applying an equivalent voltage source at the short-circuit location, the line zero-sequence capacitances and zero-sequence parallel admittances of non-rotating loads are to be considered for isolated neutral systems and resonant earthed systems.

Neglecting the line zero-sequence capacitances in earthed neutral systems leads to results which are higher than the real values of the short-circuit currents. The deviation depends on several parameters of the system, for example the length of the line between transformers with neutral earthing.

In low-voltage systems, line capacitances and parallel admittances of non-rotating loads can be neglected.

Except for special cases, the zero-sequence short-circuit impedances differ from the positive-sequence short-circuit impedances.



8.3.2 Short-circuit impedances of electrical equipment

In network feeders, transformers, overhead lines, cables, reactors and similar equipment, positive-sequence and negative-sequence short-circuit impedances are equal:

$$\underline{Z}_{(1)} = \underline{U}_{(1)} / \underline{I}_{(1)} = \underline{Z}_{(2)} = \underline{U}_{(2)} / \underline{I}_{(2)}$$

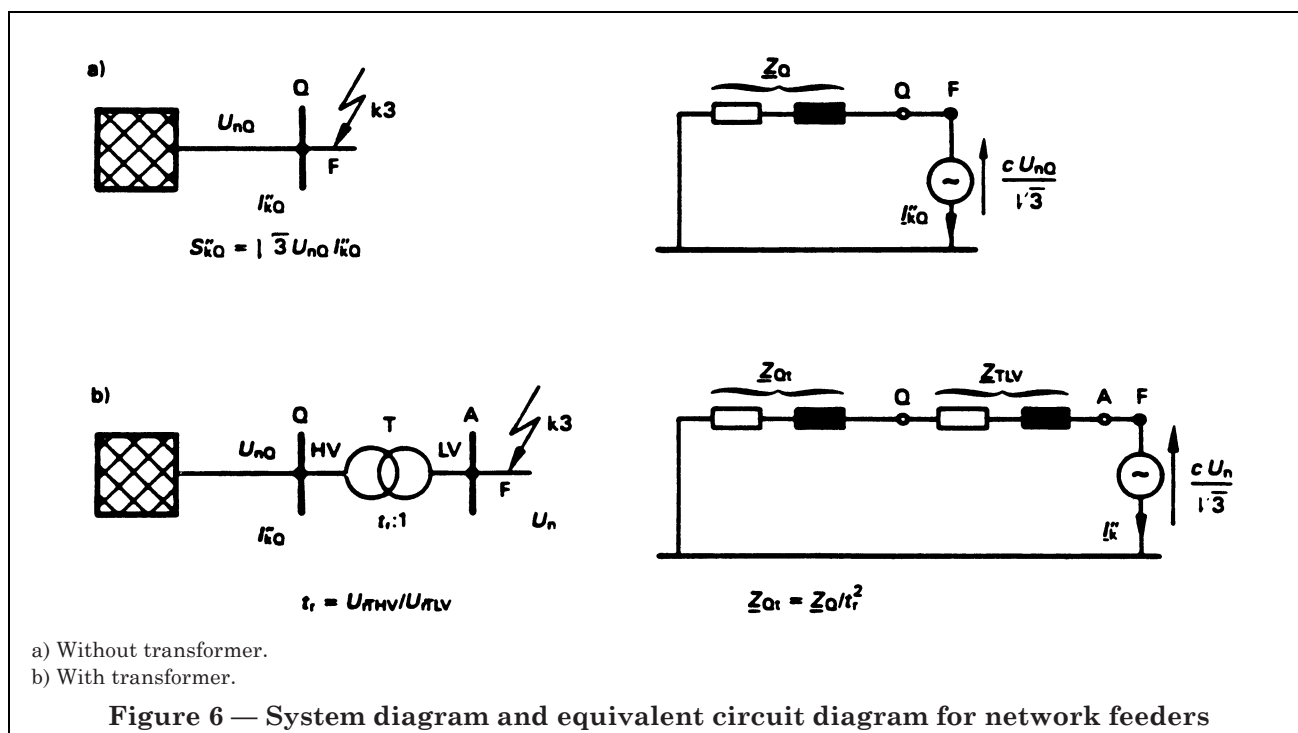
When calculating the zero-sequence short-circuit impedance of a line, for instance [see Figure 5 d), page 18], $\underline{Z}_{(0)} = \underline{U}_{(0)} / \underline{I}_{(0)}$ is determined by assuming an a.c. voltage between the three paralleled conductors and the joint return (e.g. earth, earthing device, neutral conductor, earth wire, cable sheath and cable armouring). In this case, the three-fold zero-sequence current flows through the joint return.

Normally the zero-sequence short-circuit impedances differ from the positive-sequence short-circuit impedances: $\underline{Z}_{(0)}$ may be larger than, equal to or smaller than $\underline{Z}_{(1)}$.

8.3.2.1 Network feeders

If a short circuit in accordance with Figure 6 a), page 19, is fed from a network in which only the initial symmetrical short-circuit power S''_{kQ} or the initial symmetrical short-circuit current I''_{kQ} at the feeder connection point Q is known, then the equivalent impedance Z_Q of the network (positive-sequence short-circuit impedance) at the feeder connection point Q should be determined by:

$$Z_Q = \frac{cU_{nQ}^2}{S''_{kQ}} = \frac{cU_{nQ}}{\sqrt{3} I''_{kQ}} \quad (5a)$$



If a short circuit in accordance with Figure 6 b), page 19, is fed by a transformer from a medium or high-voltage network in which only the initial symmetrical short-circuit power S''_{kQ} or the initial symmetrical short-circuit current I''_{kQ} at the feeder connection point Q is known, then the equivalent impedance Z_{Qt} referred to the low-voltage side of the transformer may be determined by:

$$Z_{Qt} = \frac{c U_{nQ}^2}{S''_{kQ}} \cdot \frac{1}{t_r^2} = \frac{c U_{nQ}}{\sqrt{3} I''_{kQ}} \cdot \frac{1}{t_r^2} \quad (5b)$$

where:

U_{nQ} = nominal system voltage at the feeder connection point Q

S''_{kQ} = initial symmetrical short-circuit apparent power at the feeder connection point Q

I''_{kQ} = initial symmetrical short-circuit current at the feeder connection point Q

c = voltage factor [see Sub-clause 3.16, Table I and Equation (2)]

t_r = rated transformation ratio at which the tap-changer is in the main position (see also Sub-clause 8.4)

In the case of high-voltage feeders with nominal voltages above 35 kV fed by overhead lines, the equivalent impedance Z_Q may be considered as a reactance, i.e. $Z_Q = 0 + jX_Q$. In other cases, if no accurate value is known for the resistance R_Q of network feeders, one may substitute $R_Q = 0.1 X_Q$ where $X_Q = 0.995 Z_Q$.

The initial symmetrical short-circuit power S''_{kQ} or the initial symmetrical short-circuit current I''_{kQ} on the high-voltage side of the supply transformers shall be given by the supply company.

In general, the equivalent zero-sequence short-circuit impedance of network feeders is not required for calculations. In special cases, however, it may be necessary to consider this impedance.

8.3.2.2 Transformers

The positive-sequence short-circuit impedances of two-winding transformers $Z_T = R_T + jX_T$ can be calculated from the rated transformer data as follows:

$$Z_T = \frac{u_{kr}}{100\%} \cdot \frac{U_{rT}^2}{S_{rT}} \quad (6)$$

$$R_T = \frac{u_{Rr}}{100\%} \cdot \frac{U_{rT}^2}{S_{rT}} = \frac{P_{krT}}{3I_{rT}^2} \quad (7)$$

$$X_T = \sqrt{Z_T^2 - R_T^2} \quad (8)$$

where:

- U_{rT} = rated voltage of the transformer on the high-voltage or low-voltage side
- I_{rT} = rated current of the transformer on the high-voltage or low-voltage side
- S_{rT} = rated apparent power of the transformer
- P_{krT} = total loss of the transformer in the windings at rated current
- u_{kr} = rated short-circuit voltage, in per cent
- u_{Rr} = rated ohmic voltage, in per cent

The necessary data may be taken from rating plates or obtained from the manufacturer.

The resistive component can be calculated from the total loss in the windings at the rated current.

The ratio X/R generally increases with transformer size. For large transformers the resistance is so small that the impedance may be assumed to consist only of reactance when calculating short-circuit current magnitude. Resistance must be considered if the peak short-circuit current i_p or the decaying aperiodic component i_{DC} is to be calculated.

The zero-sequence short-circuit impedances $Z_{(0)T} = R_{(0)T} + jX_{(0)T}$ of transformers with two or more windings may be obtained from the manufacturer.

NOTE It is sufficient for transformers with tap-changers to determine Z_T in accordance with formula (6) for the main position and to convert the impedances, currents and voltages according to Sub-clause 8.4 using the rated transformation ratio t_r corresponding to the tap-changer in the main position.

Special considerations are necessary, only if:

- a single fed short-circuit current is calculated and the short-circuit current has the same direction as the operational current before the short-circuit occurs [short circuit on the low-voltage side of one transformer or parallel transformers with tap changers according to Figure 3, page 14, or Figure 6 b), page 19],
- it is possible to change the transformation ratio of a transformer with the tap changer in a wide range, $U_{THV} = U_{rTHV} (1 \pm p_T)$ with $p_T > 0.05$,
- the minimum short-circuit voltage $u_{k \min}$ is considerably lower than the rated short-circuit voltage in the main position ($u_{k \min} < u_{kr}$),
- the voltage during operation is considerably higher than the nominal system voltage ($U \geq 1.05 U_n$).

In the case of three-winding transformers, the positive-sequence short-circuit impedances Z_A , Z_B and Z_C referring to Figure 7, page 22, can be calculated by the three short-circuit impedances (related to side A of the transformer):

$$Z_{AB} = \frac{u_{krAB}}{100\%} \cdot \frac{U_{rTA}^2}{S_{rTAB}} \quad (\text{side C open}) \quad (9a)$$

$$Z_{AC} = \frac{u_{krAC}}{100\%} \cdot \frac{U_{rTA}^2}{S_{rTAC}} \quad (\text{side B open}) \quad (9b)$$

$$Z_{BC} = \frac{u_{krBC}}{100\%} \cdot \frac{U_{rTA}^2}{S_{rTBC}} \quad (\text{side A open}) \quad (9c)$$

with the formulae:

$$\underline{Z}_A = \frac{1}{2} (\underline{Z}_{AB} + \underline{Z}_{AC} - \underline{Z}_{BC}) \quad (10a)$$

$$\underline{Z}_B = \frac{1}{2} (\underline{Z}_{BC} + \underline{Z}_{AB} - \underline{Z}_{AC}) \quad (10b)$$

$$\underline{Z}_C = \frac{1}{2} (\underline{Z}_{AC} + \underline{Z}_{BC} - \underline{Z}_{AB}) \quad (10c)$$

where:

U_{rTA} = rated voltage

S_{rTAB} = rated apparent power between sides A and B

S_{rTAC} = rated apparent power between sides A and C

S_{rTBC} = rated apparent power between sides B and C

u_{krAB} = rated short-circuit voltage, given in percent, between sides A and B

u_{krAC} = rated short-circuit voltage, given in percent, between sides A and C

u_{krBC} = rated short-circuit voltage, given in percent, between sides B and C

8.3.2.3 Overhead lines and cables

The positive-sequence short-circuit impedances $\underline{Z}_L = R_L + jX_L$ may be calculated from the conductor data, such as the cross sections and the centre-distances of the conductors.

For measurement of the zero-sequence short-circuit impedances $\underline{Z}_{(0)} = R_{(0)} + jX_{(0)}$, see Sub-clause 8.3.2 and Figure 5 d), page 18. Sometimes it is possible to calculate the zero-sequence impedances with the ratios $R_{(0)L}/R_L$ et $X_{(0)L}/X_L$.

The impedances $\underline{Z}_{(1)L}$ and $\underline{Z}_{(0)L}$ of low-voltage and high-voltage cables depend on national techniques and standards and may be taken from text-books or manufacturer's data.

The effective resistance per unit length R'_L of overhead lines at the medium conductor temperature 20 °C may be calculated from the nominal cross section q_n and the resistivity ϱ :

$$R'_L = \frac{\varrho}{q_n} \quad (11)$$

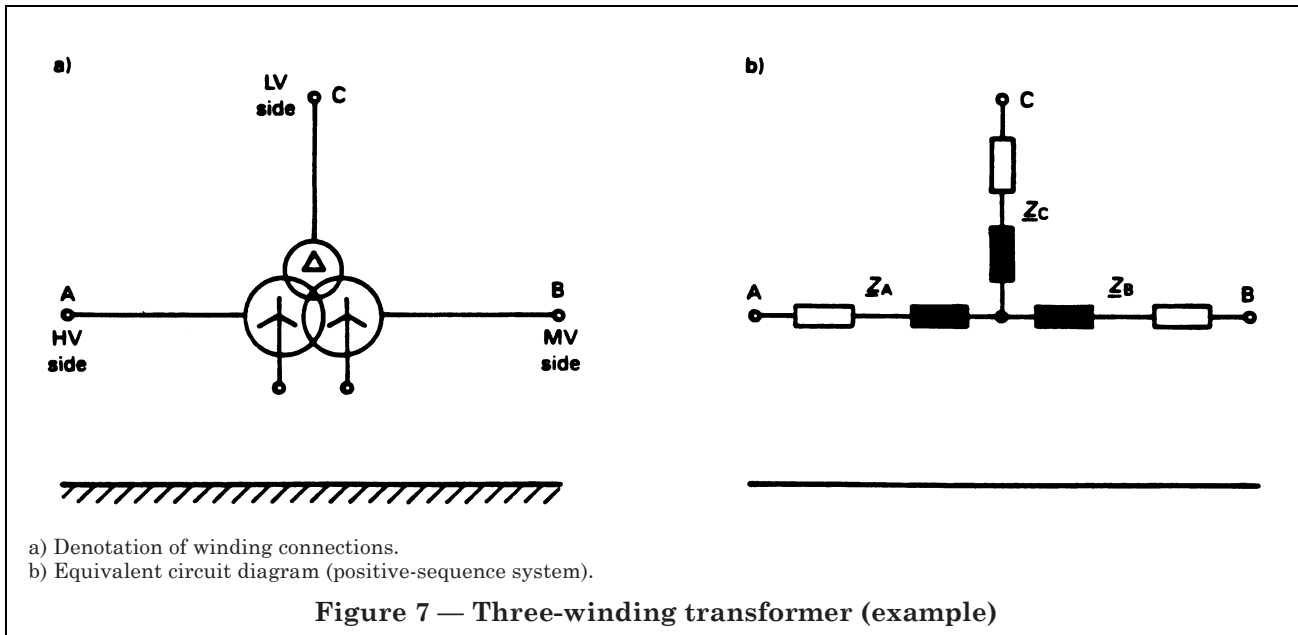
with:

$$\varrho = \frac{1}{54} \frac{\Omega \text{ mm}^2}{\text{m}} \quad \text{for copper}$$

$$\varrho = \frac{1}{34} \frac{\Omega \text{ mm}^2}{\text{m}} \quad \text{for aluminium}$$

and

$$\varrho = \frac{1}{31} \frac{\Omega \text{ mm}^2}{\text{m}} \quad \text{for aluminium alloy}$$



The reactance per unit length X'_L for overhead lines may be calculated, assuming transposition, from:

$$X'_L = 2\pi f \frac{\mu_0}{2\pi} \left(\frac{0.25}{n} + \ln \frac{d}{r} \right) = f \mu_0 \left(\frac{0.25}{n} + \ln \frac{d}{r} \right) \quad (12a)$$

where:

- $d = \sqrt[3]{d_{12} d_{23} d_{31}}$ geometric mean distance between conductors, respectively the centre of bundles
- r = radius of a single conductor. In the case of conductor bundles, r is to be substituted by $\sqrt[nr]{R^{n+1}}$, with the bundle radius R
- n = number of bundled conductors; for single conductors $n = 1$

Taking $\mu_0 = 4\pi \cdot 10^{-4}$ H/km as the permeability of a vacuum, equation (12a) may be simplified as follows:

$$\text{for } f = 50 \text{ Hz, } X'_L = 0.0628 \left(\frac{0.25}{n} + \ln \frac{d}{r} \right) \Omega / \text{km} \quad (12b)$$

$$\text{for } f = 60 \text{ Hz, } X'_L = 0.0754 \left(\frac{0.25}{n} + \ln \frac{d}{r} \right) \Omega / \text{km} \quad (12c)$$

8.3.2.4 Short-circuit current limiting reactors

The positive-sequence, the negative-sequence and the zero-sequence short-circuit impedances are equal, assuming geometric symmetry. Short-circuit current limiting reactors shall be treated as a part of the short-circuit impedance.

8.3.2.5 Motors

Synchronous motors are to be treated as synchronous generators (see Section 2).

Asynchronous motors in low-voltage and medium-voltage systems supply short-circuit currents to the short-circuit location. In the case of three-phase balanced short circuits, the short-circuit currents of asynchronous motors decay rapidly.

It is not necessary to take into account asynchronous motors or groups of asynchronous motors which have a total rated current less than 1 % of the initial symmetrical short-circuit current I''_k calculated without the influence of motors. The supplement of short-circuit currents of asynchronous motors to the current I''_k may be neglected if:

$$\Sigma I_{rM} \leq 0.01 I''_k \quad (13)$$

where:

ΣI_{rM} = sum of the rated currents of motors in the neighbourhood of the short-circuit location
(see Section 2, Sub-clause 11.5.3.5)

I''_k = short-circuit current at the short-circuit location without the influence of motors

In other cases see Section 2.

8.4 Conversion of impedances, currents and voltages

When calculating short-circuit currents in systems with different voltage levels, it is necessary to convert impedances, currents and voltages from one level to the other [e.g. see Figure 3 b), page 14]. For per unit or other similar unit systems no conversion is necessary, if these systems are coherent.

The impedances of the equipment in superimposed or subordinated networks are to be divided or multiplied by the square of the rated transformation ratio t_r or in special cases by the square of the transformation ratio t , corresponding to the actual position if it is known.

Voltages and currents are to be converted by the rated transformation ratio t_r or t .

9 Calculation of short-circuit currents

9.1 Calculation method for balanced short circuits

9.1.1 Single fed three-phase short circuit

9.1.1.1 Initial symmetrical short-circuit current I''_k

In accordance with Figure 3, page 14, the three-phase initial symmetrical short-circuit current I''_k becomes:

$$I''_k = \frac{cU_n}{\sqrt{3} \sqrt{R_k^2 + X_k^2}} = \frac{cU_n}{\sqrt{3} Z_k} \quad (14)$$

where:

$cU_n/\sqrt{3}$ = equivalent voltage source (see Clause 6)

$R_k = R_{Qt} + R_T + R_L$ = sum of series-connected resistances in accordance with Figure 3 b), page 14, R_L is the line resistance for a conductor temperature of 20 °C (see Sub-clause 8.3.2)

$X_k = X_{Qt} + X_T + X_L$ = sum of series-connected reactances in accordance with Figure 3 b) (see Sub-clause 8.3.2)

$Z_k = \sqrt{R_k^2 + X_k^2}$ = short-circuit impedance (see Sub-clause 8.3.1)

Resistances of the order of $R_k < 0.3 X_k$ may be neglected. The impedance of the system feeder $Z_{Qt} = R_{Qt} + jX_{Qt}$, referred to the voltage of that transformer side where the short circuit occurs, is to be calculated according to equations (5a) and (5b) and additional information in Sub-clause 8.3.2.1.

The scope of Section 1 supports the following equation:

$$I_k = I_b = I''_k \quad (15)$$

9.1.1.2 Peak short-circuit current i_p

Because the short circuit is fed by a series circuit, the peak short-circuit current can be expressed by:

$$i_p = x\sqrt{2} I''_k \quad (16)$$

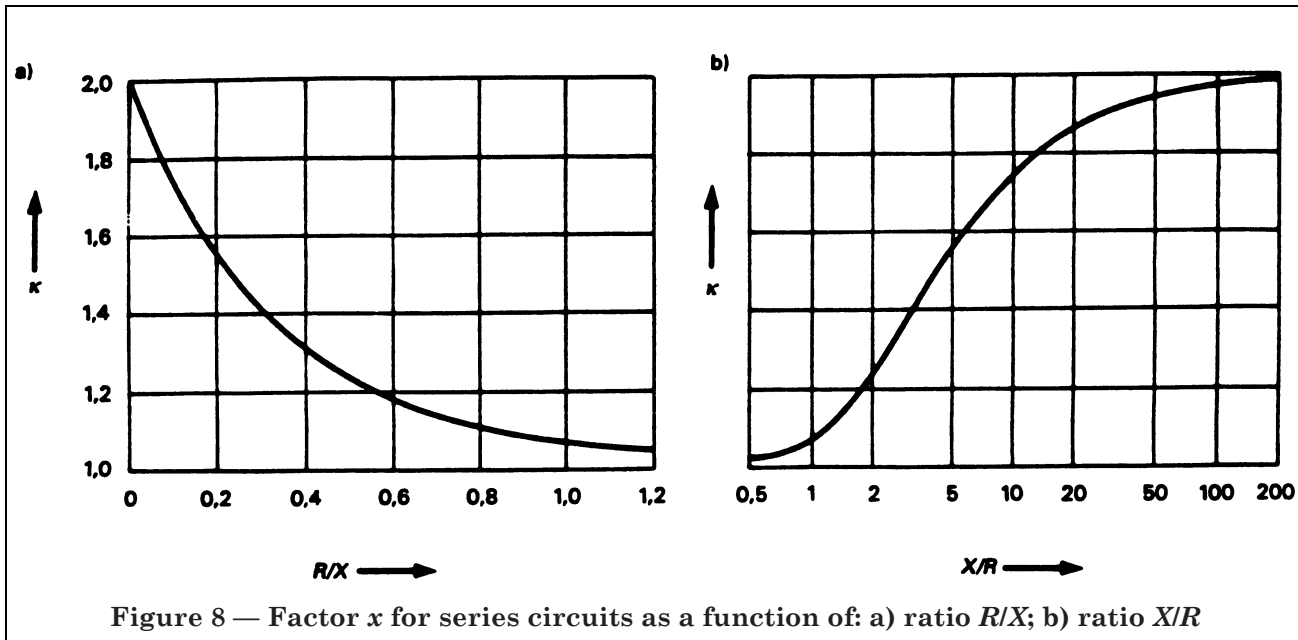


Figure 8 — Factor x for series circuits as a function of: a) ratio R/X ; b) ratio X/R

The factor x for the ratios R/X and X/R is taken from Figure 8.

The factor x may also be calculated by the approximate equation:

$$x \approx 1.02 + 0.98 e^{-3R/X}$$

9.1.2 Three-phase short circuit fed from non-meshed sources

9.1.2.1 Initial symmetrical short-circuit current I''_k

The initial symmetrical short-circuit current I''_k , the symmetrical breaking current I_b and the steady-state short-circuit current I_k at the short-circuit location F, fed from sources which are not meshed with one another in accordance with Figure 9, page 25, may be composed of the various separate branch short-circuit currents which are independent of each other:

$$I''_k = I''_{kT1} + I''_{kT2} \quad (17)$$

$$I_k = I_b = I''_k \quad (18)$$

The branch short-circuit currents are to be calculated like a single-fed three-phase short-circuit current in accordance with Sub-clause 9.1.1.

NOTE The short-circuit current at the short-circuit location F is the phasor sum of the branch short-circuit currents. In most cases the phase angles of the branch short-circuit currents are nearly the same. The short-circuit current at F is then equal to the algebraic sum of the branch short-circuit currents.

Impedances between the short-circuit location F and the busbar B, where the branch short-circuit currents flow together as shown in Figure 9, may be neglected if they are smaller than $0.05 U_n / (\sqrt{3} I''_{kB})$, where I''_{kB} is the initial symmetrical short-circuit current on the busbar determined by equation (17) with a three-phase busbar short circuit. In all other cases, calculations are made in accordance with Sub-clause 9.1.3.

9.1.2.2 Peak short-circuit current i_p

The peak short-circuit current i_p at the short-circuit location F, fed from sources which are not meshed with one another in accordance with Figure 9, may be composed of the branch short-circuit currents i_{pT1} and i_{pT2} :

$$i_p = i_{pT1} + i_{pT2} \quad (19)$$