BS EN 60909-0:2016

BSI Standards Publication

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

Part 0: Calculation of currents

bsi.

National foreword

This British Standard is the UK implementation of EN 60909-0:2016. It is identical to IEC 60909-0:2016. It supersedes BS EN 60909-0:2001 which is withdrawn.

The UK participation in its preparation was entrusted to Technical Committee PEL/73, Short circuit currents.

A list of organizations represented on this committee can be obtained on request to its secretary.

This publication does not purport to include all the necessary provisions of a contract. Users are responsible for its correct application.

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English Version

Short-circuit currents in three-phase a.c. systems - Part 0: Calculation of currents (IEC 60909-0:2016)

Courants de court-circuit dans les réseaux triphasés à courant alternatif - Partie 0: Calcul des courants (IEC 60909-0:2016)

Kurzschlussströme in Drehstromnetzen - Teil 0: Berechnung der Ströme (IEC 60909-0:2016)

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European Committee for Electrotechnical Standardization
Comité Européen de Normalisation Electrotechnique
Europäisches Komitee für Elektrotechnische Normung

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European foreword

The text of document 73/172/CDV, future edition 2 of IEC 60909-0, prepared by IEC/TC 73 "Shortcircuit currents" was submitted to the IEC-CENELEC parallel vote and approved by CENELEC as EN 60909-0:2016.

The following dates are fixed:

• latest date by which the document has to be implemented at national level by publication of an identical national standard or by endorsement	(dop)	2016-12-10
• latest date by which the national standards conflicting with the document have to be withdrawn	(dow)	2019-06-10

This document supersedes EN 60909-0:2001.

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The text of the International Standard IEC 60909-0:2016 was approved by CENELEC as a European Standard without any modification.

In the official version, for Bibliography, the following notes have to be added for the standards indicated:

IEC 60865-1	NOTE	Harmonized as EN 60865-1.
IEC 62428	NOTE	Harmonized as EN 62428.

Annex ZA
(normative)

Normative references to international publications with their corresponding European publications

The following documents, in whole or in part, are normatively referenced in this document and are indispensable for its application. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

NOTE 1 When an International Publication has been modified by common modifications, indicated by (mod), the relevant EN/HD applies.

NOTE 2 Up-to-date information on the latest versions of the European Standards listed in this annex is available here: www.cenelec.eu

Publication	Year	Title	EN/HD	Year
IEC 60038 (mod)	2009	IEC standard voltages	EN 60038	2011
IEC 60050-131	-	International Electrotechnical Vocabulary (IEV) - Part 131: Circuit theory	-	-
IEC/TR 60909-1	2002	Short-circuit currents in three-phase e.c. systems - Part 1: Factors for the calculation of short-circuit currents according to IEC 60909-0	-	-
IEC/TR 60909-2	2008	Short-circuit currents in three-phase a.c. systems - Part 2: Data of electrical equipment for short-circuit current calculations	-	-
IEC 60909-3	2009	Short-circuit currents in three-phase a.c systems - Part 3: Currents during two separate simultaneous line-to-earth short-circuits and partial short-circuit currents flowing through earth	EN 60909-3	2010
IEC/TR 60909-4	2000	Short-circuit currents in three-phase a.c. systems - Part 4: Examples for the calculation of short-circuit currents	-	-

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INTERNATIONAL ELECTROTECHNICAL COMMISSION

SHORT-CIRCUIT CURRENTS IN THREE-PHASE AC SYSTEMS –

Part 0: Calculation of currents

FOREWORD

1) The International Electrotechnical Commission (IEC) is a worldwide organization for standardization comprising all national electrotechnical committees (IEC National Committees). The object of IEC is to promote international co-operation on all questions concerning standardization in the electrical and electronic fields. To this end and in addition to other activities, IEC publishes International Standards, Technical Specifications, Technical Reports, Publicly Available Specifications (PAS) and Guides (hereafter referred to as "IEC Publication(s)"). Their preparation is entrusted to technical committees; any IEC National Committee interested in the subject dealt with may participate in this preparatory work. International, governmental and non-governmental organizations liaising with the IEC also participate in this preparation. IEC collaborates closely with the International Organization for Standardization (ISO) in accordance with conditions determined by agreement between the two organizations.
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International Standard IEC 60909-0 has been prepared by IEC technical committee 73: Short-circuit currents.

This second edition cancels and replaces the first edition published in 2001. This edition constitutes a technical revision.

This edition includes the following significant technical changes with respect to the previous edition:

a) contribution of windpower station units to the short-circuit current;
b) contribution of power station units with ful size converters to the short-circuit current;
c) new document structure.

The text of this standard is based on the following documents:

CDV	Report on voting
73/172/CDV	73/175A/RVC

Full information on the voting for the approval of this standard 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 2.

A list of all parts in the IEC 60909 series, published under the general title *Short-circuit currents in three-phase a.c. systems*, can be found on the IEC website.

This part of IEC 60909 is to be read in conjunction with the following International Standards and Technical Reports:

– IEC TR 60909-1:2002, *Short-circuit currents in three-phase a.c. systems – Part 1: Factors for the calculation of short-circuit currents according to IEC 60909-0*

– IEC TR 60909-2:2008, *Short-circuit currents in three-phase a.c. systems – Part 2: Data of electrical equipment for short-circuit current calculations*

– IEC 60909-3:2009, *Short-circuit currents in three-phase a.c. systems – Part 3: Currents during two separate simultaneous line-to-earth short circuits and partial short-circuit currents flowing through earth*

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

The committee has decided that the contents of this publication will remain unchanged until the stability date indicated on the IEC website under "http://webstore.iec.ch" in the data related to the specific publication. 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 0: Calculation of currents

1 Scope

This part of IEC 60909 is applicable to the calculation of short-circuit currents

- in low-voltage three-phase AC systems, and
- in high-voltage three-phase AC systems,

operating at a nominal frequency of 50 Hz or 60 Hz.

Systems at highest voltages of 550 kV and above with long transmission lines need special consideration.

This part of IEC 60909 establishes a general, practicable and concise procedure leading to results which are generally of acceptable accuracy. For this calculation method, an equivalent voltage source at the short-circuit location is introduced. 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. The superposition method gives the short-circuit current related to the one load flow presupposed. This method, therefore, does not necessarily lead to the maximum short-circuit current.

This part of IEC 60909 deals with the calculation of short-circuit currents in the case of balanced or unbalanced short circuits.

A single line-to-earth fault is beyond the scope of this part of IEC 60909.

For currents during two separate simultaneous single-phase line-to-earth short circuits in an isolated neutral system or a resonance earthed neutral system, see IEC 60909-3.

Short-circuit currents and short-circuit impedances may also be determined by system tests, by measurement on a network analyser, 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 is in general based on the rated data of the electrical equipment and the topological arrangement of the system and has the advantage of being possible both for existing systems and for systems at the planning stage.

In general, two types short-circuit currents, which differ in their magnitude, are considered:

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

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 may lead to higher aperiodic components of short-circuit current, are beyond the scope of this part of IEC 60909.

This part of IEC 60909 does not cover short-circuit currents deliberately created under controlled conditions (short-circuit testing stations).

This part of IEC 60909 does not deal with the calculation of short-circuit currents in installations on board ships and aeroplanes.

2 Normative references

The following documents, in whole or in part, are normatively referenced in this document and are indispensable for its application. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

IEC 60038:2009, *IEC standard voltages*

IEC 60050-131, *International Electrotechnical Vocabulary – Part 131: Circuit theory* (available at: www.electropedia.org)

IEC TR 60909-1:2002, *Short-circuit currents in three-phase a.c. systems – Part 1: Factors for the calculation of short-circuit currents according to IEC 60909-0*

IEC TR 60909-2:2008, *Short-circuit currents in three-phase a.c. systems – Data of electrical equipment for short-circuit current calculations*

IEC 60909-3:2009, *Short-circuit currents in three-phase a.c. systems – Part 3: Currents during two separate simultaneous line-to-earth short circuits and partial short-circuit currents flowing through earth*

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

3 Terms and definitions

For the purposes of this document, the terms and definitions given in IEC 60050-131 and the following apply.

3.1
short circuit
accidental or intentional conductive path between two or more conductive parts (e.g. three-phase short circuit) forcing the electric potential differences between these conductive parts to be equal or close to zero

3.1.1
line-to-line short circuit
two-phase short circuit
accidental or intentional conductive path between two line conductors with or without earth connection

3.1.2
line-to-earth short circuit
single-phase short circuit
accidental or intentional conductive path in a solidly earthed neutral system or an impedance earthed neutral system between a line conductor and local earth

3.2
short-circuit current
over-current resulting from a short circuit in an electric system

Note 1 to entry: It is necessary to distinguish between the short-circuit current at the short-circuit location and partial short-circuit currents in the network branches (see Figure 3) at any point of the network.

3.3
prospective short-circuit current
current that would flow if the short circuit were replaced by an ideal connection of negligible impedance without any change of the supply

Note 1 to entry: The current in a three-phase short circuit is assumed to be made simultaneously in all poles. Investigations of non-simultaneous short circuits, which may lead to higher aperiodic components of short-circuit current, are beyond the scope of this part of IEC 60909.

3.4
symmetrical short-circuit current
rms value of the AC symmetrical component of a prospective short-circuit current (see 3.3), the aperiodic component of current, if any, being neglected

3.5
initial symmetrical short-circuit current
I_k''
rms value of the AC symmetrical component of a prospective short-circuit current (see 3.3), applicable at the instant of short circuit if the impedance remains at zero-time value

SEE: Figures 1 and 2

3.6
initial symmetrical short-circuit power
S_k''
fictitious value determined as a product of the initial symmetrical short-circuit current I_k'' (see 3.5), the nominal system voltage U_n (see 3.13) and the factor $\sqrt{3}$: $S_k'' = \sqrt{3} \cdot U_n \cdot I_k''$

Note 1 to entry: The initial symmetrical short-circuit power S_k'' is not used for the calculation procedure in this part of IEC 60909. If S_k'' is used in spite of this in connection with short-circuit calculations, for instance to calculate the internal impedance of a network feeder at the connection point Q, then the definition given should be used in the following form: $S_{kQ}'' = \sqrt{3} \cdot U_{nQ} \cdot I_{kQ}''$ or $Z_Q = c \cdot U_{nQ}^2 / S_{kQ}''$.

3.7
decaying (aperiodic) component of short-circuit current or DC component
i_{DC}
mean value between the top and bottom envelope of a short-circuit current decaying from an initial value to zero according to Figures 1 and 2

3.8
peak short-circuit current
i_p
maximum possible instantaneous value of the prospective short-circuit current

SEE: Figures 1 and 2

Note 1 to entry: Sequential short circuits are not considered.

3.9
symmetrical short-circuit breaking current
I_b
rms value of an integral cycle of the symmetrical AC component of the prospective short-circuit current at the instant of contact separation of the first pole to open of a switching device

3.10
steady-state short-circuit current
I_k
rms value of the short-circuit current which remains after the decay of the transient phenomena

SEE: Figures 1 and 2

3.11
symmetrical locked-rotor current
I_{LR}
symmetrical rms current of an asynchronous motor with locked rotor fed with rated voltage U_{rM} at rated frequency

3.12
equivalent electric circuit
model to describe the behaviour of a circuit by means of a network of ideal elements

3.13
nominal system voltage
U_n
voltage (line-to-line) by which a system is designated, and to which certain operating characteristics are referred

Note 1 to entry: Values are given in IEC 60038.

3.14
equivalent voltage source
$cU_n / \sqrt{3}$
voltage of an ideal source applied at the short-circuit location for calculating the short-circuit current according to 5.3.1

Note 1 to entry: This is the only active voltage of the network.

3.15
voltage factor
c
ratio between the equivalent voltage source and the nominal system voltage U_n divided by $\sqrt{3}$

Note 1 to entry: The values are given in Table 1.

Note 2 to entry: 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 5.2,
– the subtransient behaviour of generators and motors.

3.16
far-from-generator short circuit
short circuit during which the magnitude of the symmetrical AC component of the prospective short-circuit current remains essentially constant

SEE: Figure 1

3.17
near-to-generator short circuit
short circuit during which the magnitude of the symmetrical AC component of the prospective short-circuit current decreases

SEE: Figure 2

Note 1 to entry: A near-to-generator short circuit can be assumed if at least one synchronous machine contributes a prospective initial symmetrical short-circuit current which is more than twice the machine's rated current, or a short circuit to which asynchronous motors contribute more than 5 % of the initial symmetrical short-circuit current without motors.

3.18
short-circuit impedances at the short-circuit location F

3.18.1
positive-sequence short-circuit impedance
$\underline{Z}_{(1)}$
<three-phase AC system> impedance of the positive-sequence system as viewed from the short-circuit location

Note 1 to entry: See 5.3.2.

3.18.2
short-circuit impedance
$\underline{Z}_{\text{k}}$
<three-phase AC system> abbreviated expression for the positive-sequence short-circuit impedance $\underline{Z}_{(1)}$ according to 3.18.1 for the calculation of three-phase short-circuit currents

3.18.3
negative-sequence short-circuit impedance
$\underline{Z}_{(2)}$
<three-phase AC system> impedance of the negative-sequence system as viewed from the short-circuit location

Note 1 to entry: See 5.3.2.

3.18.4
zero-sequence short-circuit impedance
$\underline{Z}_{(0)}$
<three-phase AC system> impedance of the zero-sequence system as viewed from the short-circuit location (see 5.3.2)

Note 1 to entry: It includes three times the neutral-to-earth impedance $\underline{Z}_{\text{N}}$.

3.19
short-circuit impedances of electrical equipment

3.19.1
positive-sequence short-circuit impedance
$\underline{Z}_{(1)}$
<electrical equipment> ratio of the line-to-neutral voltage to the short-circuit current of the corresponding line conductor of electrical equipment when fed by a symmetrical positive-sequence system of voltages

Note 1 to entry: See Clause 6 and IEC TR 60909-4.

Note 2 to entry: The 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.

3.19.2
negative-sequence short-circuit impedance
$\underline{Z}_{(2)}$
<electrical equipment> ratio of the line-to-neutral voltage to the short-circuit current of the corresponding line conductor of electrical equipment when fed by a symmetrical negative-sequence system of voltages

Note 1 to entry: See Clause 6 and IEC TR 60909-4.

3.19.3
zero-sequence short-circuit impedance
$\underline{Z}_{(0)}$
<electrical equipment> ratio of the line-to-earth voltage to the short-circuit current of one line conductor of electrical equipment when fed by an AC voltage source, if the three paralleled line conductors are used for the outgoing current and a fourth line and/or earth as a joint return

Note 1 to entry: See Clause 6 and IEC TR 60909-4.

3.20
subtransient reactance
X_d''
effective reactance of a synchronous machine at the moment of short circuit

Note 1 to entry: For the calculation of short-circuit currents the saturated value of X_d'' is taken.

3.21
minimum time delay
t_{min}
shortest time between the beginning of the short-circuit current and the contact separation of the first pole to open of the switching device

Note 1 to entry: The time t_{min} is the sum of the shortest possible operating time of a protective relay and the shortest opening time of a circuit-breaker. It does not take into account adjustable time delays of tripping devices.

3.22
thermal equivalent short-circuit current
I_{th}
the rms value of a current having the same thermal effect and the same duration as the actual short-circuit current, which may contain a DC component and may subside in time

3.23
maximum short-circuit current
i_{kWDmax}
<doubly fed asynchronous generator> instantaneous maximum short-circuit current of a wind power station unit with doubly fed asynchronous generator in case of a three-phase short-circuit at the high-voltage side of the unit transformer

3.24
maximum short-circuit current
I_{kPFmax}
<full size converter> maximum steady state current of a power station unit with full size converter in case of a three-phase short-circuit at the high-voltage side of the unit transformer

3.25
maximum source current
I_{skPF}
<full size converter, three phase> rms value of the maximum source current of a power station unit with full size converter and current regulation in case of three-phase short circuit at the high-voltage side of the unit transformer

3.26
maximum source current
$I_{(1)sk2PF}$
<full size converter, two phase> rms value of the maximum source current (positive-sequence system) of a power station unit with full size converter and current regulation in case of a line-to-line short circuit or a line-to-line short circuit with earth connection at the high-voltage side of the unit transformer

3.27
maximum source current
$I_{(1)\mathrm{sk1PF}}$
<full size converter, single phase> rms value of the maximum source current (positive-sequence system) of a power station unit with full size converter and current regulation in case of a line-to-earth short-circuit at the high-voltage side of the unit transformer

3.28
impedance of the nodal impedances matrix
$\underline{Z}_{(1)ii}$, $\underline{Z}_{(2)ii}$, $\underline{Z}_{(0)ii}$
<self-admittance> diagonal elements of the positive-sequence, or negative-sequence or zero-sequence nodal impedance matrix for the short-circuit location i

Note 1 to entry: See Annex B.

3.29
impedance of the nodal impedances matrix
$\underline{Z}_{(1)ij}$
<mutual admittance> elements of the positive-sequence nodal impedance matrix, where i is the node of the short circuit and j the node where the high-voltage side of a power station unit with full size converter is connected

Note 1 to entry: See Annex B.

4 Symbols, subscripts and superscripts

4.1 General

The formulas given in this standard are written without specifying units. The symbols represent physical quantities possessing both numerical values and dimensions that are independent of units, provided a consistent unit system is chosen, for example the international system of units (SI). Symbols of complex quantities are underlined, for example $\underline{Z} = R + \mathrm{j}X$.

4.2 Symbols

A	Initial value of the DC component i_{DC}
$\underline{\mathrm{a}}$	Complex operator
a	Ratio between unbalanced short-circuit current and three-phase short-circuit current
c	Voltage factor
$U_{\mathrm{n}} / \sqrt{3}$	Equivalent voltage source (rms)
f	Frequency (50 Hz or 60 Hz)
I_{b}	Symmetrical short-circuit breaking current (rms)
I_{k}	Steady-state short-circuit current (rms)
I_{kP}	Steady-state short-circuit current at the terminals (poles) of a generator with compound excitation
I_{k}''	Initial symmetrical short-circuit current (rms)
I_{LR}	Symmetrical locked-rotor current of an asynchronous generator or motor
I_{r}	Rated current of electrical equipment
I_{th}	Thermal equivalent short-circuit current
i_{DC}	DC component of short-circuit current
i_{p}	Peak short-circuit current

K	Correction factor for impedances
m	Factor for the heat effect of the DC component
n	Factor for the heat effect of the AC component
p	Pair of poles of an asynchronous motor
p_{G}	Range of generator voltage regulation
p_{T}	Range of transformer voltage adjustment
P_{krT}	Total loss in transformer windings at rated current
P_{rM}	Rated active power of an asynchronous motor ($P_{rM} = S_{rM} \cos(\varphi_{rM})\, \eta_{rM}$)
q	Factor for the calculation of breaking current of asynchronous motors
q_{n}	Nominal cross-section
R resp. r	Resistance, absolute respectively relative value
R_{G}	Resistance of a synchronous machine
R_{Gf}	Fictitious resistance of a synchronous machine when calculating i_{p}
S_{k}''	Initial symmetrical short-circuit power (see 3.6)
S_{r}	Rated apparent power of electrical equipment
t_{min}	Minimum time delay
t_{r}	Rated transformation ratio (tap-changer in main position); $t_{r} \geq 1$
T_{k}	Duration of the short-circuit current
U_{m}	Highest voltage for equipment, line-to-line (rms)
U_{n}	Nominal system voltage, line-to-line (rms)
U_{r}	Rated voltage, line-to-line (rms)
u_{kr}	Rated short-circuit voltage of a transformer in per cent
u_{kR}	Short-circuit voltage of a short-circuit limiting reactor in per cent
u_{Rr}	Rated resistive component of the short-circuit voltage of a transformer in per cent
u_{Xr}	Rated reactive component of the short-circuit voltage of a transformer in per cent
$U_{(1)}$, $U_{(2)}$, $U_{(0)}$	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)
X_{d}'' resp. X_{q}''	Saturated subtransient reactance of a synchronous machine, direct axis respectively quadrature axis
x_{d}	Unsaturated synchronous reactance, relative value
$x_{d\,sat}$	Saturated synchronous reactance, relative value, reciprocal of the saturated no-load short-circuit ratio
Z resp. z	Impedance, absolute respectively relative value
Z_{k}	Short-circuit impedance of a three-phase AC 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

κ	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_{WA}	Factor for the calculation of the symmetrical short-circuit breaking current of a wind power station unit with asynchronous generator
μ_{WD}	Factor for the calculation of the symmetrical short-circuit breaking current of a wind power station unit with doubly fed asynchronous generator
μ_0	Absolute permeability of vacuum, $\mu_0 = 4\pi \times 10^{-4}$ H/km
ρ	Resistivity
φ	Phase angle
ϑ_e	Conductor temperature at the end of the short circuit
01	Positive-sequence neutral reference
02	Negative-sequence neutral reference
00	Zero-sequence neutral reference

4.3 Subscripts

(1)	Positive-sequence component
(2)	Negative-sequence component
(0)	Zero-sequence component
AC	Alternating current
DC	Direct current
f	Fictitious
k or k3	Three-phase short circuit (see Figure 3a)
k1	Line-to-earth short circuit, line-to-neutral short circuit (see Figure 3d)
k2	Line-to-line short circuit (see Figure 3b)
k2EL2	Line-to-line short circuit with earth connection (see Figure 3c)
k2EL3	Line-to-line short circuit with earth connection (see Figure 3c)
kE2E	Line-to-line short circuit with earth connection (see Figure 3c)
max	Maximum
min	Minimum
n	Nominal value
r	Rated value
s	Source current
t	Transferred value
AT	Auxiliary transformer
B	Busbar
E	Earth
F	Short-circuit location
G	Generator
HV	High-voltage, high-voltage side of a transformer
K	Corrected impedances with the impedance correction factors K_T, K_G, K_S or K_{TO}
LV	Low-voltage, low-voltage side of a transformer
L	Line

LR	Locked rotor
L1, L2, L3	Line conductors of a three-phase AC system
M	Asynchronous motor or group of asynchronous motors
MO	Without motor
MV	Medium-voltage, medium-voltage side of a transformer
N	Neutral of a three-phase AC system, star point of a generator or a transformer
P	Generator with compound excitation
PF	Power station unit with full size converter
PFO	Without current sources of power station units with full size converters
PV	Photovoltaic power station unit
Q	Feeder connection point
R	Short-circuit limiting reactor
S	Power station unit (generator and unit transformer with on-load tap-changer)
SO	Power station unit (generator and unit transformer with constant transformation ratio or off-load taps)
T	Transformer
WA	Wind power station unit with asynchronous generator
WD	Wind power station unit with doubly fed asynchronous generator
WF	Wind power station unit with full size converter

4.4 Superscripts

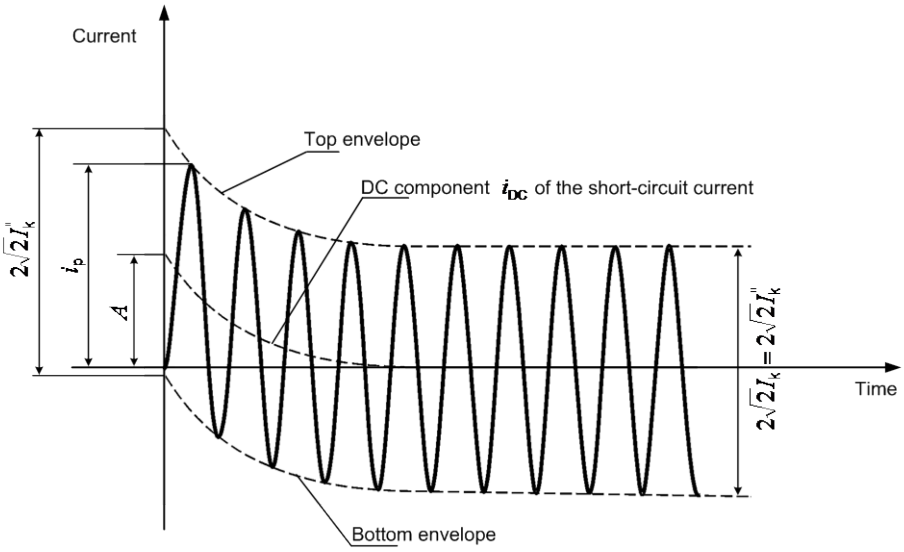
"	Subtransient (initial) value
'	Resistance or reactance per unit length
b	Before the short circuit

5 Characteristics of short-circuit currents: calculating method

5.1 General

A complete calculation of short-circuit currents should give the currents as a function of time at the short-circuit location from the initiation of the short circuit up to its end (see Figures 1 and 2), corresponding to the instantaneous value of the voltage before the short circuit.

NOTE In real networks the short-circuit current can deviate from the current shape of Figures 1 and 2.



Key

I''_k initial symmetrical short-circuit current

i_p peak short-circuit current

I_k steady-state short-circuit current

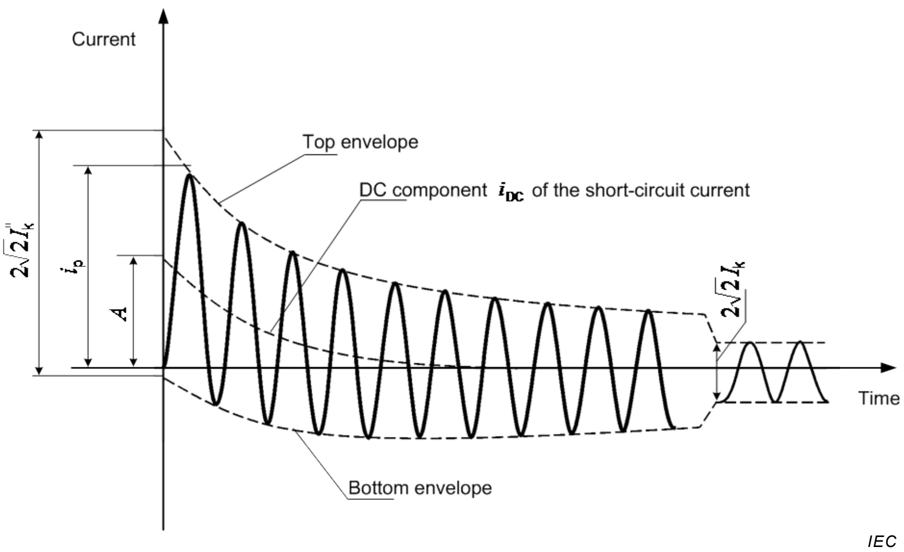
i_{DC} DC component of short-circuit current

A initial value of the DC component i_{DC}

Figure 1 – Short-circuit current of a far-from-generator short circuit with constant AC component (schematic diagram)

In most practical cases a determination like this is not necessary. Depending on the application of the results, it is of interest to know the rms value of the symmetrical AC component and the peak value i_p of the short-circuit current following the occurrence of a short circuit. The highest value i_p depends on the time constant of the decaying aperiodic component and the frequency f, that is on the ratio R/X or X/R of the short-circuit impedance $\underline{Z}_k$, and is reached if the short circuit starts at zero voltage. i_p also depends on the decay of the symmetrical AC component of the short-circuit current.

In meshed networks there are several direct-current time constants. That is why it is not possible to give an easy method of calculating i_p and i_{DC}. Special methods to calculate i_p with sufficient accuracy are given in Clause 8.



Key

I_k''	initial symmetrical short-circuit current
i_p	peak short-circuit current
I_k	steady-state short-circuit current
i_{DC}	DC component of short-circuit current
A	initial value of the DC component i_{DC}

Figure 2 – Short-circuit current of a near-to-generator short-circuit with decaying AC component (schematic diagram)

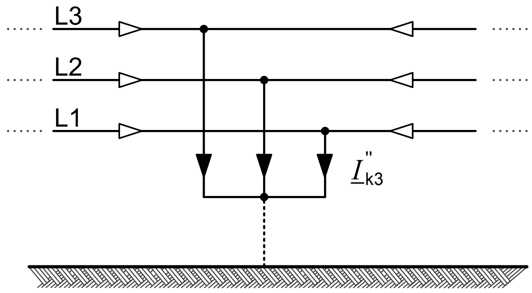


Figure 3a – Three-phase short circuit

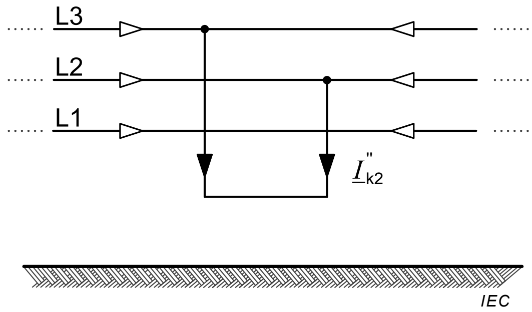


Figure 3b – Line-to-line short circuit

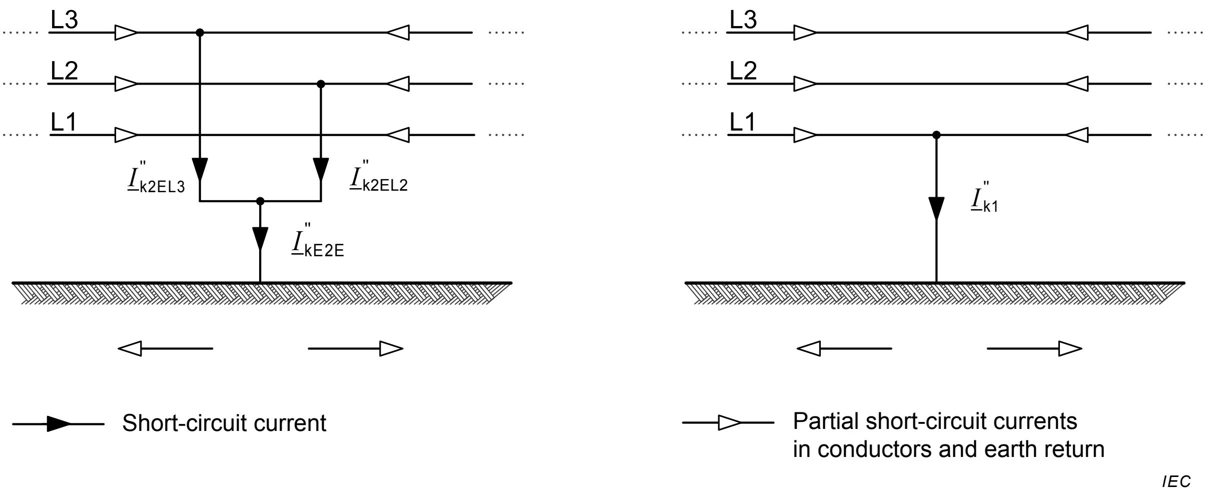


Figure 3c – Line-to-line short circuit with earth connection

Figure 3d – Line-to-earth short circuit

Figure 3 – Characterization of short-circuits and their currents

5.2 Calculation assumptions

The calculation of maximum and minimum short-circuit currents is based on the following simplifications.

a) For the duration of the short circuit there is no change in the type of short circuit 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.

b) For the duration of the short circuit, there is no change in the network involved.

c) The impedance of the transformers is referred to the tap-changer in main position.

d) Arc resistances are not taken into account.

e) Shunt admittances of non-rotating loads shall be neglected in the positive-, the negative- and the zero-sequence system.

f) Line capacitances shall be neglected in the positive- and negative-sequence system. Line capacitances in the zero-sequence system shall be taken into account in low-impedance earthed networks having an earth-fault factor (see IEC 60027-1) higher than 1,4.

g) Magnetising admittances of transformers shall be neglected in the positive- and negative-sequence system.

Despite these assumptions being not strictly true for the power systems considered, the result of the calculation does fulfil the objective to give results which are generally of acceptable accuracy.

For balanced and unbalanced short-circuits as shown in Figure 3, the short-circuit currents can be calculated by the application of symmetrical components (see 5.3.2).

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}. Voltages and currents are to be converted only by the rated transformation ratio t_{r}. If there are several transformers with slightly differing rated transformation ratios (t_{rT1}, t_{rT2}, ... t_{rTn}), in between two systems, the arithmetic mean value can be used.

For per unit or other similar unit systems, no transformation is necessary if these systems are coherent, i.e. $U_{\mathrm{rTHV}}/U_{\mathrm{rTLV}} = U_{\mathrm{nHV}}/U_{\mathrm{nLV}}$ for each transformer in the system with partial short-circuit currents. $U_{\mathrm{rTHV}}/U_{\mathrm{rTLV}}$ is normally not equal to $U_{\mathrm{nHV}}/U_{\mathrm{nLV}}$ (see IEC TR 60909-2 and the examples given in IEC TR 60909-4).

5.3 Method of calculation

5.3.1 Equivalent voltage source at the short-circuit location

The method used for calculation is based on the introduction of an equivalent voltage source at the short-circuit location. 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 Clause 6).

In all cases 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 and the 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.

Figure 4 shows an example of the equivalent voltage source at the short-circuit location F as the only active voltage of the system fed by a transformer without or with on-load tap-changer. All other active voltages in the system are short-circuited. Thus the network feeder in Figure 4a is represented by its internal impedance $\underline{Z}_{\mathrm{Qt}}$ transferred to the LV-side of the transformer (see 6.2) and the transformer by its impedance referred to the LV-side (see 6.3). The shunt admittances of the line, of the transformer and of the non-rotating loads are not considered in accordance with 5.2 e) to g).

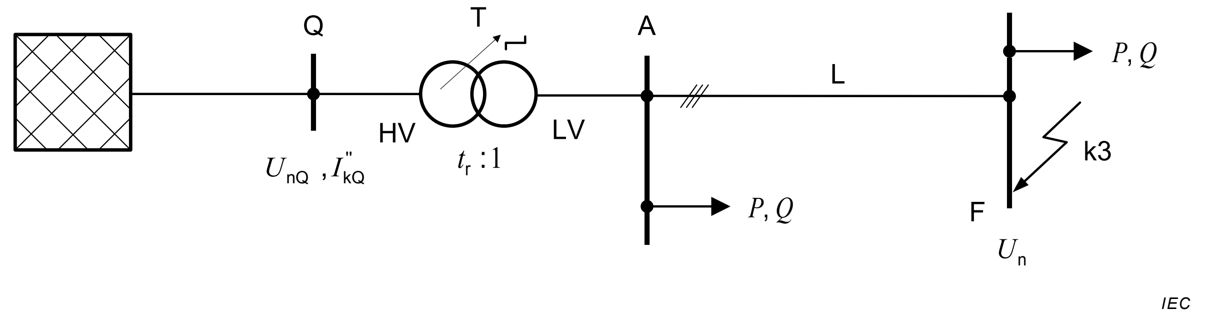


Figure 4a – System diagram

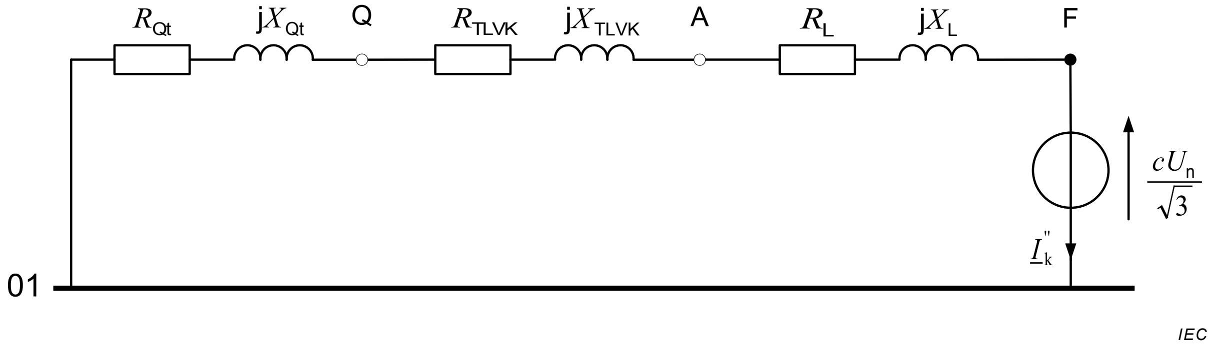


Figure 4b – Equivalent circuit diagram of the positive-sequence system

NOTE The index (1) for the impedances of the positive-sequence system is omitted. 01 marks the positive-sequence neutral reference. The impedances of the network feeder and the transformer are converted to the LV-side and the last one is also corrected with K_T (see 6.3.3).

Figure 4 – Illustration for calculating the initial symmetrical short-circuit current I''_k in compliance with the procedure for the equivalent voltage source

If there are no national standards, it seems adequate to choose a voltage factor c according to Table 1, considering that the highest voltage in a normal (undisturbed) system does not differ, on average, by more than approximately +5 % (some LV systems) or +10 % (some HV systems) from the nominal system voltage U_n.

Table 1 – Voltage factor c

Nominal system voltage U_n	Voltage factor c for the calculation of maximum short-circuit currents c_{max} [a]	minimum short-circuit currents c_{min}
Low voltage 100 V to 1 000 V (IEC 60038:2009, Table 1)	1,05[c] 1,10[d]	0,95[c] 0,90[d]
High voltage[b] >1 kV to 230 kV (IEC 60038:2009, Tables 3, 4)	1,10	1,00
High voltage[b, e] > 230 kV (IEC 60038:2009, Table 5)	1,10	1,00

[a] $c_{max}U_n$ should not exceed the highest voltage U_m for equipment of power systems.

[b] If no nominal system voltage is defined $c_{max}U_n = U_m$ or $c_{min}U_n = 0{,}90 \cdot U_m$ should be applied.

[c] For low-voltage systems with a tolerance of ±6 %, for example systems renamed from 380 V to 400 V.

[d] For low-voltage systems with a tolerance of ±10 %.

[e] For nominal system voltages related to $U_m > 420$ kV, the voltage factors c are not defined in this standard.

5.3.2 Symmetrical components

In three-phase AC systems the calculation of the current values resulting from balanced and unbalanced short circuits is simplified by the use of symmetrical components. This postulates that the electrical equipment has a balanced structure, for example in the case of transposed overhead lines. The results of the short-circuit current calculation have an acceptable accuracy also in the case of untransposed overhead lines.

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

– positive-sequence current $\underline{I}_{(1)}$;
– negative-sequence current $\underline{I}_{(2)}$;
– zero-sequence current $\underline{I}_{(0)}$.

Taking the line conductor L1 as reference, the currents $\underline{I}_{L1}$, $\underline{I}_{L2}$, and $\underline{I}_{L3}$ are given by

$$\underline{I}_{L1} = \underline{I}_{(1)} + \underline{I}_{(2)} + \underline{I}_{(0)} \tag{1}$$

$$\underline{I}_{L2} = \underline{a}^2 \cdot \underline{I}_{(1)} + \underline{a} \cdot \underline{I}_{(2)} + \underline{I}_{(0)} \tag{2}$$

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

with $\underline{a} = -\frac{1}{2} + \mathrm{j}\frac{1}{2}\sqrt{3} \qquad \underline{a}^2 = -\frac{1}{2} - \mathrm{j}\frac{1}{2}\sqrt{3}$

Each of the three symmetrical component systems has its own impedance.

The following types of unbalanced short-circuits are treated in this standard:

– line-to-line short-circuit (see Figure 3b),
– line-to-line short-circuit with earth connection (see Figure 3c),
– line-to-earth short-circuit (see Figure 3d).

For the purpose of this standard, one has to make a distinction between short-circuit impedances at the short-circuit location F and the short-circuit impedances of individual electrical equipment.

The values of positive-sequence and negative-sequence impedances can differ from each other in the case of rotating machines and power station units with full size converter.

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

NOTE See IEC 62428.

6 Short-circuit impedances of electrical equipment

6.1 General

In network feeders, transformers, overhead lines, cables and reactors, positive-sequence and negative-sequence short-circuit impedances are equal: $\underline{Z}_{(2)} = \underline{Z}_{(1)}$.

The impedances of generators (G), network transformers (T) and power station units (S) respectively (SO) shall be multiplied with the impedance correction factors K_G, K_T and K_S or K_{SO} when calculating maximum short-circuit currents with the equivalent voltage source at the short-circuit location according to this standard.

NOTE Examples for the introduction of impedance correction factors are given in IEC TR 60909-4.

6.2 Network feeders

If a three-phase short circuit in accordance with Figure 5a is fed from a network in which only 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:

$$Z_Q = \frac{c \cdot U_{nQ}}{\sqrt{3} \cdot I''_{kQ}} \qquad (4)$$

If R_Q/X_Q is known, then X_Q has to be calculated as follows:

$$X_Q = \frac{Z_Q}{\sqrt{1 + (R_Q / X_Q)^2}} \qquad (5)$$

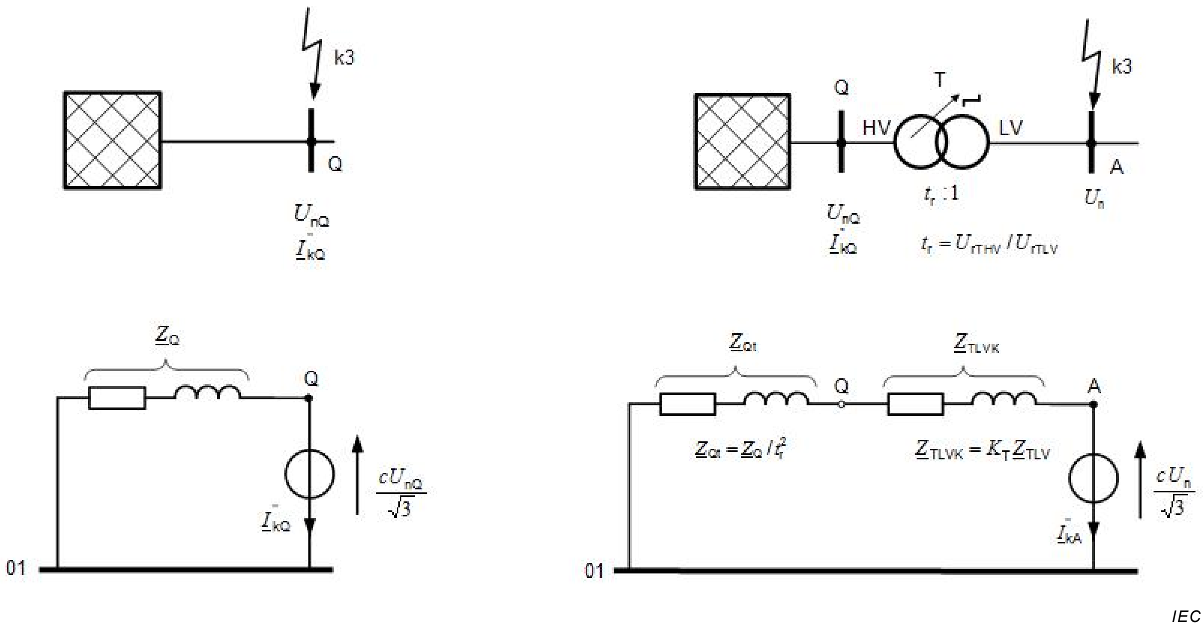


Figure 5a – Without transformer

Fig. 5b – With transformer

Figure 5 – System diagram and equivalent circuit diagram for network feeders

If a short circuit in accordance with Figure 5b is fed by a transformer from a high-voltage network in which only the initial symmetrical short-circuit current I''_{kQ} at the feeder connection point Q is known, then the positive-sequence equivalent short-circuit impedance Z_{Qt} referred to the low-voltage side of the transformer is to be determined by:

$$Z_{Qt} = \frac{c \cdot U_{nQ}}{\sqrt{3} \cdot I''_{kQ}} \cdot \frac{1}{t_r^2} \tag{6}$$

where

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

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

c is the voltage factor (see Table 1) for the nominal system voltage U_n;

t_r is the rated transformation ratio at which the on-load tap-changer is in the main position.

In the case of high-voltage feeders with nominal voltages above 35 kV fed by overhead lines, the equivalent impedance $\underline{Z}_Q$ may in many cases be considered as a reactance, i.e. $\underline{Z}_Q = 0 + jX_Q$. 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 resistance has to be considered, if the peak short-circuit current i_p or the DC-component i_{DC} is to be calculated.

The initial symmetrical short-circuit currents I''_{kQmax} and I''_{kQmin} on the high-voltage side of the transformer shall be given by the supply company or by an adequate calculation according to this standard.

In special cases the zero-sequence equivalent short-circuit impedance of network feeders may need to be considered, depending on the winding configuration and the star point earthing of the transformer.

NOTE See for instance items 6 and 8 in Table 1 of IEC TR 60909-4:2000.

6.3 Transformers

6.3.1 Two-winding transformers

The positive-sequence short-circuit impedances of two-winding transformers $\underline{Z}_T = R_T + jX_T$ with and without on-load tap-changer can be calculated from the rated transformer data as follows:

$$Z_T = \frac{u_{kr}}{100\ \%} \cdot \frac{U_{rT}^2}{S_{rT}} \tag{7}$$

$$R_T = \frac{u_{Rr}}{100\ \%} \cdot \frac{U_{rT}^2}{S_{rT}} = \frac{P_{krT}}{3 \cdot I_{rT}^2} \tag{8}$$

$$X_T = \sqrt{Z_T^2 - R_T^2} \tag{9}$$

where

U_{rT} is the rated voltage of the transformer on the high-voltage or low-voltage side;

I_{rT} is the rated current of the transformer on the high-voltage or low-voltage side;

S_{rT} is the rated apparent power of the transformer;

P_{krT} is the total loss of the transformer in the windings at rated current;

u_{kr} is the short-circuit voltage at rated current in per cent;

u_{Rr} is the rated resistive component of the short-circuit voltage in per cent.

The resistive component u_{Rr} can be calculated from the total losses P_{krT} in the windings at the rated current I_{rT}, both referred to the same transformer side (see Formula (8)).

The ratio R_T/X_T generally decreases 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 currents. The resistance is to be considered if the peak short-circuit current i_p or the DC component i_{DC} is to be calculated.

The necessary data for the calculation of $\underline{Z}_T = R_T + jX_T = \underline{Z}_{(1)} = \underline{Z}_{(2)}$ may be taken from the rating plate. The zero-sequence short-circuit impedance $\underline{Z}_{(0)T} = R_{(0)T} + jX_{(0)T}$ may be obtained from the rating plate or from the manufacturer.

NOTE Actual data for two-winding transformers used as network transformers or in power stations are given in IEC TR 60909-2. Zero-sequence impedance arrangements for the calculation of unbalanced short-circuit currents are given in IEC TR 60909-4.

6.3.2 Three-winding transformers

In the case of three-winding transformers, the positive-sequence short-circuit impedances $\underline{Z}_A$, $\underline{Z}_B$, and $\underline{Z}_C$ referring to Figure 6 can be calculated by the three short-circuit impedances (referred to side A of the transformer):

$$\underline{Z}_{\text{AB}} = \left(\frac{u_{\text{RrAB}}}{100\ \%} + \text{j} \frac{u_{\text{XrAB}}}{100\ \%} \right) \cdot \frac{U_{\text{rTA}}^2}{S_{\text{rTAB}}} \text{ (side C open)} \tag{10a}$$

$$\underline{Z}_{\text{AC}} = \left(\frac{u_{\text{RrAC}}}{100\ \%} + \text{j} \frac{u_{\text{XrAC}}}{100\ \%} \right) \cdot \frac{U_{\text{rTA}}^2}{S_{\text{rTAC}}} \text{ (side B open)} \tag{10b}$$

$$\underline{Z}_{\text{BC}} = \left(\frac{u_{\text{RrBC}}}{100\ \%} + \text{j} \frac{u_{\text{XrBC}}}{100\ \%} \right) \cdot \frac{U_{\text{rTA}}^2}{S_{\text{rTBC}}} \text{ (side A open)} \tag{10c}$$

with

$$u_{\text{Xr}} = \sqrt{u_{\text{kr}}^2 - u_{\text{Rr}}^2} \tag{10d}$$

by the formulas

$$\underline{Z}_{\text{A}} = \frac{1}{2}\left(\underline{Z}_{\text{AB}} + \underline{Z}_{\text{AC}} - \underline{Z}_{\text{BC}}\right) \tag{11a}$$

$$\underline{Z}_{\text{B}} = \frac{1}{2}\left(\underline{Z}_{\text{BC}} + \underline{Z}_{\text{AB}} - \underline{Z}_{\text{AC}}\right) \tag{11b}$$

$$\underline{Z}_{\text{C}} = \frac{1}{2}\left(\underline{Z}_{\text{AC}} + \underline{Z}_{\text{BC}} - \underline{Z}_{\text{AB}}\right) \tag{11c}$$

where

U_{rTA} is the rated voltage of side A;

S_{rTAB} is the rated apparent power between sides A and B;

S_{rTAC} is the rated apparent power between sides A and C;

S_{rTBC} is the rated apparent power between sides B and C;

u_{RrAB}, u_{XrAB} are the rated resistive and reactive components of the short-circuit voltage, given in per cent between sides A and B;

u_{RrAC}, u_{XrAC} are the rated resistive and reactive components of the short-circuit voltage, given in per cent between sides A and C;

u_{RrBC}, u_{XrBC} are the rated resistive and reactive components of the short-circuit voltage, given in per cent between sides B and C.

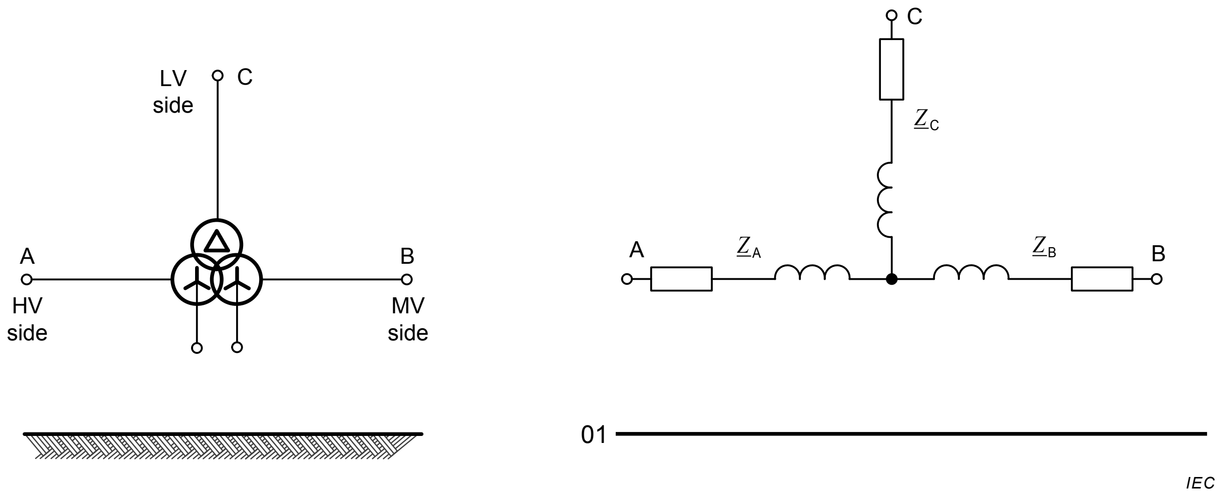


Figure 6a – Denotation of winding connections

Figure 6b – Equivalent circuit diagram (positive-sequence system)

Figure 6 – Three-winding transformer (example)

The zero-sequence impedances of three-winding transformers may be obtained from the manufacturer.

NOTE Examples for the impedances of three-winding transformers are given in IEC TR 60909-2. Additional information can be found in IEC TR 60909-4.

6.3.3 Impedance correction factors for two- and three-winding network transformers

A network transformer is a transformer connecting two or more networks at different voltages. The impedance correction factors shall be applied when calculating maximum short-circuit currents only. In case of unbalanced short-crc uits the impedance correction factors shall be applied also to the negative-sequence and the zero-sequence impedances.

For two-winding network transformers with and without on-load tap-changer, an impedance correction factor K_T is to be introduced in addition to the impedance evaluated according to Formulas (7) to (9): $\underline{Z}_\mathrm{TK} = K_\mathrm{T}\underline{Z}_\mathrm{T}$ where $\underline{Z}_\mathrm{T} = R_\mathrm{T} + \mathrm{j}X_\mathrm{T}$.

$$K_\mathrm{T} = 0{,}95 \cdot \frac{c_\mathrm{max}}{1 + 0{,}6 \cdot x_\mathrm{T}} \qquad (12a)$$

where x_T is the relative reactance of the transformer $x_\mathrm{T} = X_\mathrm{T} /(U_\mathrm{rT}^2 / S_\mathrm{rT})$ and c_max from Table 1 is related to the nominal voltage of the network connected to the low-voltage side of the network transformer. This correction factor shall not be introduced for unit transformers of power station units (see 6.7), and of wind power station units (see 6.8).

If the long-term operating conditions of network transformers before the short-circuit are known for sure, then Formula (12b) may be used instead of Formula (12a).

$$K_\mathrm{T} = \frac{U_\mathrm{n}}{U^\mathrm{b}} \cdot \frac{c_\mathrm{max}}{1 + x_\mathrm{T} \cdot \left(I_\mathrm{T}^\mathrm{b} / I_\mathrm{rT}\right) \cdot \sqrt{1 - \cos^2 \varphi_\mathrm{T}^\mathrm{b}}} \qquad (12b)$$

where

c_max is the voltage factor from Table 1, related to the nominal voltage of the network connected to the low-voltage side of the network transformer;

x_T = $X_T / (U_{rT}^2 / S_{rT})$;

U^b is the highest operating voltage before short circuit;

I_T^b is the highest operating current before short circuit (this depends on network configuration and relevant reliability philosophy);

$\cos\varphi_T^b$ is the power factor of the transformer before short circuit.

For three-winding network transformers with and without on-load tap-changer, three impedance correction factors can be found using the relative values of the reactances of the transformer (see 6.3.2):

$$K_{TAB} = 0{,}95 \cdot \frac{c_{max}}{1 + 0{,}6 \cdot x_{TAB}} \quad (13a)$$

$$K_{TAC} = 0{,}95 \cdot \frac{c_{max}}{1 + 0{,}6 \cdot x_{TAC}} \quad (13b)$$

$$K_{TBC} = 0{,}95 \cdot \frac{c_{max}}{1 + 0{,}6 \cdot x_{TBC}} \quad (13c)$$

Together with the impedances $\underline{Z}_{AB}$, $\underline{Z}_{AC}$ and $\underline{Z}_{BC}$ according to Formula (10), the corrected values $\underline{Z}_{ABK} = K_{TAB}\,\underline{Z}_{AB}$, $\underline{Z}_{ACK} = K_{TAC}\,\underline{Z}_{AC}$ and $\underline{Z}_{BCK} = K_{TBC}\,\underline{Z}_{BC}$ can be found. With these impedances the corrected equivalent impedances $\underline{Z}_{AK}$, $\underline{Z}_{BK}$ and $\underline{Z}_{CK}$ shall be calculated using the procedure given in Formula (11).

The three impedance correction factors given in Formula (13) shall be introduced also to the negative-sequence and to the zero-sequence systems.

Impedances between a star point and earth shall be introduced without correction factor.

NOTE Equivalent circuits of the positive-sequence and the zero-sequence system are given in IEC TR 60909-4:2000, Table 1, items 4 to 7 for different cases of star point earthing. In general the impedances $\underline{Z}_{(0)A}$, $\underline{Z}_{(0)B}$ or $\underline{Z}_{(0)C}$ are similar to $\underline{Z}_{(1)A}$, $\underline{Z}_{(1)B}$ or $\underline{Z}_{(1)C}$. An example for the introduction of the correction factors of Formula (13) to the positive-sequence and the zero-sequence system impedances of the equivalent circuits is given in 2.2 of IEC TR 60909-4:2000.

If in special cases, for instance in the case of auto-transformers with on-load tap-changer, the short-circuit voltages of transformers u_{k+} at the position $+p_T$ and u_{k-} at the position $-p_T$ (see IEC TR 60909-2) both are considerably higher than the value u_{kr}, it may be unnecessary to introduce impedance correction factors K_T.

6.4 Overhead lines and cables

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

For measurement of the positive-sequence short-circuit impedance $\underline{Z}_L$ and the zero-sequence short-circuit impedance $\underline{Z}_{(0)L} = R_{(0)L} + jX_{(0)L}$, see IEC TR 60909-4. Sometimes it is possible to estimate the zero-sequence short-circuit impedances with the ratios $R_{(0)L}/R_L$ and $X_{(0)L}/X_L$ (see IEC TR 60909-2).

The impedances $\underline{Z}_L$ and $\underline{Z}_{(0)L}$ of low-voltage and high-voltage cables may be taken from IEC TR 60909-2 or from textbooks or manufacturer's data.

For higher temperatures than 20 °C, see Formula (32).

The effective resistance per unit length $R_L^{'}$ of overhead lines at the conductor temperature 20 °C may be calculated from the nominal cross-section q_n and the resistivity ρ:

$$R_L^{'} = \frac{\rho}{q_n} \tag{14}$$

The following values for resistivity may be used:

Copper $\rho = \frac{1}{54} \frac{\Omega \text{mm}^2}{\text{m}}$

Aluminium $\rho = \frac{1}{34} \frac{\Omega \text{mm}^2}{\text{m}}$

Aluminium alloy $\rho = \frac{1}{31} \frac{\Omega \text{mm}^2}{\text{m}}$

The reactance per unit length $X_L^{'}$ for overhead lines may be calculated, assuming transposition, from:

$$X_L^{'} = \omega \cdot \frac{\mu_0}{2\pi} \cdot \left(\frac{1}{4n} + \ln \frac{d}{r} \right) \tag{15}$$

where

d is the geometric mean distance between conductors, or the centre of bundles: $d = \sqrt[3]{d_{L1L2} \cdot d_{L2L3} \cdot d_{L3L1}}$;

r is the radius of a single conductor. In the case of conductor bundles, r is to be substituted by $r_B = \sqrt[n]{nrR^{n-1}}$, where R is the bundle radius (see IEC TR 60909-2);

n is the number of bundled conductors; for single conductors n = 1;

μ_0 = $4\pi \cdot 10^{-4}$ H/km.

6.5 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.

$$Z_R = \frac{u_{kR}}{100\,\%} \cdot \frac{U_n}{\sqrt{3} \cdot I_{rR}} \text{ and } R_R << X_R \tag{16}$$

where

u_{kR} and I_{rR} are given on the rating plate;

U_n is the nominal system voltage.

6.6 Synchronous machines

6.6.1 Synchronous generators

When calculating maximum initial symmetrical short-circuit currents in systems fed directly from generators without unit transformers, for example in industrial networks or in low-voltage networks, the following impedance shall be used in the positive-sequence system:

$$\underline{Z}_{GK} = K_G \cdot \underline{Z}_G = K_G \cdot \left(R_G + jX''_d\right) \tag{17}$$

with the correction factor

$$K_G = \frac{U_n}{U_{rG}} \cdot \frac{c_{max}}{1 + x''_d \cdot \sqrt{1 - \cos^2 \varphi_{rG}}} \tag{18}$$

where

$\underline{Z}_{GK}$	is the corrected subtransient impedance of the generator;
c_{max}	is the voltage factor according to Table 1;
U_n	is the nominal system voltage;
U_{rG}	is the rated voltage of the generator;
R_G	is the resistance of the generator;
X''_d	is the saturated subtransient reactance of the generator;
$\underline{Z}_G$	is the subtransient impedance of the generator in the positive-sequence system;
$\cos\varphi_{rG}$	is the power factor of the generator under rated conditions;
x''_d	is the relative saturated subtransient reactance of the generator related to the rated impedance: $x''_d = X''_d / Z_{rG}$ where $Z_{rG} = U^2_{rG} / S_{rG}$.

If the terminal voltage of the generator is permanently different from U_{rG}, it may be necessary to introduce $U_G = U_{rG}\ (1 + p_G)$ instead of U_{rG} to Formula (18), when calculating maximum three-phase short-circuit currents.

For the short-circuit impedances of synchronous generators in the negative-sequence system, the following applies with K_G from Formula (18):

$$\underline{Z}_{(2)GK} = K_G \cdot \underline{Z}_{(2)G} = K_G \cdot \left(R_{(2)G} + jX_{(2)G}\right) \tag{19}$$

with $X_{(2)G} = (X''_d + X''_q)/2$

If X''_q is not known, it is allowed to take $X_{(2)G} = X''_d$.

For the short-circuit impedance of synchronous generators in the zero-sequence system, the following applies with K_G from Formula (18):

$$\underline{Z}_{(0)GK} = K_G \cdot Z_{(0)G} = K_G \cdot \left(R_{(0)G} + jX_{(0)G}\right) \tag{20}$$

If an impedance is present between the neutral point of the generator and earth, the correction factor K_G shall not be applied to this impedance.

When calculating the minimum short-circuit current use $K_G = 1$.

The need for the calculations of minimum short-circuit currents may arise because of underexcited operation of generators (low-load condition in cable systems or in systems including long overhead lines, hydro pumping stations). In this case special considerations beyond the scope and procedure given in this standard have to be taken into account (see for instance 2.2.1 of IEC TR 60909-1:2002).

6.6.2 Synchronous compensators and motors

When calculating the initial symmetrical short-circuit current $I_k^{"}$, the peak short-circuit current i_p, the symmetrical short-circuit breaking current I_b, and the steady-state short-circuit current I_k, synchronous compensators are treated in the same way as synchronous generators.

If synchronous motors have a voltage regulation, they are treated like synchronous generators. If not, they are subject to additional considerations.

6.7 Power station units

6.7.1 Power station units with on-load tap-changer

For the calculation of maximum short-circuit currents of power station units (S) with on-load tap-changer, the following formula for the impedance of the whole power station unit is used for short circuits on the high-voltage side of the unit transformer (see Figure 8c):

$$\underline{Z}_{SK} = K_S \cdot \left(t_r^2 \cdot \underline{Z}_G + \underline{Z}_{THV}\right) \tag{21}$$

with the correction factor

$$K_S = \frac{U_{nQ}^2}{U_{rG}^2} \cdot \frac{U_{rTLV}^2}{U_{rTHV}^2} \cdot \frac{c_{max}}{1 + \left|x_d^{"} - x_T\right| \cdot \sqrt{1 - \cos^2 \varphi_{rG}}} \tag{22}$$

where

$\underline{Z}_{SK}$	is the corrected impedance of a power station unit with on-load tap-changer referred to the high-voltage side;
$\underline{Z}_G$	is the subtransient impedance of the generator $\underline{Z}_G = R_G + jX_d^{"}$, see 6.6.1;
$\underline{Z}_{THV}$	is the impedance of the unit transformer related to the high-voltage side (without correction factor K_T);
U_{nQ}	is the nominal system voltage at the feeder connection point Q of the power station unit;
U_{rG}	is the rated voltage of the generator;
$\cos \varphi_{rG}$	is the power factor of the generator under rated conditions;
$x_d^{"}$	is the relative saturated subtransient reactance of the generator related to the rated impedance: $x_d^{"} = X_d^{"} / Z_{rG}$ where $Z_{rG} = U_{rG}^2 / S_{rG}$;
x_T	is the relative saturated reactance of the unit transformer at the main position of the on-load tap-changer: $x_T = X_T / (U_{rT}^2 / S_{rT})$;
t_r	is the rated transformation ratio of the unit transformer: $t_r = U_{rTHV}/U_{rTLV}$.

When calculating the minimum short-circuit current, use $K_S = 1$.

If the minimum operating voltage $U_{Qmin}^{b} \geq U_{nQ}$ at the high-voltage side of the unit transformer of the power station unit is well established from long-term operating experience of the system, then the product $U_{nQ} \cdot U_{Qmin}^{b}$ may be used instead of U_{nQ}^2 in Formula (22).

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_{Gmax}= U_{rG} (1+p_G) should be introduced instead of U_{rG}, with, for instance, p_G = 0,05.

If underexcited operation of the power station unit is expected at some time (for instance to a large extent especially in pumped storage plants), then only when calculating unbalanced short-circuit currents with earth connection (see Figures 3c and 3d) the application of K_S according to Formula (22) may lead to results at the non-conservative side. Special considerations are necessary in this case, for instance with the superposition method.

When calculating the partial short-circuit current I''_{kS} at the high-voltage side of the unit transformer or the total short-circuit current at the short-circuit location on the high-voltage side of a power station unit, it is not necessary to take into account the contribution to the short circuit I''_{kS} of the motors connected to the auxiliary transformer.

NOTE IEC TR 60909-4 provides help for users in such cases.

6.7.2 Power station units without on-load tap-changer

For the calculation of maximum short-circuit currents of power station units (SO) without on-load tap-changer, the following formula for the impedance of the whole power station unit is used for a short circuit on the high-voltage side of the unit transformer (see Figure 8d):

$$\underline{Z}_{SOK} = K_{SO} \cdot \left(t_r^2 \cdot \underline{Z}_G + \underline{Z}_{THV}\right) \tag{23}$$

with the correction factor

$$K_{SO} = \frac{U_{nQ}}{U_{rG} \cdot (1+p_G)} \cdot \frac{U_{rTLV}}{U_{rTHV}} \cdot (1 \pm p_T) \cdot \frac{c_{max}}{1 + x''_d \cdot \sqrt{1-\cos^2 \varphi_{rG}}} \tag{24}$$

where

$\underline{Z}_{SOK}$	is the corrected short-circuit impedance of the power station unit without on-load tap-changer;
$\underline{Z}_G$	is the subtransient impedance of the generator, see 6.6.1;
$\underline{Z}_{THV}$	is the impedance of the unit transformer related to the high-voltage side (without correction factor K_T);
U_{nQ}	is the nominal system voltage at the feeder connection point Q of the power station unit;
U_{rG}	is the rated voltage of the generator; U_{Gmax} = U_{rG} (1+p_G), with for instance p_G = 0,05 up to 0,10;
cos φ_{rG}	is the power factor of the generator under rated conditions;
x''_d	is the relative saturated subtransient reactance of the generator related to the rated impedance: $x''_d = X''_d / Z_{rG}$ where $Z_{rG} = U_{rG}^2 / S_{rG}$;
t_r	is the rated transformation ratio of the unit transformer t_r = U_{rTHV}/U_{rTLV};
1 ± p_T	is to be introduced if the unit transformer has off-load taps and if one of these taps is permanently used, if not choose 1 ± p_T = 1. If the highest partial short-circuit current of the power station unit at the high-voltage side of the unit transformer with off-load taps is searched for, choose 1 – p_T.

In the case of unbalanced short-circuits, the impedance correction factor K_{SO} from Formula (24) shall be applied to the positive-sequence, the negative-sequence and the zero-sequence impedances of the power station unit. When an impedance is present between the star point of the transformer and earth, the correction factor K_{SO} shall not be applied to this impedance.

The correction factor is not conditional upon whether the generator was overexcited or under-excited before the short circuit.

When calculating the partial short-circuit current I''_{kSO} at the high-voltage side of the unit transformer or the total short-circuit current at the short-circuit location on the high-voltage side of a power station unit, it is not necessary to take into account the contribution to the short-circuit current I''_{kSO} of the motors connected to the auxiliary transformer.

When calculating the minimum short-circuit current, use K_{SO} = 1.

6.8 Wind power station units

6.8.1 General

In 6.8, the short-circuit currents of wind power stations with asynchronous generators as well as doubly fed asynchronous generators are considered. Wind power stations with full size converter are treated in 6.9.

For the calculation of short-circuit currents the generators of wind power stations and their unit transformers are combined into one unit. All quantities are related to the high-voltage side of the unit transformer.

Short-circuit currents are not dealt with in this standard, which occur at the terminals of doubly fed asynchronous generators or the converter terminals of wind power stations with synchronous or asynchronous generators connected to full size converters. The manufacturer may give information for this case.

In many cases grid connection rules will require the wind power station to feed in mostly reactive current during a short circuit. During this interval the station will act as a regulated current source (see 7.2.1).

An impedance correction factor K_T for the unit transformers of a wind power station unit shall not be taken into account.

6.8.2 Wind power station units with asynchronous generator

The impedance Z_G of the asynchronous generator shall be calculated as follows:

$$Z_G = \frac{1}{I_{LR} / I_{rG}} \cdot \frac{U_{rG}}{\sqrt{3} \cdot I_{rG}} = \frac{1}{I_{LR} / I_{rG}} \cdot \frac{U_{rG}^2}{S_{rG}} \qquad (25)$$

where

U_{rG} is the rated voltage of the asynchronous generator;

I_{rG} is the rated current of the asynchronous generator;

S_{rG} is rated apparent power of the asynchronous generator;

I_{LR}/I_{rG} is the ratio of the symmetrical locked-rotor current to the rated current of the asynchronous generator.

The complex value of the impedance $\underline{Z}_G$ shall be calculated with:

$$\underline{Z}_G = R_G + jX_G = \left(\frac{R_G}{X_G} + j\right) \cdot \frac{Z_G}{\sqrt{1 + (R_G / X_G)^2}} \tag{26}$$

If R_G/X_G is not provided by the manufacturer, then R_G/X_G = 0,1 can be used.

The total positive-sequence short-circuit impedance $\underline{Z}_{WA}$ of a wind power station unit with asynchronous generator for the calculation of the short-circuit current contribution on the high-voltage side of the unit transformer shall be calculated with Formula (27):

$$\underline{Z}_{WA} = t_r^2 \cdot \underline{Z}_G + \underline{Z}_{THV} \tag{27}$$

where

$\underline{Z}_G$ is the impedance of the asynchronous generator, Formula (26);

$\underline{Z}_{THV}$ is the impedance of the unit transformer at the high-voltage side;

t_r is the rated transformation ratio of the unit transformer: $t_r = U_{rTHV}/U_{rTLV}$.

In case of unbalanced short circuits, $\underline{Z}_{(2)WA}/\underline{Z}_{WA} = 1$ can be used. The zero-sequence impedance $\underline{Z}_{(0)WA}$ depends on the type of transformer and earthing.

6.8.3 Wind power station units with doubly fed asynchronous generator

The total positive-sequence short-circuit impedance Z_{WD} of a wind power station with doubly fed asynchronous generator shall be calculated as follows.

$$Z_{WD} = \frac{\sqrt{2} \cdot \kappa_{WD} \cdot U_{rTHV}}{\sqrt{3} \cdot i_{WDmax}} \tag{28}$$

where

U_{rTHV} is the rated voltage of the unit transformer at the high-voltage side;

κ_{WD} is the factor for the calculation of the peak short-circuit current, given by the manufacturer and referred to the high-voltage side;

i_{WDmax} is the highest instantaneous short-circuit value in case of a three-phase short-circuit.

The factor κ_{WD} depends on the influences of the converter protection equipment as crowbar and chopper resistance. If κ_{WD} is not known, then κ_{WD} = 1,7 shall be used.

The complex value of the short-circuit impedance $\underline{Z}_{WD}$ shall be calculated by Formula (29).

$$\underline{Z}_{WD} = R_{WD} + jX_{WD} = \left(\frac{R_{WD}}{X_{WD}} + j\right) \cdot \frac{Z_{WD}}{\sqrt{1 + (R_{WD} / X_{WD})^2}} \tag{29}$$

If R_{WD}/X_{WD} is not provided by the manufacturer, then R_{WD}/X_{WD} = 0,1 can be used.

In case of unbalanced short-circuits, $\underline{Z}_{(2)WD}$ depends on the design and control strategies, the zero-sequence impedance $\underline{Z}_{(0)WD}$ depends on the type of transformer and earthing. The values are given by the manufacturer.

NOTE There is no direct relationship between the factor κ_{WD} of Formula (28) and the ratio R_{WD}/X_{WD} of Formula (29) due to the influence of the converter and its protection system on the maximum i_{WDmax}

6.9 Power station units with full size converter

Power stations units with full size converter (PF), e.g. wind power station units (WF) and photovoltaic station units (PV), are modelled in the positive-sequence system by a current source. The source current depends on the type of short circuit and has to be provided by the manufacturer. The positive-sequence shunt impedance Z_{PF} is assumed to be infinite.

In case of unbalanced short circuits the negative-sequence impedances $\underline{Z}_{(2)PF}$ depend on the design and control strategies, the values are given by the manufacturer. The zero-sequence impedance $\underline{Z}_{(0)PF}$ is infinite.

Power station units with full size converter may be neglected if their contributions are not higher than 5 % of the initial short circuit without these power station units.

6.10 Asynchronous motors

The impedance Z_M of asynchronous motors in the positive- and negative-sequence systems can be determined by:

$$Z_M = \frac{1}{I_{LR}/I_{rM}} \cdot \frac{U_{rM}}{\sqrt{3} \cdot I_M} = \frac{1}{I_{LR}/I_{rM}} \cdot \frac{U_{rM}^2}{S_{rM}} \tag{30}$$

where

U_{rM} is the rated voltage of the motor;

I_{rM} is the rated current of the motor;

S_{rM} is the rated apparent power of the motor: $S_{rM} = P_{rM}/(\eta_{rM} \cos\varphi_{rM})$;

I_{LR}/I_{rM} is the ratio of the locked-rotor current to the rated current of the motor.

The complex value of the impedance $\underline{Z}_M$ shall be calculated with:

$$\underline{Z}_M = R_M + \mathrm{j}X_M = \left(\frac{R_M}{X_M} + \mathrm{j}\right) \cdot \frac{Z_M}{\sqrt{1 + (R_M/X_M)^2}} \tag{31}$$

If R_M/X_M is not provided by the manufacturer, the following relations may be used with sufficient accuracy for R_M/X_M:

$R_M/X_M = 0{,}10$, with $X_M = 0{,}995\ Z_M$ for high-voltage motors with powers P_{rM} per pair of poles ≥ 1 MW;

$R_M/X_M = 0{,}15$, with $X_M = 0{,}989\ Z_M$ for high-voltage motors with powers P_{rM} per pair of poles < 1 MW;

$R_M/X_M = 0{,}42$, with $X_M = 0{,}922\ Z_M$ for low-voltage motor groups with connection cables.

The saturated impedance $\underline{Z}_M$ may also be calculated from the parameters of the electrical equivalent circuit for locked-rotor conditions.

The zero-sequence system impedance $\underline{Z}_{(0)M}$ of the motor shall be given by the manufacturer, if needed (see Clause 11).

6.11 Static converter fed drives

Reversible static converter-fed drives (for example, rolling mill drives) are considered for three-phase short circuits only, if the rotational masses of the motors and the static equipment provide reverse transfer of energy for deceleration (a transient inverter operation) at the time of short circuit. Then they contribute only to the initial symmetrical short-circuit current I_k'' and to the peak short-circuit current i_p. They do not contribute to the symmetrical short-circuit breaking current I_b and the steady-state short-circuit current I_k.

As a result, reversible static converter-fed drives are treated for the calculation of short-circuit currents in a similar way to asynchronous motors. The following applies:

Z_M is the impedance according to Formula (30);

U_{rM} is the rated voltage of the static converter transformer on the network side or rated voltage of the static converter, if no transformer is present;

I_{rM} is the rated current of the static converter transformer on the network side or rated current of the static converter, if no transformer is present;

I_{LR}/I_{rM} = 3;

R_M/X_M = 0,10 with X_M = 0,995 Z_M.

All other static converters are disregarded for the short-circuit current calculation according to this standard.

6.12 Capacitors and non-rotating loads

Due to the calculation methods given in Clause 5, it is not allowed to take into account parallel admittances and non-rotating loads as stated in 5.2 e) and 5.2 f).

The discharge current of the shunt capacitors may be neglected for the calculation of the peak short-circuit current.

The effect of series capacitors can be neglected in the calculation of short-circuit currents, if they are equipped with voltage-limiting devices in parallel, acting if a short circuit occurs.

In the case of high-voltage direct-current transmission systems, the capacitor banks and filters need special considerations when calculating AC short-circuit currents.

7 Calculation of initial short-circuit current

7.1 General

7.1.1 Overview

The maximum short-circuit current is responsible for the rating of equipment regarding the mechanical and thermal stresses, the minimum short-circuit current has to be calculated for the selection of the system protection. Table 2 shows an overview of the short-circuit currents and types of failures that have to be considered.

Table 2 – Importance of short-circuit currents

Short-circuit currents	Equipment	Relevant currents		
		k3	k2	k1
maximum currents stress:				
– dynamic	components of installations	i_p	i_p	–
– switching on	switching devices	i_p	–	i_p
– switching off	switching devices	I_b	–	I_b
– thermal	components of installations, lines	I_{th}	–	I_{th}
minimum currents				
tripping of relays	protection	–	I''_k , I_k	I''_k , I_k

In general, a distinction is made between far-from-generator and near-to-generator short circuits (see 3.16 and 3.17).

In addition, it is necessary to distinguish between single-fed short-circuit, multiple single-fed short circuits and multiple-fed short circuits.

Single-fed short circuits supplied by a transformer according to Figure 4 may a priori be regarded as far-from-generator short-circuits if $X_{TLVK} \geq 2X_{Qt}$ with X_{Qt} calculated in accordance with 6.2 and $X_{TLVK} = K_T X_{TLV}$ in accordance with 6.3.

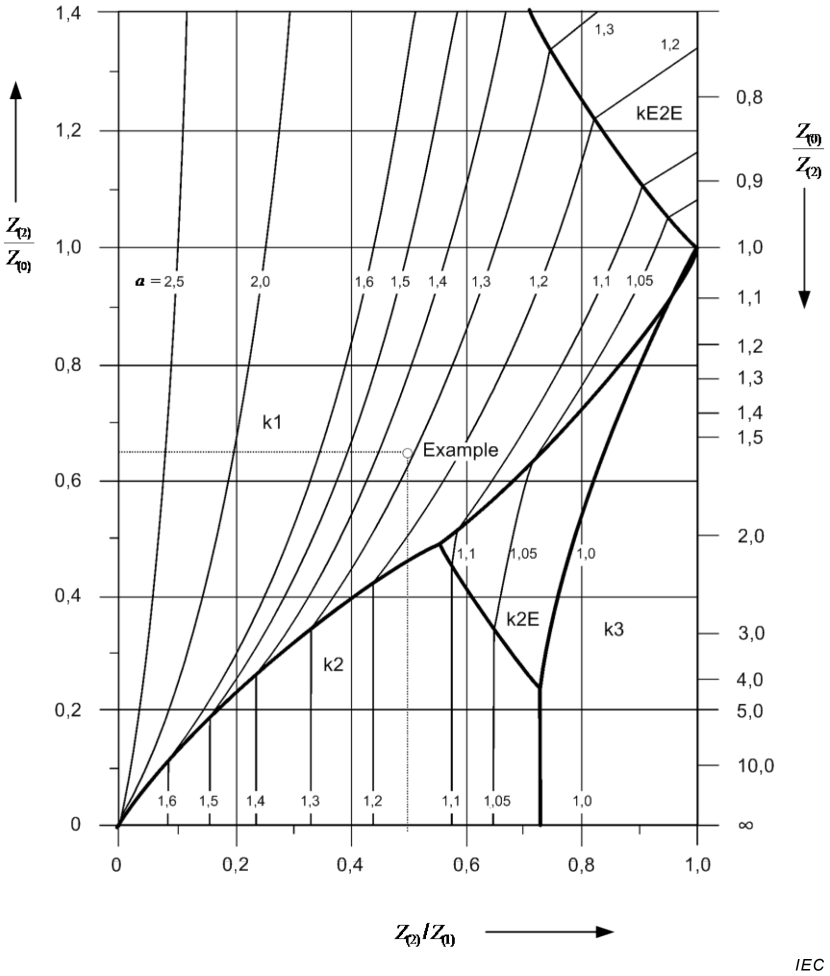
In the calculation of the short-circuit currents in systems supplied by generators, power-stations and motors (near-to-generator and/or near-to-motor short-circuits), it is of interest to know not only the initial symmetrical short-circuit current I''_k and the peak short-circuit current i_p, but also the symmetrical short-circuit breaking current I_b and the steady-state short-circuit current I_k. In this case, the symmetrical short-circuit breaking current I_b is smaller than the initial symmetrical short-circuit current I''_k. Normally, the steady-state short-circuit current I_k is smaller than the symmetrical short-circuit breaking current I_b.

In a near-to-generator short circuit, the AC component of the short-circuit current normally decays with time. An example is shown in Figure 2. It could happen that the decaying short-circuit current reaches zero for the first time, some cycles after the short circuit took place. This is possible if the DC time constant of a synchronous machine is larger than the subtransient time constant. This phenomenon is not dealt with in this standard.

The decaying aperiodic component i_{DC} of the short-circuit current can be calculated according to Formula (81).

If $\underline{Z}_{(2)}$ is not known for the calculation of the initial symmetrical short-circuit current, it is allowed to take $\underline{Z}_{(2)} = \underline{Z}_{(1)}$.

The type of short circuit which leads to the highest short-circuit current depends on the values of the positive-sequence, negative-sequence, and zero-sequence short-circuit impedances of the system. Figure 7 illustrates this for the special case where $\underline{Z}_{(0)}$, $\underline{Z}_{(1)}$ and $\underline{Z}_{(2)}$ have the same impedance angle. Figure 7 is useful for information but should not be used instead of calculation.



a is the relationship of the unbalanced short-circuit current to the three-phase short-circuit current.

Example:

$Z_{(2)} / Z_{(1)} = \mathbf{0{,}50}$
$Z_{(2)} / Z_{(0)} = \mathbf{0{,}65}$
The single line-to-earth short circuit will give the highest short-circuit current

Figure 7 – Diagram to determine the short-circuit type (Figure 3) for the highest initial short-circuit current referred to the initial three-phase short-circuit current when the impedance angles of the sequence impedances $\underline{Z}_{(1)}$, $\underline{Z}_{(2)}$, $\underline{Z}_{(0)}$ are identical

For the common case when $Z_{(0)}$ is larger than $Z_{(2)} = Z_{(1)}$, the highest initial short-circuit current will occur for the three-phase short-circuit. However, for short-circuits near transformers with low zero-sequence impedance, $Z_{(0)}$ may be smaller than $Z_{(1)}$. In that case, the highest initial short-circuit current I''_{kE2E} will occur for a line-to-line short-circuit with earth connection (see Figure 7 for $Z_{(2)}/Z_{(1)} = 1$ and $Z_{(2)}/Z_{(0)} > 1$.

Short circuits may have one or more sources, as shown in Figures 8, 9 and 10. Calculations are simplest for balanced short circuits on radial systems, as the individual contributions to a balanced short circuit can be evaluated separately for each source (Figure 9).

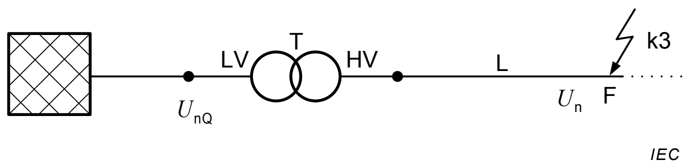


Figure 8a – Short circuit fed from a network feeder via a transformer

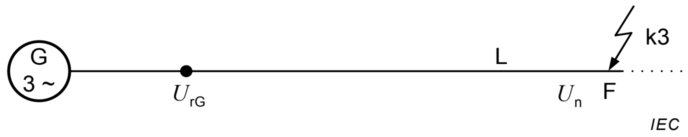


Figure 8b – Short circuit fed from one generator

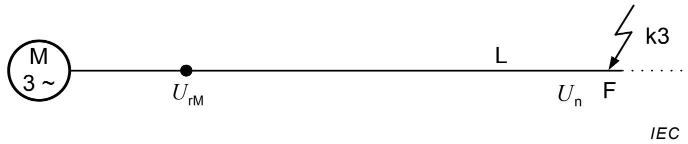


Figure 8c – Short circuit fed from one asynchronous motor

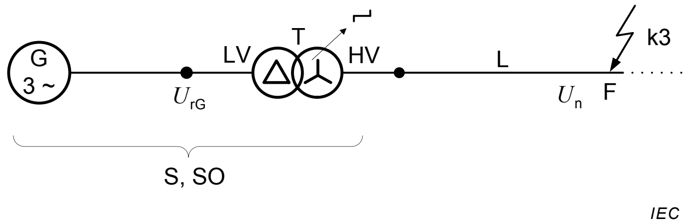


Figure 8d – Short circuit fed from one power station unit (generator and unit transformer with or without on-load tap-changer)

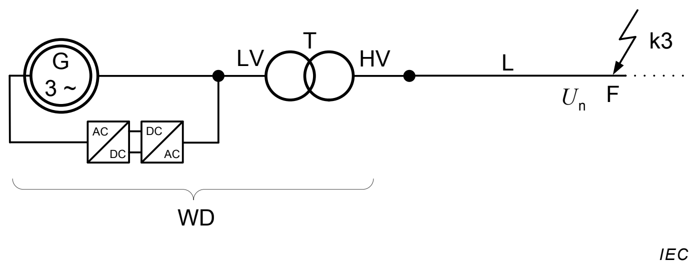


Figure 8e – Short circuit fed from one wind power station unit with doubly fed asynchronous generator

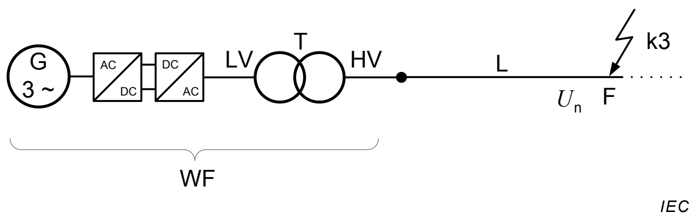


Figure 8f – Short circuit fed from one wind power station unit with full size converter

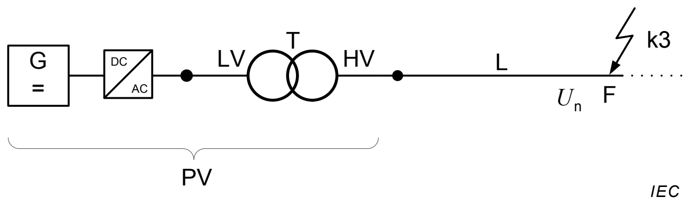


Figure 8g – Short circuit fed from one photovoltaic power station unit with full size converter

Figure 8 – Examples of single-fed short-circuits

While using fuses or current-limiting circuit-breakers to protect substations, the initial symmetrical short-circuit current is first calculated as if these devices were not available. From the calculated initial symmetrical short-circuit current and characteristic curves of the fuses or current-limiting circuit-breakers, the cut-off current is determined, which is the peak short-circuit current of the downstream substation.

For the calculation of the initial symmetrical short-circuit current I_k'' the symmetrical short-circuit breaking current I_b, and the steady-state short-circuit current I_k at the short-circuit location, the system may be converted by network reduction into an equivalent short-circuit impedance $\underline{Z}_k$ at the short-circuit location. This procedure is not allowed when calculating the peak short-circuit current i_p.

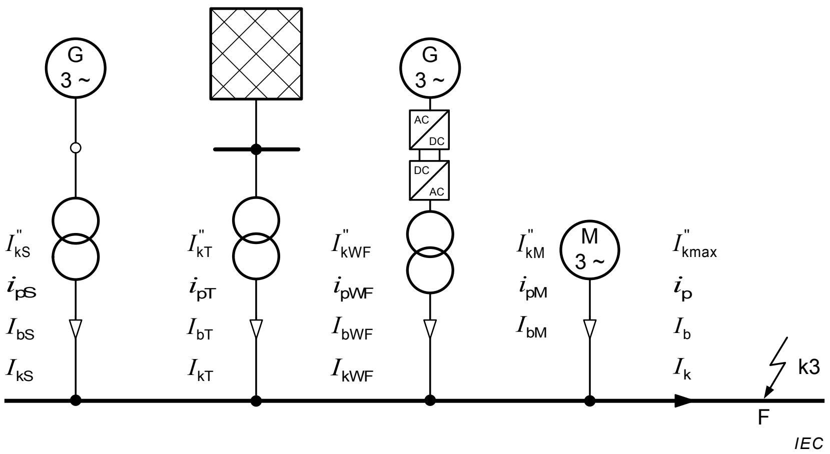


Figure 9 – Example of a multiple single-fed short circuit

In case of multiple-fed short circuit as in Figure 10, and for all cases of unbalanced short circuits, network reduction is necessary to calculate short-circuit impedances $\underline{Z}_{(1)}$, $\underline{Z}_{(2)}$ and $\underline{Z}_{(0)}$ at the short-circuit location.

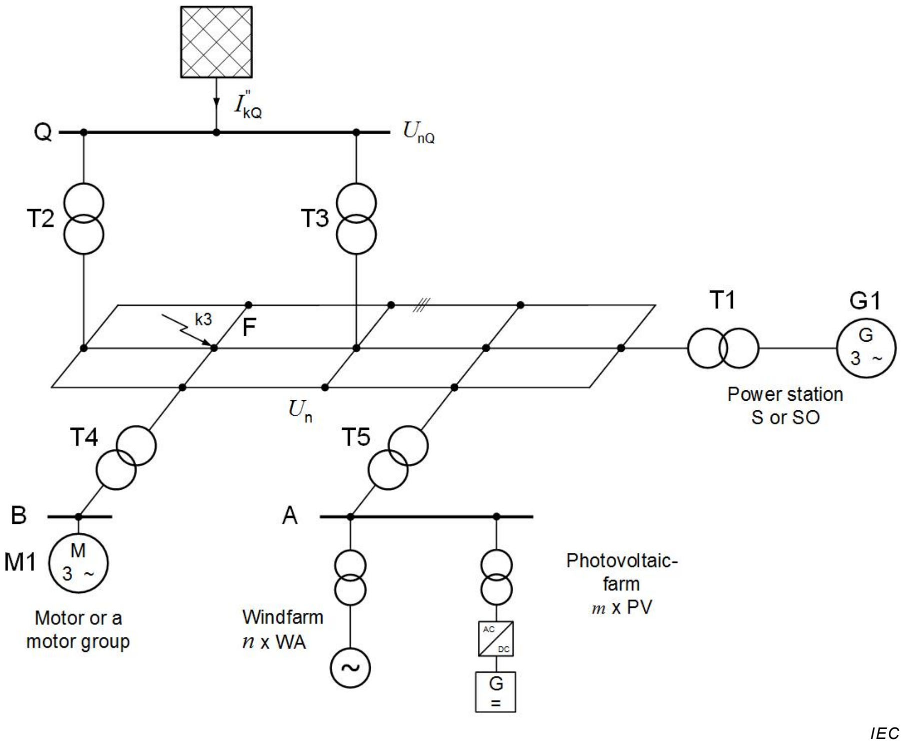


Figure 10a – System diagram

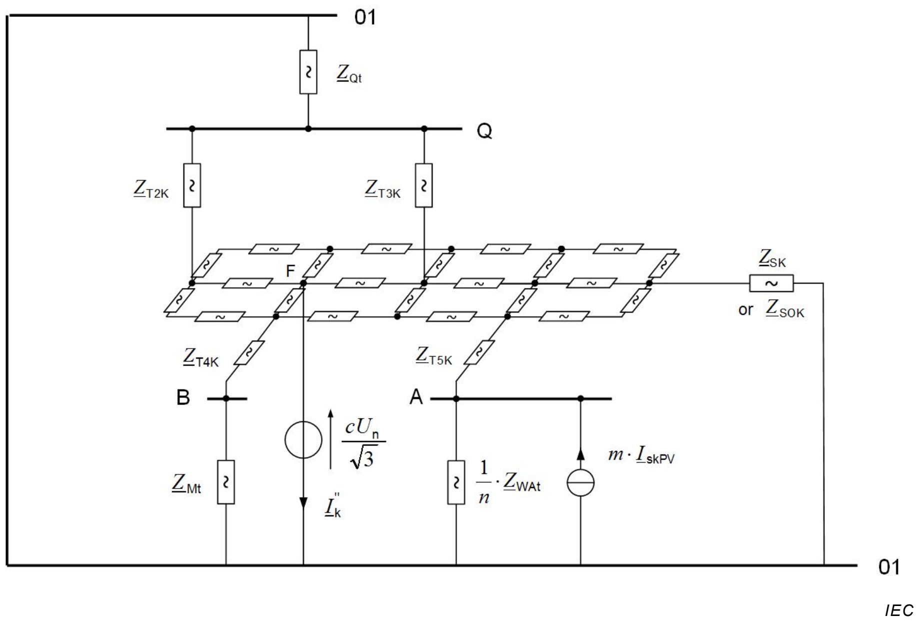


Figure 10b – Equivalent circuit diagram for the calculation of the short-circuit current (cables of the power stations units are neglected)

Figure 10 – Example of multiple-fed short circuit

7.1.2 Maximum and minimum short-circuit currents

When calculating maximum short-circuit currents, the following conditions apply.

a) Voltage factor c_{max} according to Table 1 shall be applied for the calculation of maximum short-circuit currents in the absence of a national standard.

b) Choose the system configuration and the maximum contribution from power station units and network feeders which lead to the maximum value of short-circuit current at the short-circuit location, or for accepted sectioning of the network to control the short-circuit current.

c) Impedance correction factors shall be introduced in the positive-, the negative- and the zero-sequence system with exception of the impedances between neutral point and earth.

d) When equivalent impedances $\underline{Z}_Q$ are used to represent external networks, the minimum equivalent short-circuit impedance shall be used which corresponds to the maximum short-circuit current contribution from the network feeders.

e) Motors shall be included if appropriate in accordance with 6.10.

f) Resistance R_L of lines (overhead lines and cables) shall be introduced at a temperature of 20 °C.

When calculating minimum short-circuit currents, the following conditions apply.

1) Voltage factor c_{min} for the calculation of minimum short-circuit currents shall be applied according to Table 1.
2) Choose the system configuration and the minimum contribution from power station units and network feeders which lead to a minimum value of short-circuit current at the short-circuit location.
3) The impedance correction factors are equal to 1.
4) Contributions of wind power stations units shall be neglected.
5) Contributions of photovoltaic power station units shall be neglected.
6) Contributions of motors shall be neglected.
7) Resistances R_L of lines (overhead lines and cables, line conductors, and neutral conductors) shall be introduced at a higher temperature:

$$R_L = \left[1 + \alpha \cdot \left(\vartheta_e - 20\,°\text{C}\right)\right] \cdot R_{L20} \qquad (32)$$

where

R_{L20} is the resistance at a temperature of 20 °C;

ϑ_e is the conductor temperature in degrees Celsius at the end of the short-circuit duration;

α is a factor equal to 0,004/K, valid with sufficient accuracy for most practical purposes for copper, aluminium and aluminium alloy.

NOTE For ϑ_e, see for instance IEC 60865-1, IEC 60949 and IEC 60986.

7.1.3 Contribution of asynchronous motors to the short-circuit current

Asynchronous motors have to be considered in the calculation of maximum short-circuit current. Low-voltage motors are to be taken into account in auxiliaries of power station units and in industrial and similar installations, for example in networks of chemical and steel industries and pump-stations.

Those high-voltage and low-voltage motors may be neglected, provided that they are not switched in at the same time according to the circuit diagram (interlocking) or to the process (reversible drives).

Low-voltage motors are usually connected to the busbar by cables with different lengths and cross-sections. For simplification of the calculation, groups of motors including their connection cables may be combined to a single equivalent motor.

For these equivalent asynchronous motors, including their connection cables, the following may be used:

Z_M is the impedance according to Formula (30);

I_{rM} is the sum of the rated currents of all motors in a group of motors (equivalent motor);

I_{LR}/I_{rM} = 5;

R_M/X_M = 0,42, leading to κ_M = 1,3;

P_{rM}/p = 0,05 MW if nothing definite is known, where p is the number of pairs of poles.

In the case of a short circuit on the high-voltage side, the rated current of the transformer may be used for the calculation of Z_M according to Formula (30) instead of the sum of the rated currents I_{rM} of all motors.

7.2 Three-phase initial short-circuit current

7.2.1 General

In general, the initial symmetrical short-circuit current I_k'' shall be calculated using Formula (33) with the equivalent voltage source $cU_n/\sqrt{3}$ at the short-circuit location and the short-circuit impedance $Z_k = |R_k + jX_k|$.

$$I_k'' = \frac{c \cdot U_n}{\sqrt{3} \cdot Z_k} = \frac{c \cdot U_n}{\sqrt{3} \cdot \sqrt{R_k^2 + X_k^2}} \qquad (33)$$

The equivalent voltage source $cU_n/\sqrt{3}$ shall be introduced at the short-circuit location (see Figure 4) with the factor c according to Table 1.

The short-circuit impedance can be found by network reduction or from the diagonal element of the nodal impedance matrix of the positive-sequence system for the node i, where the short circuit occurs ($Z_k = Z_{ii}$). The nodal impedance matrix is the inverse of the nodal admittance matrix, see Annex B.

If power station units with full size converter are to be considered, then the maximum initial short-circuit current shall be calculated as follows.

$$I_{kmax}'' = \frac{1}{Z_k}\frac{c_{max} \cdot U_n}{\sqrt{3}} + \frac{1}{Z_k}\sum_{j=1}^{n} Z_{ij} \cdot I_{skPFj} = I_{kmaxPFO}'' + I_{kPF}'' \qquad (34)$$

where

I_{skPFj} is the rms value of the maximum source current (positive-sequence system) in case of three-phase short-circuit at the high-voltage side of the unit transformer, given by the manufacturer;

Z_{ii}, Z_{ij} are the absolute values of the elements of the nodal impedance matrix of the positive-sequence system, where i is the short-circuit node and j are the nodes where power station units with full size converters are connected (see Annex B);

$I_{kmaxPFO}''$ is the maximum initial symmetrical short-circuit current without the influence of power station units with full size converter calculated by Formula (33) using c_{max};

I_{kPF}'' is the sum of the contributions of power station units with full size converter to the initial short-circuit current.

7.2.2 Short-circuit currents inside a power station unit with on-load tap-changer

For calculating the partial short-circuit currents I''_{kG} and I''_{kT} with a short circuit at F1 in Figure 11, in the case of a power station unit with on-load tap-changer, the partial initial symmetrical short-circuit currents are given by:

$$I''_{kG} = \frac{c_{max} \cdot U_{rG}}{\sqrt{3} \cdot K_{G,S} \cdot Z_G} \tag{35}$$

with

$$K_{G,S} = \frac{c_{max}}{1 + x''_d \cdot \sqrt{1 - \cos^2 \varphi_{rG}}} \tag{36}$$

$$I''_{kT} = \frac{c_{max} \cdot U_{rG}}{\sqrt{3} \cdot \left| \underline{Z}_{TLV} + \frac{\underline{Z}_{Qmin}}{t_r^2} \right|} \tag{37}$$

where

Z_G is the subtransient impedance of the generator, see 6.6.1;

x''_d is the saturated subtransient reactance referred to the rated impedance: $x''_d = X''_d / Z_{rG}$ with $Z_{rG} = U^2_{rG} / S_{rG}$;

$\underline{Z}_{TLV}$ is the transformer short-circuit impedance referred to the low-voltage side according to 6.3.1, Formulas (7) to (9);

t_r is the rated transformation ratio;

$\underline{Z}_{Qmin}$ is the minimum value of the impedance of the network feeder, corresponding to I''_{kQmax}.

For I''_{kQmax} the maximum possible value during the lifetime of the power station unit shall be introduced.

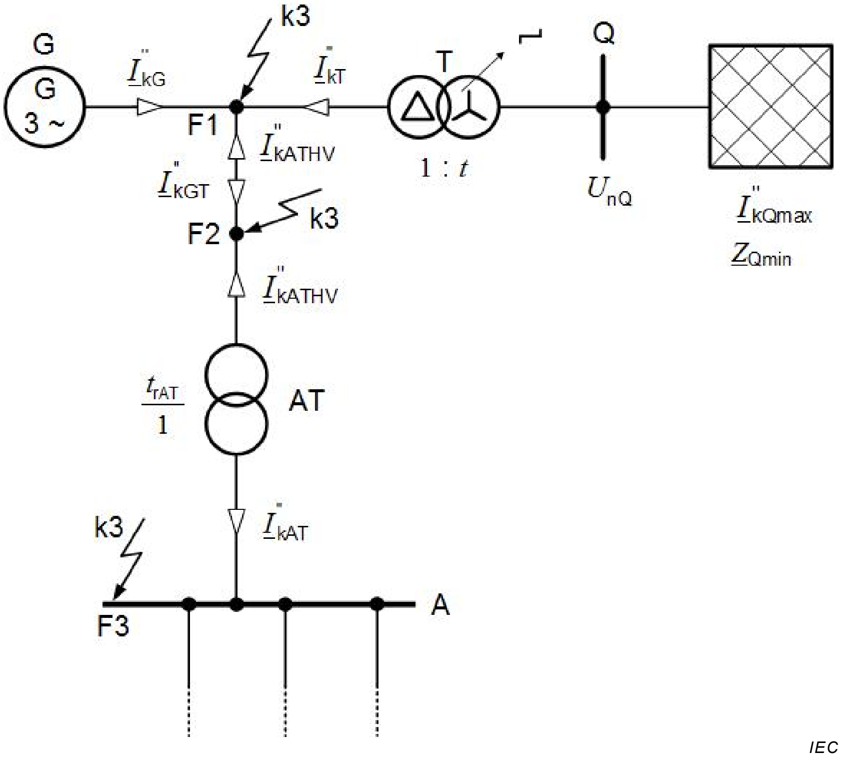


Figure 11 – Short-circuit currents and partial short-circuit currents for three-phase short circuits between generator and unit transformer with or without on-load tap-changer, or at the connection to the auxiliary transformer of a power station unit and at the auxiliary busbar A

For the calculation of the partial short-circuit current $\underline{I}''_{kGT}$ feeding into the short-circuit location F2, for example at the connection to the high-voltage side of the auxiliary transformer AT in Figure 11, it is sufficient to take:

$$\underline{I}''_{kGT} = \frac{c_{max} \cdot U_{rG}}{\sqrt{3}} \cdot \left[\frac{1}{K_{G,S} \cdot \underline{Z}_G} + \frac{1}{K_{T,S} \cdot \underline{Z}_{TLV} + \dfrac{\underline{Z}_{Qmin}}{t_r^2}} \right] = \frac{c_{max} \cdot U_{rG}}{\sqrt{3} \cdot \underline{Z}_S} \tag{38}$$

with

$$K_{T,S} = \frac{c_{max}}{1 - x_T \cdot \sqrt{1 - \cos^2 \varphi_{rG}}} \tag{39}$$

and $K_{G,S}$ according to Formula (36).

If the unit transformer has an on-load tap-changer on the high-voltage side, it is assumed that the operating voltage at the terminals of the generator is equal to U_{rG}. If, even in this case, the voltage region of the generator $U_G = U_{rG}$ $(1 \pm p_G)$ is used permanently, take Formulas (40) to (41) instead of (35) to (36).

The total short-circuit current in F1 or F2 (Figure 11) is found by adding the partial short-circuit current $\underline{I}''_{\text{kATHV}}$, caused by the medium- and low-voltage auxiliary motors of the power station unit.

7.2.3 Short-circuit currents inside a power station unit without on-load tap-changer

For a power station unit without on-load tap-changer of the unit transformer, the partial initial symmetrical short-circuit currents in Figure 11 are given by:

$$I''_{\text{kG}} = \frac{c_{\max} \cdot U_{\text{rG}}}{\sqrt{3} \cdot K_{\text{G,SO}} \cdot Z_{\text{G}}} \tag{40}$$

with

$$K_{\text{G,SO}} = \frac{1}{1 + p_{\text{G}}} \cdot \frac{c_{\max}}{1 + x''_{\text{d}} \cdot \sqrt{1 - \cos^2 \varphi_{\text{rG}}}} \tag{41}$$

$$I''_{\text{kT}} = \frac{c_{\max} \cdot U_{\text{rG}}}{\sqrt{3} \cdot \left| \underline{Z}_{\text{TLV}} + \dfrac{\underline{Z}_{\text{Qmin}}}{t_{\text{r}}^2} \right|} \tag{42}$$

The partial short-circuit current $\underline{I}''_{\text{kGT}}$ in Figure 11 can be calculated by:

$$\underline{I}''_{\text{kGT}} = \frac{c_{\max} \cdot U_{\text{rG}}}{\sqrt{3}} \cdot \left[\frac{1}{K_{\text{G,SO}} \cdot \underline{Z}_{\text{G}}} + \frac{1}{K_{\text{T,SO}} \cdot \underline{Z}_{\text{TLV}} + \dfrac{\underline{Z}_{\text{Qmin}}}{t_{\text{r}}^2}} \right] = \frac{c_{\max} \cdot U_{\text{rG}}}{\sqrt{3} \cdot \underline{Z}_{\text{SO}}} \tag{43}$$

with

$$K_{\text{T,SO}} = \frac{1}{1 + p_{\text{G}}} \cdot \frac{c_{\max}}{1 - x_{\text{T}} \cdot \sqrt{1 - \cos^2 \varphi_{\text{rG}}}} \tag{44}$$

and $K_{\text{G,SO}}$ according to Formula (41).

For $\underline{Z}_{\text{G}}$, x''_{d}, $\underline{Z}_{\text{TLV}}$, t_{r} and $\underline{Z}_{\text{Qmin}}$, see 7.2.2.

The Formula (38) or (43) and the impedance $\underline{Z}_{\text{S}}$ resp. $\underline{Z}_{\text{SO}}$ are used to determine the partial short-circuit current $\underline{I}''_{\text{kAT}}$ in Figure 11 for the short-circuit in F3. The impedance of the auxiliary transformer AT in Figure 11 is to be corrected with K_{T} from 6.3.3.

The total short-circuit current in F1 or F2 (Figure 11) is found by adding the partial short-circuit current $\underline{I}''_{\text{kATHV}}$, caused by the high- and low-voltage auxiliary motors of the power station unit.

7.3 Line-to-line short circuit

In the case of a line-to-line short circuit, according to Figure 3b, the initial short-circuit current shall be calculated by:

$$I''_{k2} = \frac{\sqrt{3}}{\left|\underline{Z}_{(1)} + \underline{Z}_{(2)}\right|} \cdot \frac{c \cdot U_n}{\sqrt{3}} \tag{45}$$

If $\underline{Z}_{(2)} = \underline{Z}_{(1)}$, then Formula (45) becomes

$$I''_{k2} = \frac{\sqrt{3}}{2} I''_k \tag{46}$$

If power station units with full size converter are to be considered, the maximum initial short-circuit current shall be calculated as follows.

$$I''_{k2max} = \frac{\sqrt{3}}{\left|\underline{Z}_{(1)ii} + \underline{Z}_{(2)ii}\right|} \frac{c_{max} \cdot U_n}{\sqrt{3}} + \frac{\sqrt{3}}{\left|\underline{Z}_{(1)ii} + \underline{Z}_{(2)ii}\right|} \sum_{j=1}^{n} \underline{Z}_{(1)ij} \cdot I_{(1)sk2PFj} = I''_{k2maxPFO} + I''_{k2PF} \tag{47}$$

where

$I_{(1)sk2PFj}$	is the rms value of the maximum source current (positive-sequence system) in case of a line-to-line short circuit at the high-voltage side of the unit transformer, given by the manufacturer;
$\underline{Z}_{(1)ii} = \underline{Z}_{ii}$	is the i^{th} diagonal element of the nodal impedance matrix of the positive-sequence system, where i is the short-circuit node;
$\underline{Z}_{(2)ii}$	is the i^{th} diagonal element of the nodal impedance matrix of the negative-sequence system including the impedances of the power station units with full size converter, where i is the short-circuit node;
$\underline{Z}_{(1)ij} = \underline{Z}_{ij}$	are the elements of the nodal impedance matrix of the positive-sequence system, where i is the short-circuit node and j are the nodes where power station units with full size converters are connected;
$I''_{k2maxPFO}$	is the maximum initial symmetrical short-circuit current calculated by the equivalent voltage source at the short-circuit location without influence of the source currents of the power station units with full size converter;
I''_{k2PF}	is the sum of the contributions of power station units with full size converter to the initial short-circuit current.

7.4 Line-to-line short circuit with earth connection

To calculate the initial symmetrical short-circuit currents it is necessary to distinguish between the currents I''_{k2EL2}, I''_{k2EL3}, and I''_{kE2E} (see Figure 3c).

If $\underline{Z}_{(0)}$ is less than $\underline{Z}_{(2)} = \underline{Z}_{(1)}$, the current I''_{kE2E} in the line-to-line short circuit with earth connection generally is the largest of all initial symmetrical short-circuit currents $I''_k = I''_{k3}$, I''_{k2}, I''_{k2E} and I''_{k1} (see Figure 7).

The currents I''_{k2EL2} and I''_{k2EL3} (see Figure 3c) are calculated according to Formulas (48) and (49):

$$\underline{I}''_{\text{k2EL2}} = \left| \frac{\sqrt{3}\left(\underline{Z}_{(0)} - \underline{a}\underline{Z}_{(2)}\right)}{\underline{Z}_{(1)}\underline{Z}_{(2)} + \underline{Z}_{(1)}\underline{Z}_{(0)} + \underline{Z}_{(2)}\underline{Z}_{(0)}} \right| \cdot \frac{cU_{\text{n}}}{\sqrt{3}} \tag{48}$$

$$I''_{\text{k2EL3}} = \left| \frac{\sqrt{3}\left(\underline{Z}_{(0)} - \underline{a}^2\underline{Z}_{(2)}\right)}{\underline{Z}_{(1)}\underline{Z}_{(2)} + \underline{Z}_{(1)}\underline{Z}_{(0)} + \underline{Z}_{(2)}\underline{Z}_{(0)}} \right| \cdot \frac{cU_{\text{n}}}{\sqrt{3}} \tag{49}$$

The initial short-circuit current I''_{kE2E}, flowing to earth and/or grounded wires, according to Figure 3c, is calculated by:

$$I''_{\text{kE2E}} = \left| \frac{3\underline{Z}_{(2)}}{\underline{Z}_{(1)}\underline{Z}_{(2)} + \underline{Z}_{(1)}\underline{Z}_{(0)} + \underline{Z}_{(2)}\underline{Z}_{(0)}} \right| \cdot \frac{cU_{\text{n}}}{\sqrt{3}} \tag{50}$$

If power station units with full size converter are to be considered, then the maximum initial short-circuit currents shall be calculated as follows.

$$\begin{aligned} I''_{\text{k2EL2max}} &= \left| \frac{\sqrt{3}\left(\underline{Z}_{(0)ii} - \underline{a}\underline{Z}_{(2)ii}\right)}{\underline{Z}_{(1)ii}\underline{Z}_{(2)ii} + \underline{Z}_{(1)ii}\underline{Z}_{(0)ii} + \underline{Z}_{(2)ii}\underline{Z}_{(0)ii}} \right| \cdot \left(\frac{c_{\max}U_{\text{n}}}{\sqrt{3}} + \sum_{j=1}^{n} Z_{(1)ij} I_{(1)\text{sk2PF}j} \right) \\ &= I''_{\text{k2EL2maxPFO}} + I''_{\text{k2EL2PF}} \end{aligned} \tag{51}$$

$$\begin{aligned} I''_{\text{k2EL3max}} &= \left| \frac{\sqrt{3}\left(\underline{Z}_{(0)ii} - \underline{a}^2\underline{Z}_{(2)ii}\right)}{\underline{Z}_{(1)ii}\underline{Z}_{(2)ii} + \underline{Z}_{(1)ii}\underline{Z}_{(0)ii} + \underline{Z}_{(2)ii}\underline{Z}_{(0)ii}} \right| \cdot \left(\frac{c_{\max}U_{\text{n}}}{\sqrt{3}} + \sum_{j=1}^{n} Z_{(1)ij} I_{(1)\text{sk2PF}j} \right) \\ &= I''_{\text{k2EL3maxPFO}} + I''_{\text{k2EL3PF}} \end{aligned} \tag{52}$$

$$\begin{aligned} I''_{\text{kE2Emax}} &= \left| \frac{3\underline{Z}_{(2)ii}}{\underline{Z}_{(1)ii}\underline{Z}_{(2)ii} + \underline{Z}_{(1)ii}\underline{Z}_{(0)ii} + \underline{Z}_{(2)ii}\underline{Z}_{(0)ii}} \right| \cdot \left(\frac{c_{\max}U_{\text{n}}}{\sqrt{3}} + \sum_{j=1}^{n} Z_{(1)ij} I_{(1)\text{sk2PF}j} \right) \\ &= I''_{\text{k2E2maxPFO}} + I''_{\text{kE2EPF}} \end{aligned} \tag{53}$$

where

$I_{(1)\text{sk2PF}j}$ is the rms value of the maximum source current (positive-sequence system) in case of a line-to-line short circuit at the high-voltage side of the unit transformer, given by the manufacturer;

$\underline{Z}_{(1)ii} = \underline{Z}_{ii}$ is the i^{th} diagonal element of the nodal impedance matrix of the positive-sequence system, where i is the short-circuit node;

$\underline{Z}_{(2)ii}$ is the i^{th} diagonal element of the nodal impedance matrix of the negative-sequence system including the impedances of the power station units with full size converter, where i is the short-circuit node;

$\underline{Z}_{(0)ii}$ is the i^{th} diagonal element of the nodal impedance matrix of the zero-sequence system, where i is the short-circuit node;

$\underline{Z}_{(1)ij} = \underline{Z}_{ij}$ are the elements of the nodal impedance matrix of the positive-sequence system, where i is the short-circuit node and j are the nodes where power station units with full size converters are connected.

7.5 Line-to-earth short circuit

The initial line-to-earth short-circuit current I''_{k1} in Figure 3d shall be calculated by:

$$I''_{k1} = \frac{3}{\left|\underline{Z}_{(1)} + \underline{Z}_{(2)} + \underline{Z}_{(0)}\right|} \cdot \frac{cU_n}{\sqrt{3}} \tag{54}$$

If $Z_{(0)}$ is less than $Z_{(2)} = Z_{(1)}$, the initial line-to-earth short-circuit current I''_{k1} is larger than the three-phase short-circuit current I''_k, but smaller than I''_{kE2E} (see Figure 7). However, I''_{k1} will be the highest current to be interrupted by a circuit breaker if 1,0 > $Z_{(0)}/Z_{(1)}$ > 0,23.

If power stations with full size converter are to be considered, then the maximum initial short-circuit current shall be calculated as follows.

$$I''_{k1max} = \frac{3}{\left|\underline{Z}_{(1)ii} + \underline{Z}_{(2)ii} + \underline{Z}_{(0)ii}\right|} \frac{c_{max} \cdot U_n}{\sqrt{3}} + \frac{3}{\left|\underline{Z}_{(1)ii} + \underline{Z}_{(2)ii} + \underline{Z}_{(0)ii}\right|} \sum_{j=1}^{n} \underline{Z}_{(1)ij} \cdot I_{(1)sk1PFj} = I''_{k1maxPFO} + I''_{k1PF} \tag{55}$$

where

$I_{(1)sk1PFj}$ is the rms value of the maximum source current (positive-sequence system) in case of a line-to-earth short circuit at the high-voltage side of the unit transformer, given by the manufacturer;

$\underline{Z}_{(1)ii} = \underline{Z}_{ii}$ is the i^{th} diagonal element of the nodal impedance matrix of the positive-sequence system, where i is the short-circuit node;

$\underline{Z}_{(2)ii}$ is the i^{th} diagonal element of the nodal impedance matrix of the negative-sequence system including the impedances of the power station units with full size converter, where i is the short-circuit node;

$\underline{Z}_{(0)ii}$ is the i^{th} diagonal element of the nodal impedance matrix of the zero-sequence system, where i is the short-circuit node;

$\underline{Z}_{(1)ij} = \underline{Z}_{ij}$ are the elements of the nodal impedance matrix of the positive-sequence system, where i is the short-circuit node and j are the nodes where power station units with full size converters are connected;

$I''_{k1maxPFO}$ is the maximum initial symmetrical short-circuit current calculated by the equivalent voltage source at the short-circuit location without influence of the source currents of the power station units with full size converter;

I''_{k1PF} is the sum of the contributions of wind power station units with full size converter to the initial short-circuit current.

8 Calculation of peak short-circuit current

8.1 Three-phase short circuit

8.1.1 Single-fed and multiple single-fed short circuits

For single-fed and multiple single-fed three-phase short circuits, the contribution of each source to the peak short-circuit current can be calculated separately and has to be added to the resultant peak short-circuit current. For branches with synchronous generators/motors and asynchronous motors/generators as in Figures 8a to 8d the peak short-circuit current can be calculated by:

$$i_p = \kappa\sqrt{2}I''_k \tag{56}$$

In this case, it is assumed that the branches do not include parallel impedances. Networks with branches with parallel impedances are to be treated as multiple-fed short circuits (see 8.1.2).

The factor κ for the R/X or X/R ratio shall be obtained from Figure 12 or calculated by the following expression:

$$\kappa = 1{,}02 + 0{,}98\mathrm{e}^{-3R/X} \tag{57}$$

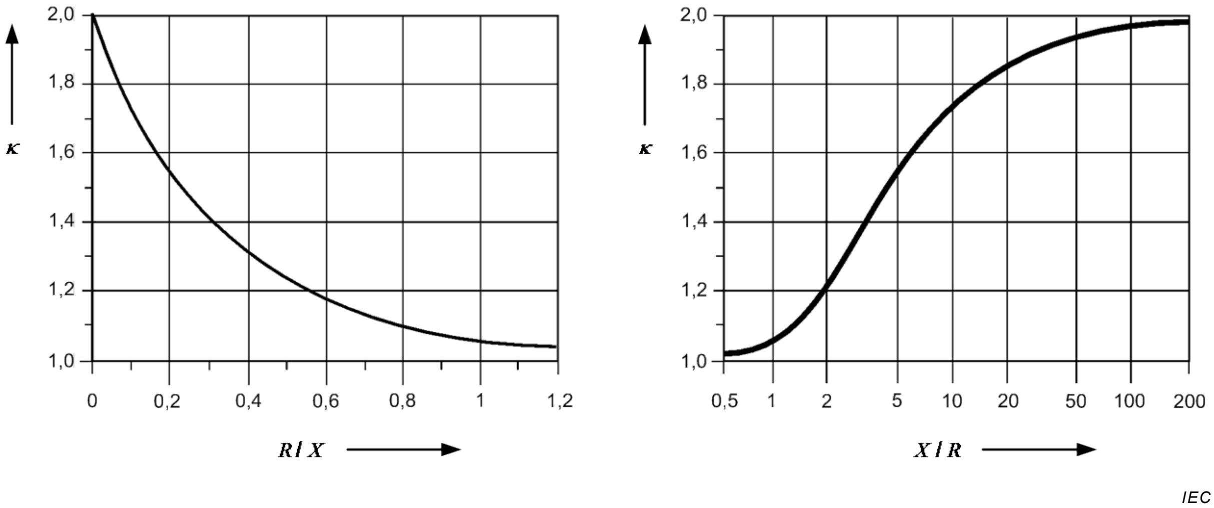


Figure 12 – Factor κ for series circuit as a function of ratio R/X or X/R

In case of branches with synchronous generators and power station units, the following values for the fictitious resistances R_{Gf} are to be used for the calculation of the peak short-circuit current with sufficient accuracy.

$R_{\mathrm{Gf}} = 0{,}05 \cdot X''_{\mathrm{d}}$ for generators with $U_{\mathrm{rG}} > 1$ kV and $S_{\mathrm{rG}} \geq 100$ MVA

$R_{\mathrm{Gf}} = 0{,}07 \cdot X''_{\mathrm{d}}$ for generators with $U_{\mathrm{rG}} > 1$ kV and $S_{\mathrm{rG}} < 100$ MVA

$R_{\mathrm{Gf}} = 0{,}15 \cdot X''_{\mathrm{d}}$ for generators with $U_{\mathrm{rG}} \leq 1000$ V

In addition to the decay of the DC component, the factors 0,05, 0,07, and 0,15 also take into account the decay of the AC component of the short-circuit current during the first half-cycle after the short circuit took place. The influence of various winding-temperatures on R_{Gf} is not considered.

The values R_{Gf} should be used for the calculation of the peak short-circuit current. These values cannot be used when calculating the aperiodic component i_{DC} of the short-circuit current according to Formula (76). The effective resistance of the stator of synchronous machines lies generally much below the given values for R_{Gf}. In this case the manufacturer's values for R_{G} should be used.

For one power station unit with full size converter, according to Figures 8f and 8g, the peak short-circuit current is determined by:

$$i_{\mathrm{p}} = \sqrt{2} I''_{\mathrm{kPF}} = \sqrt{2} I_{\mathrm{skPF}} \tag{58}$$

The peak short-circuit current i_p at a short-circuit location F is the sum of the partial short-circuit currents:

$$i_p = \sum_i i_{pi} \tag{59}$$

Figure 9 example:

$$i_p = i_{pS} + i_{pT} + i_{pWF} + i_{pM} \tag{60}$$

8.1.2 Multiple-fed short circuit

For calculating the peak short-circuit current i_p the following formula shall be used:

$$i_p = \kappa\sqrt{2} \cdot I''_{kmaxPFO} + \sqrt{2} \cdot I''_{kPF} \tag{61}$$

where

$I''_{kmax\,PFO}$ is the maximum initial three-phase short-circuit current without influence of power station units with full size converter calculated by Formula (33);

I''_{kPF} is the contribution of the power station units with full size converter calculated by Formula (34).

The factor κ shall be calculated by Formula (57) with one of the following methods a), b), or c) for determination of the ratio R/X. Method c) is recommended (see IEC TR 60909-1).

a) Uniform ratio R/X or X/R

For this method the smallest ratio of R/X or the largest ratio of X/R of all branches of the network is taken.

It is necessary to choose only the branches which carry partial short-circuit currents at the nominal voltage corresponding to the short-circuit location and branches with transformers feeding the voltage level of the short-circuit location. Any branch may be a series combination of several impedances.

b) Ratio R/X or X/R at the short-circuit location

For this method, the ratio R_k/X_k given by the short-circuit impedance $\underline{Z}_k = R_k + jX_k$ (seen from the short-circuit location) of the initial short-circuit calculation is used.

To cover inaccuracies, the factor κ determined with the ratio R_k/X_k is multiplied by a factor 1,15.

As long as R/X remains smaller than 0,3 in all branches which carry a short-circuit current, it is not necessary to use the factor 1,15. It is also not necessary for the product $1{,}15 \cdot \kappa$ to exceed 1,8 in low-voltage networks or to exceed 2,0 in high-voltage networks.

c) Equivalent frequency f_c

An equivalent impedance $Z_c = R_c + jX_c$ of the positive-sequence system as seen from the short-circuit location is calculated assuming a frequency f_c = 20 Hz (for a nominal frequency of f = 50 Hz) or f_c = 24 Hz (for a nominal frequency of f = 60 Hz). The R/X or X/R ratio is then determined according to Formula (62).

$$\frac{R}{X} = \frac{R_c}{X_c} \cdot \frac{f_c}{f} \qquad \frac{X}{R} = \frac{X_c}{R_c} \cdot \frac{f}{f_c} \tag{62}$$

where

$\underline{Z}_c$ = R_c + jX_c is the equivalent impedance of the system as seen from the short-circuit location for the assumed frequency f_c;

R_c is the real part of $\underline{Z}_c$ (R_c is generally not equal to the R at nominal frequency);

X_c is the imaginary part of $\underline{Z}_c$ (X_c is generally not equal to the X at nominal frequency).

When using this method with transformers, generators and power station units, the impedance correction factors K_T, K_G and K_S, respectively K_{SO}, shall be introduced with the same values as for the 50 Hz or 60 Hz calculations.

8.2 Line-to-line short circuit

For a line-to-line short circuit in a network with power station units with full size converter, the peak short-circuit current can be expressed by:

$$i_{p2} = \kappa\sqrt{2}I''_{k2maxPFO} + \sqrt{2}I''_{k2PF} \tag{63}$$

where

$I''_{k2max\,PFO}$ is the maximum initial line-to-line short-circuit current without influence of the source currents of power station units with full size converter calculated according to Formula (47);

I''_{k2PF} is the contribution of the power station units with full size converter calculated according to Formula (47).

The factor κ shall be calculated according to 8.1 depending on the system configuration.

8.3 Line-to-line short circuit with earth connection

For a line-to-line short circuit with earth connection, the peak short-circuit current (e.g. of line L2) can be expressed by:

$$i_{p2EL2} = \kappa\sqrt{2}I''_{k2EL2maxPFO} + \sqrt{2}I''_{k2EL2PF} \tag{64}$$

where

$I''_{k2EL2max\,PFO}$ is the maximum initial line-to-line short-circuit current without influence of the source currents of power station units with full size converter calculated according to Formula (51);

$I''_{k2EL2PF}$ is the contribution of the power station units with full size converter calculated according to Formula (51).

The factor κ shall be calculated according to 8.1 depending on the system configuration.

8.4 Line-to-earth short circuit

For a line-to-earth short circuit, the peak short-circuit current can be expressed by:

$$i_{p1} = \kappa\sqrt{2}I''_{k1maxPFO} + \sqrt{2}I''_{k1PF} \tag{65}$$

where

$I''_{k1max\,PFO}$ is the maximum initial line-to-earth short-circuit current without influence of the source currents of power station units with full size converter calculated according to Formula (55);

I''_{k1PF} is the contribution of the power station units with full size converter calculated according to Formula (55).

The factor κ shall be calculated according to 8.1 depending on the system configuration.

9 Calculation of symmetrical breaking current

9.1 Three-phase short circuit

9.1.1 Symmetrical breaking current of synchronous machines

For a near-to-generator short circuit, in the case of a single-fed short circuit as in Figure 8b, 8c and 8d or multiple single-fed short circuit as in Figure 9, the decay to the symmetrical short-circuit breaking current of a synchronous generator is taken into account by the factor μ according to Formula (67).

$$I_b = \mu \cdot I''_{kmax} \tag{66}$$

The factor μ depends on the minimum time delay t_{min} and the ratio I''_{kG}/I_{rG}, where I_{rG} is the rated generator current. The values of μ in Formula (67) apply if synchronous machines are excited by rotating exciters or by static converter exciters (provided, for static exciters, the minimum time delay t_{min} is less than 0,25 s and the maximum excitation voltage is less than 1,6 times the rated load excitation-voltage). For all other cases take μ = 1, if the exact value is unknown.

NOTE The AC component of the current in case of near-to-generator short circuits may decay faster than the DC component. The magnitude of the AC component of the current depends upon the operating conditions of the generator before short circuit; the decay of the AC component is governed by the subtransient and transient time constants, the decay of the DC component by the armature time constant. As a consequence, the DC component during a certain period of time can be higher than the peak value of the AC component. In such a case the fault current shows delayed current zero. In order to evaluate if power station equipment can handle this current, the AC and DC components of the short-circuit current have to be calculated taking into account the synchronous, transient and subtransient reactances, the transient and subtransient time constants, the circuit-breaker arc resistance as well as the operation condition before short circuit.

When there is a unit transformer between the generator and the short-circuit location, the partial short-circuit current I''_{kS} at the high-voltage side of the unit transformer (in Figure 8c) shall be transferred by the rated transformation ratio to the terminal of the generator $I''_{kG} = t_r \cdot I''_{kS}$ before calculating μ, using the following formulas:

$$\begin{aligned}
\mu &= 0{,}84 + 0{,}26\,e^{-0{,}26 I''_{kG}/I_{rG}} && \text{for } t_{min} = 0{,}02 \text{ s} \\
\mu &= 0{,}71 + 0{,}51\,e^{-0{,}30 I''_{kG}/I_{rG}} && \text{for } t_{min} = 0{,}05 \text{ s} \\
\mu &= 0{,}62 + 0{,}72\,e^{-0{,}32 I''_{kG}/I_{rG}} && \text{for } t_{min} = 0{,}10 \text{ s} \\
\mu &= 0{,}56 + 0{,}94\,e^{-0{,}38 I''_{kG}/I_{rG}} && \text{for } t_{min} \geq 0{,}25 \text{ s}
\end{aligned} \tag{67}$$

If I''_{kG}/I_{rG} is not greater than 2, apply μ = 1 for all values of the minimum time delay t_{min}. The factor μ may also be obtained from Figure 13. For other values of minimum time delay, linear interpolation between curves is acceptable.

Figure 13 can be used also for compound excited low-voltage generators with a minimum time delay t_{min} not greater than 0,1 s. The calculation of low-voltage breaking currents after a time delay t_{min} greater than 0,1 s is not included in this standard; generator manufacturers may be able to provide information.

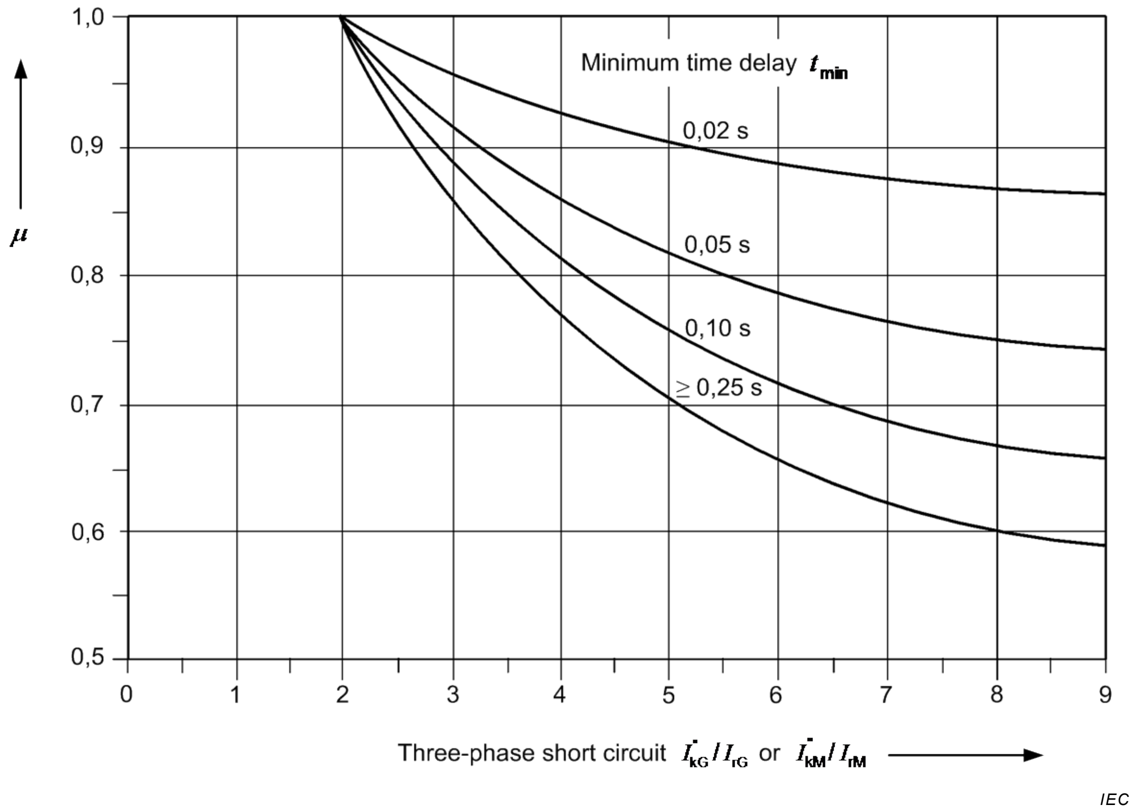


Figure 13 – Factor μ for calculation of short-circuit breaking current I_b

9.1.2 Symmetrical breaking current of asynchronous machines

The symmetrical short-circuit breaking current of an asynchronous machine shall be calculated by Formula (68) with factor μ according to Formula (67) or Figure 13 using I''_{kM}/I_{rM} (see Table 4) and the factor q.

$$I_b = \mu \cdot q \cdot I''_{kmax} \tag{68}$$

Formula (67) shall also be used for the calculation of the symmetrical short-circuit breaking current of wind power stations with asynchronous generator with I''_{kWA}.

The factor q may be determined as a function of the minimum time delay t_{min} or may be taken from Figure 14.

$$\begin{aligned}
q &= 1{,}03 + 0{,}12 \ln(P_{rM}/p) && \text{for } t_{min} = 0{,}02 \text{ s} \\
q &= 0{,}79 + 0{,}12 \ln(P_{rM}/p) && \text{for } t_{min} = 0{,}05 \text{ s} \\
q &= 0{,}57 + 0{,}12 \ln(P_{rM}/p) && \text{for } t_{min} = 0{,}10 \text{ s} \\
q &= 0{,}26 + 0{,}10 \ln(P_{rM}/p) && \text{for } t_{min} \geq 0{,}25 \text{ s}
\end{aligned} \tag{69}$$

where

P_{rM} is the rated active power in MW and p is the number of pairs of poles of the asynchronous machine.

If the calculation in Formula (69) provides larger values than 1 for q, assume that q = 1.

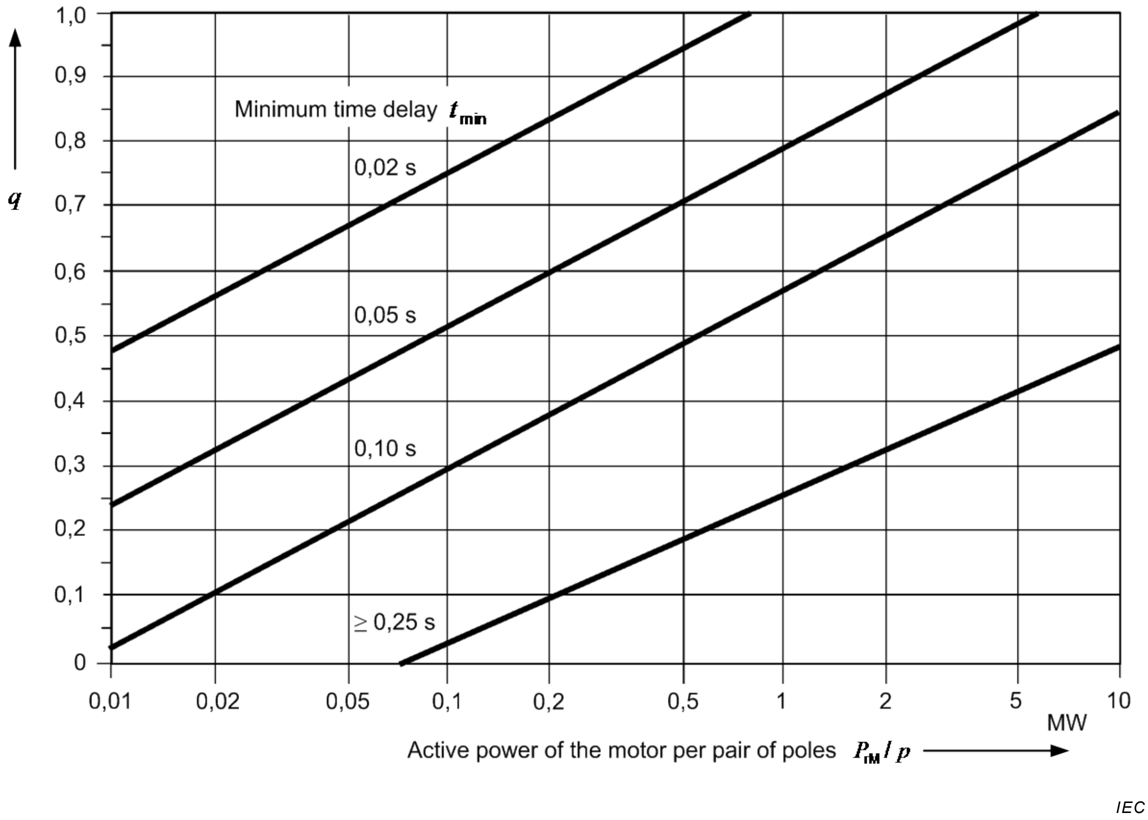


Figure 14 – Factor q for the calculation of the symmetrical short-circuit breaking current of asynchronous motors

9.1.3 Symmetrical breaking current of power station units with doubly fed asynchronous generator

The symmetrical breaking current of power station units with doubly fed asynchronous generators can be calculated according to Formula (70).

$$I_b = \mu_{WD} \cdot I''_{kWD} \tag{70}$$

with

$$\mu_{WD} = \frac{I_{kWDmax}}{I''_{kWD}} \tag{71}$$

I_{kWDmax} is the maximum steady state short-circuit current, given by the manufacturer (see 11.2.3)

9.1.4 Symmetrical breaking current of power station units with full size converter

The symmetrical breaking current of power station units with full size converters can be calculated according to Formula (72).

$$I_b = I_{kPFmax} \tag{72}$$

where

I_{kPFmax} is the maximum steady state short-circuit current, see 11.2.4.

9.1.5 Symmetrical breaking current of network feeder

The symmetrical breaking current of network feeders can be calculated according to Formula (73).

$$I_b = I''_{kmax} \tag{73}$$

9.1.6 Symmetrical breaking current in case of multiple single-fed short-circuits

For multiple single-fed three-phase short circuits as in Figure 9, the symmetrical breaking current at the short-circuit location can be calculated by the summation of the individual breaking current contributions:

$$I_b = \sum_i I_{bi} \tag{74}$$

Figure 9 example:

$$I_b = I_{bS} + I_{bT} + I_{bWF} + I_{bM} = \mu \cdot I''_{kS} + I''_{kT} + I''_{kWFmax} + \mu \cdot q \cdot I''_{kM} \tag{75}$$

where

I''_{kS}, I''_{kT}, I''_{kWF} and I''_{kM} are taken as its contributions to I''_{kmax} at the short-circuit location.

At first the maximum short-circuit current is calculated, and then the partial currents in the branches where the circuit breakers are located.

9.1.7 Symmetrical breaking current in case of multiple-fed short circuits

In case of multiple-fed short circuits, current I_b can be calculated by:

$$I_b = I''_{kmax} \tag{76}$$

Currents calculated with Formula (76) are larger than the real symmetrical short-circuit breaking currents. For increased accuracy, Formula (77) can be used.

$$\begin{aligned} \underline{I}_b = \underline{I}''_{kmax} &- \sum_i \frac{\underline{Z}_{GKi} \cdot \underline{I}''_{kGi}}{cU_n/\sqrt{3}} \cdot (1-\mu_i) \cdot \underline{I}''_{kGi} - \sum_j \frac{\underline{Z}_{Mj} \cdot \underline{I}''_{kMj}}{cU_n/\sqrt{3}} \cdot (1-\mu_j q_j) \cdot \underline{I}''_{kMj} \\ &- \sum_k \frac{\underline{Z}_{SKk} \cdot \underline{I}''_{kSk}}{cU_n/\sqrt{3}} \cdot (1-\mu_k) \cdot \underline{I}''_{kSk} - \sum_l \frac{\underline{Z}_{SOKl} \cdot \underline{I}''_{kSOl}}{cU_n/\sqrt{3}} \cdot (1-\mu_l) \cdot \underline{I}''_{kSOl} \\ &- \sum_m \frac{\underline{Z}_{WAm} \cdot \underline{I}''_{kWAm}}{cU_n/\sqrt{3}} \cdot (1-\mu_m) \cdot \underline{I}''_{kWAm} - \sum_n \frac{\underline{Z}_{WDn} \cdot \underline{I}''_{kWDn}}{cU_n/\sqrt{3}} \cdot (1-\mu_n) \cdot \underline{I}''_{kWDn} \end{aligned} \tag{77}$$

where

μ_i, μ_j, μ_k, μ_l, μ_m	are calculated with Formula (67);
μ_n	is calculated with Formula (71);
q_j	is calculated with Formula (69);
$cU_n/\sqrt{3}$	is the equivalent voltage source at the short-circuit location;

$\underline{Z}_{GKi}$	is the corrected short-circuit impedance of the i^{th} synchronous machine;
$\underline{Z}_{Mj}$	is the short-circuit impedance of the j^{th} asynchronous motor;
$\underline{Z}_{SKk}$	is the corrected short-circuit impedance of the k^{th} power station unit with on-load tap-changer;
$\underline{Z}_{SOKl}$	is the corrected short-circuit impedance of the l^{th} power station unit without on-load tap-changer;
$\underline{Z}_{WAm}$	is the short–circuit impedance of the m^{th} wind power station unit with asynchronous generator;
$\underline{Z}_{WDn}$	is the short–circuit impedance of the n^{th} wind power station unit with doubly-fed asynchronous generator;
$\underline{I}''_{kGi}$, $\underline{I}''_{kMj}$	are the contributions from the i^{th} synchronous generator or the j^{th} the asynchronous motor;
$\underline{I}''_{kSk}$, $\underline{I}''_{kSOl}$	are the contributions from the k^{th} power station unit with on-load tap-changer or the l^{th} power station unit without on-load tap-changer;
$\underline{I}''_{kWAm}$, $\underline{I}''_{kWDn}$	are the contributions from the m^{th} wind power station unit with asynchronous generator or from the n^{th} wind power station unit with doubly fed asynchronous generator;
c	is the voltage factor according to Table 1 (c_{max}).

The partial short-circuit currents and the impedances of Formula (77) shall be related to the voltage level U_n, where the short-circuit current is calculated

If μ_j = 1, then take 1 – $\mu_j \cdot q_j$ = 0, independent of the value q_j.

9.2 Unbalanced short-circuits

The short-circuit breaking current is assumed to be equal to the initial short-circuit currents:

$$I_{b2} = I''_{k2max} \tag{78}$$

$$I_{b2E} = I''_{k2Emax} \tag{79}$$

$$I_{b1} = I''_{k1max} \tag{80}$$

NOTE For near-to-generator short circuits, the flux decay in the generator is not taken into account.

10 DC component of the short-circuit current

The maximum DC component i_{DC}. of the short-circuit current may be calculated with sufficient accuracy by Formula (81).

$$i_{DC} = \sqrt{2} \cdot I''_k \cdot e^{-2\pi \cdot f \cdot t \cdot R/X} \tag{81}$$

where

I''_k	is the initial symmetrical short-circuit current;
f	is the nominal frequency;
t	is the time;

R/X is the ratio according to 8.1 or the ratios according to the methods a) and c) in 8.1.

The correct resistance R_G of the generator armature should be used and not R_{Gf}.

Power station units with full converter are neglected when calculating the DC component of the short-circuit current.

For multiple-fed or single-fed with parallel branches, the ratio R/X or X/R is to be determined by the method c) in 8.1. Depending on the product $f \cdot t$; where f is the frequency and t is the time, the equivalent frequency f_c should be used as follows:

$f \cdot t$	<1	<2,5	<5	<12,5
f_c/f	0,27	0,15	0,092	0,055

For example, the DC component of the short-circuit current is used to calculate the asymmetrical breaking current I_{basyn} (rms value) according to Formula (82).

$$I_{basyn} = \sqrt{I_b^2 + i_{DC}^2} = I_b \sqrt{1 + \left(\frac{i_{DC}}{I_b}\right)^2} \qquad (82)$$

where

I_b is the symmetrical breaking current;

i_{DC} is the DC component of a short-circuit current depending on the minimum time delay, see Formula (81).

11 Calculation of steady-state short-circuit current

11.1 General

The calculation of the steady-state short-circuit current I_k is less accurate than the calculation of the initial short-circuit current I_k''.

11.2 Three-phase short circuit

11.2.1 Steady-state short-circuit current of one synchronous generator or one power station unit

11.2.1.1 General

For near-to-generator three-phase short circuits fed directly from one synchronous generator or one power station unit only, according to Figure 8b or 8d, the steady-state short-circuit current I_k depends on the excitation system, the voltage regulator action, and saturation influences.

Synchronous machines (generators, motors, or compensators) with terminal-fed static exciters do not contribute to I_k in the case of a short circuit at the terminals of the machine, but they contribute to I_k if there is an impedance between the terminals and the short-circuit location. A contribution is also given if, in case of a power station unit, the short circuit occurs on the high-voltage side of the unit transformer (see Figure 8d).

All other cases have to be treated according to 11.2.7.

11.2.1.2 Maximum steady-state short-circuit current

For the calculation of the maximum steady-state short-circuit current, the synchronous generator may be set at the maximum excitation.

$$I_{\mathrm{kmax}} = \lambda_{\mathrm{max}} \cdot I_{\mathrm{rG}} \tag{83}$$

For static excitation systems fed from the generator terminals and a short circuit at the terminals, the field voltage collapses as the terminal voltage collapses, therefore take λ_{max} $\lambda_{\mathrm{max}} = \lambda_{\mathrm{min}}$ in this case.

When calculating I_{kmax} or I_{kmin}, the factor c_{max} or c_{min} is taken from Table 1.

λ_{max} may be obtained from Figures 15 or 16 for cylindrical rotor generators or salient-pole generators. The saturated reactance x_{dsat} is the reciprocal of the saturated no-load short-circuit ratio.

λ_{max}-curves of series 1 are based on the highest possible excitation voltage according to either 1,3 times the rated excitation at rated apparent power and power factor for cylindrical rotor generators (Figure 15a) or 1,6 times the rated excitation voltage for salient-pole generators (Figure 16a).

λ_{max}-curves of series 2 are based on the highest possible excitation-voltage according to either 1,6 times the rated excitation at rated apparent power and power factor for cylindrical rotor generators (Figure 15b), or 2,0 times the rated excitation voltage for salient-pole generators (Figure 16b).

λ_{max}-curves of series 1 or 2 may also be applied in the case of terminal-fed static exciters, if the short circuit is at the high-voltage side of the unit transformer of a power station unit or in the system, and if the maximum excitation voltage is chosen with respect to the partial breakdown of the terminal voltage of the generator during the short circuit.

NOTE The calculation of the λ_{max}-curves is possible with Formula (87) from IEC TR 60909-1:2002, taking into account that $I''_{\mathrm{kG}}/I_{\mathrm{rG}} = \lambda_{\mathrm{max}}$ is valid for ratios $I''_{\mathrm{kG}}/I_{\mathrm{rG}} \le 2$. This occurs in the case of a far-from-generator short circuit.

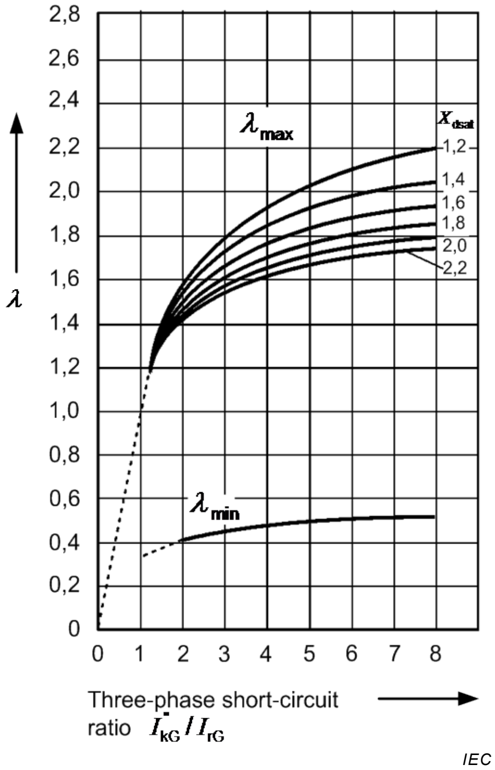


Figure 15a – λ_{min} and λ_{max} factors of series 1

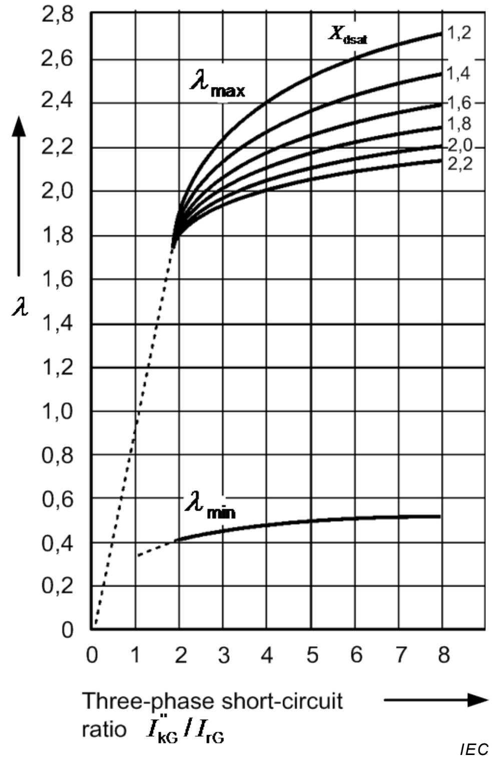


Fig. 15b – λ_{min} and λ_{max} factors of series 2

Figure 15 – Factors λ_{min} and λ_{max} factors for cylindrical rotor generators

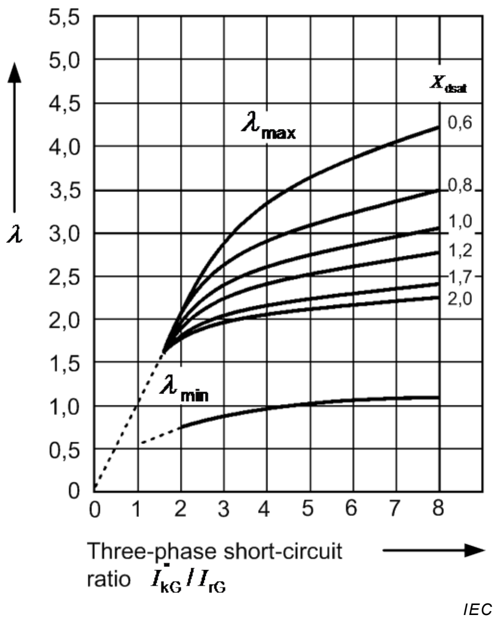


Figure 16a – λ_{min} and λ_{max} factors of series 1

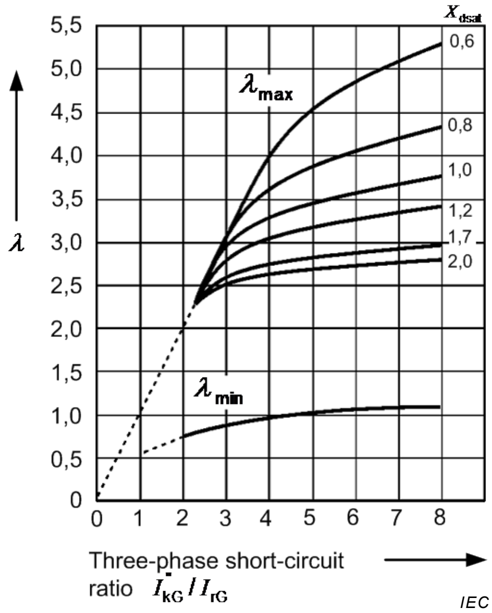


Fig. 16b – λ_{min} and λ_{max} factors of series 2

Figure 16 – Factors λ_{min} and λ_{max} for salient-pole generators

11.2.1.3 Minimum steady-state short-circuit current

For the minimum steady-state short-circuit current in the case of a single-fed short circuit from one generator or one power station unit according to Figures 8b and 8c, constant no-load excitation (voltage regulator not being effective) of the synchronous machine is assumed:

$$I_{\text{kmin}} = \lambda_{\text{min}} \cdot I_{\text{rG}} \tag{84}$$

λ_{min} may be obtained from Figures 15 and 16. In the case of minimum steady-state short circuit introduce $c = c_{\text{min}}$, according to Table 1.

The calculation of the minimum steady-state short-circuit current in the case of a near-to-generator short circuit, fed by one or several similar and parallel working generators with compound excitation, is made as follows:

$$I_{\text{kmin}} = \frac{c_{\text{min}} \cdot U_{\text{n}}}{\sqrt{3} \cdot Z_{\text{k}}} \tag{85}$$

For the effective reactance of generators introduce:

$$X_{\text{dP}} = \frac{U_{\text{rG}}}{\sqrt{3} \cdot I_{\text{kP}}} \tag{86}$$

I_{kP} is the steady-state short-circuit current of a generator at a three-phase terminal short circuit. The value should be obtained from the manufacturer.

11.2.2 Steady-state short-circuit current of asynchronous motor or generator

With respect to Formula (105) of Table 4, the steady-state short-circuit current of an asynchronous motor/generator is zero in case of a three-phase short circuit at the terminals, Figure 9 and Formula (89).

11.2.3 Steady-state short-circuit current of wind power station unit with doubly fed asynchronous generator

The steady-state short-circuit currents I_{kWDmax} and I_{kWDmin} are to be provided by the manufacturer.

11.2.4 Steady-state short-circuit current of wind power station unit with full size converter

The steady-state short-circuit currents I_{kPFmax} and I_{kPFmin} are to be provided by the manufacturer.

11.2.5 Steady-state short-circuit current of network feeder

The steady-state short-circuit current is equal to the initial short-circuit current.

$$I_{\text{k}} = I_{\text{k}}'' \tag{87}$$

11.2.6 Steady-state short-circuit current in case of multiple single-fed short circuits

The steady-state short-circuit current at the short-circuit location can be calculated by the summation of the individual steady-state short-circuit current contributions:

$$I_{k} = \sum_{i} I_{ki} \tag{88}$$

Figure 9 example:

$$I_{k} = I_{kS} + I_{kT} + I_{kWF} = \lambda I_{rGt} + I''_{kT} + I_{kWF} \tag{89}$$

λ (λ_{max} or λ_{min}) is found from Figures 15 and 16. I_{rGt} is the rated current of the synchronous generator transferred to the high-voltage side (see 7.1.1) of the unit transformer in Figure 9.

In the case of network feeders or network feeders in series with transformers (see Figure 9) $I_{k} = I''_{k}$ is valid (far-from-generator short circuit).

11.2.7 Steady-state short-circuit current in case of multiple-fed short circuits

The steady-state short-circuit current may be calculated approximately by:

$$I_{kmax} = I_{bMO} \tag{90}$$

$$I_{kmin} = I''_{kmin} \tag{91}$$

I_{bMO} is calculated according to 9.1 without the influence of asynchronous motors/generators according to 7.1.2.

Formulas (90) and (91) are valid in the case of far-from-generator and near-to-generator short circuits.

11.3 Unbalanced short circuits

In all cases of unbalanced short circuits, the flux decay in the generator is not taken into account and the following formulas should be used:

$$I_{k2} = I''_{k2} \tag{92}$$

$$I_{k2E} = I''_{k2E} \tag{93}$$

$$I_{kE2E} = I''_{kE2E} \tag{94}$$

$$I_{k1} = I''_{k1} \tag{95}$$

In the case of maximum or minimum steady-state short circuits, the voltage factor c_{max} resp. c_{min} according to Table 1 shall be applied, see 7.1.2.

12 Short circuits at the low-voltage side of transformers, if one line conductor is interrupted at the high-voltage side

When fuses are used as incoming protection at the high-voltage side of network transformers, a short circuit at the secondary side may cause one fuse to clear before the other high-voltage fuses or a circuit-breaker eliminates the short circuit. This can lead to a situation where the partial short-circuit currents are too small to operate any further protection device, particularly in the case of minimum short-circuit currents. Electrical equipment may be overstressed due to the short-circuit duration.

Figure 17 describes this situation with balanced and unbalanced short circuits with earth connection at the short-circuit location F.

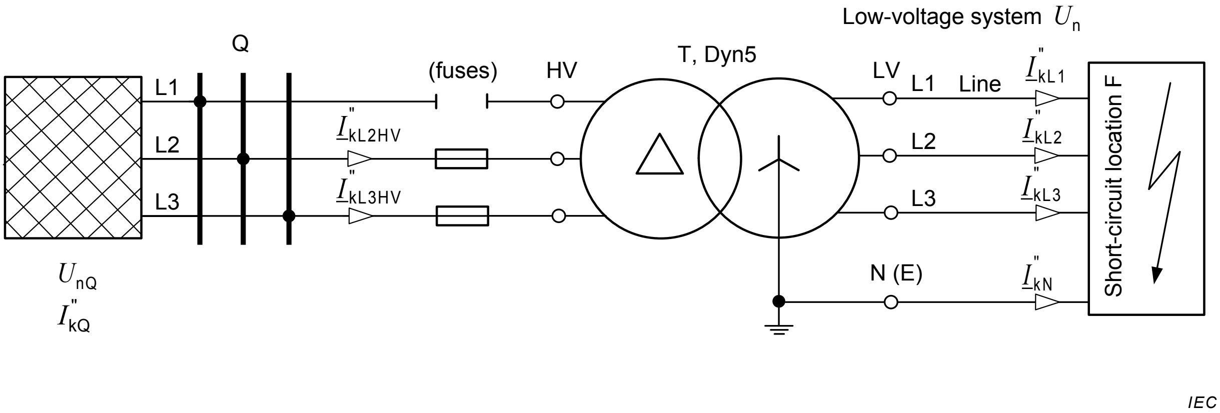


Figure 17 – Transformer secondary short-circuits, if one line (fuse) is opened on the high-voltage side of a transformer Dyn5

The short-circuit currents, I''_{kL1}, I''_{kL2}, I''_{kL3} and I''_{kN} at the low-voltage side of the transformer in Figure 17 can be calculated using Formula (96) with the equivalent voltage source $cU_n/\sqrt{3}$ at the short-circuit location F. The partial short-circuit currents $I''_{kL2HV} = I''_{kL3HV}$ at the high-voltage side in Figure 17 may also be calculated with Formula (96) using appropriate values for the factor α. In all cases $I''_{k\nu}$ is equal to $I_{k\nu}$, because the short circuits are far-from-generator short circuits (see 3.16 and Figure 1).

$$I''_{k\nu} = \alpha \cdot \frac{cU_n}{\sqrt{3} \cdot \left| \underline{Z}_{Qt} + K_T \underline{Z}_T + \underline{Z}_L + \beta \cdot \left(K_T \underline{Z}_{(0)T} + \underline{Z}_{(0)L} \right) \right|} \qquad (96)$$

where

ν	represents L1, L2, L3, N(E) at the low-voltage side and L2 HV, L3 HV at the high-voltage side;
$\underline{Z}_{Qt} + K_T\underline{Z}_T + \underline{Z}_L$	is the resultant impedance in the positive-sequence system at the LV-side ($\underline{Z}_T = \underline{Z}_{TLV}$);
$K_T\underline{Z}_{(0)T} + \underline{Z}_{(0)L}$	is the resultant impedance in the zero-sequence system at the LV-side;
α, β	are factors given in Table 3.

Any line-to-line short circuits without earth connection cause currents smaller than the rated currents, therefore this case is not taken into account in Table 3.

No short-circuit current on the low-voltage or on the high-voltage side of the transformer in Figure 17 is higher than the highest balanced or unbalanced short-circuit current in the case of an intact HV-feeding (see Figure 7). Therefore Formula (96) is normally of interest for the calculation of minimum short-circuit currents (see Table 1 for $c = c_{min}$, and 7.1.1).

Table 3 – Factors α and β for the calculation of short-circuit currents with Formula (96), rated transformation ratio $t_r = U_{rTHV}/U_{rTLV}$

Short-circuit in F (see Figure 17)	**Three-phase short circuit**	**Line-to-line short circuit with earth connection**		**Line-to-earth short circuit**
Affected lines at the low-voltage side	L1, L2, L3 L1, L2, L3, N(E)	L1, L3, N(E)	L1, L2, N(E) L2, L3, N(E)	L2, N(E)[a]
Factor β	0	2	0,5	0,5
Factor α (LV) for the currents				
I''_{kL1}	0,5	1,5	–	–
I''_{kL2}	1,0	–	1,5	1,5
I''_{kL3}	0,5	1,5	–	–
I''_{kN}	–	3,0	1,5	1,5
Factor α (HV) for the currents $I''_{k\nu}$ $I''_{kL2HV} = I''_{kL3HV}$	$\frac{1}{t_r}\cdot\frac{\sqrt{3}}{2}$	$\frac{1}{t_r}\cdot\frac{\sqrt{3}}{2}$	$\frac{1}{t_r}\cdot\frac{\sqrt{3}}{2}$	$\frac{1}{t_r}\cdot\frac{\sqrt{3}}{2}$

[a] In the case of line-to-earth short circuits L1, N(E) or L3, N(E), the resulting small currents are stipulated by the transformer open-circuit impedances. They may be neglected.

13 Terminal short circuit of asynchronous motors

In the case of three-phase and line-to-line short circuits at the terminals of asynchronous motors, the partial short-circuit currents I''_{kM}, i_{pM}, I_{bM}, and I_{kM} are evaluated as shown in Table 4. The influence of motors on the line-to-earth short-circuit current cannot be neglected in case of grounded systems. Take the impedances of the motors with $\underline{Z}_{(1)M} = \underline{Z}_{(2)M} = \underline{Z}_M$ and $\underline{Z}_{(0)M}$. If the star point of the motor is not earthed, the zero-sequence impedance becomes $\underline{Z}_{(0)M} = \infty$.

Table 4 – Calculation of short-circuit currents of asynchronous motors in the case of a short circuit at the terminals

Short circuit	Three-phase short circuit	Line-to-line short circuit	Line-to-earth short circuit
Initial symmetrical short-circuit current	$I''_{k3M} = \frac{cU_n}{\sqrt{3} \cdot Z_M}$ (97)	$I''_{k2M} = \frac{\sqrt{3}}{2} \cdot I''_{k3M}$ (98)	See Clause 10
Peak short-circuit current	$i_{p3M} = \kappa_M \sqrt{2} \cdot I''_{k3M}$ (99)	$i_{p2M} = \frac{\sqrt{3}}{2} \cdot i_{p3M}$ (100)	$i_{p1M} = \kappa_M \sqrt{2} \cdot I''_{k1M}$ (101)
	High-voltage motors: $\kappa_M = 1{,}65$ (corresponding to $R_M/X_M = 0{,}15$) for motor powers per pair of poles < 1 MW $\kappa_M = 1{,}75$ (corresponding to $R_M/X_M = 0{,}10$) for motor powers per pair of poles ≥ 1 MW Low voltage motor groups with connection cables: $\kappa_M = 1{,}3$ (corresponding to $R_M/X_M = 0{,}42$)		
Symmetrical short-circuit breaking current	$I_{b3M} = \mu q \cdot I''_{k3M}$ (102)	$I_{b2M} \approx \frac{\sqrt{3}}{2} \cdot I''_{k3M}$ (103)	$I_{b1M} \approx I''_{k1M}$ (104)
	μ according to Formula (67) or Figure 13, with I''_{kM}/I_{rM} q according to Formula (69) or Figure 14.		
Steady-state short-circuit current	$I_{k3M} = 0$ (105)	$I_{k2M} \approx \frac{\sqrt{3}}{2} \cdot I''_{k3M}$ (106)	$I_{k1M} \approx I''_{k1M}$ (107)

14 Joule integral and thermal equivalent short-circuit current

The Joule integral $\int i^2 \, dt$ is a measure of the energy generated in the resistive element of the system by the short-circuit current. In this standard it is calculated using a factor m for the time-dependent heat effect of the DC component of the short-circuit current and a factor n for the time-dependent heat effect of the AC component of the short-circuit current for one individual short circuit (see Figures 18 and 19).

$$\int_0^{T_k} i^2 \mathrm{d}t = \left(I''_k\right)^2 \cdot (m+n) \cdot T_k = I_{th}^2 \cdot T_k \qquad (108)$$

The thermal equivalent short-circuit current is:

$$I_{th} = I''_k \sqrt{m+n} \qquad (109)$$

For a series of i three-phase successive individual short-circuit currents, the following formula shall be used for the calculation of the Joule integral or the thermal equivalent short-circuit current.

$$\int i^2 \mathrm{d}t = \sum_i \left(I''_{\mathrm{k}i}\right)^2 \left(m_i + n_i\right) \cdot T_{\mathrm{k}i} = I_{\mathrm{th}}^2 \cdot T_{\mathrm{k}} \tag{110}$$

$$I_{\mathrm{th}} = \sqrt{\frac{\int i^2 \mathrm{d}t}{T_{\mathrm{k}}}} \tag{111}$$

with

$$T_{\mathrm{k}} = \sum_i T_{\mathrm{k}i} \tag{112}$$

where

$I''_{\mathrm{k}i}$ is the initial symmetrical three-phase short-circuit current for each short circuit;

I_{th} is the thermal equivalent short-circuit current;

m_i is the factor for the heat effect of the DC component for each short-circuit current;

n_i is the factor for the heat effect of the AC component for each short-circuit current;

$T_{\mathrm{k}i}$ is the duration of the short-circuit current for each short circuit;

T_{k} is the sum of the durations for each short-circuit current, see Formula (112).

The Joule integral and the thermal equivalent short-circuit current should always be given with the short-circuit duration with which they are associated.

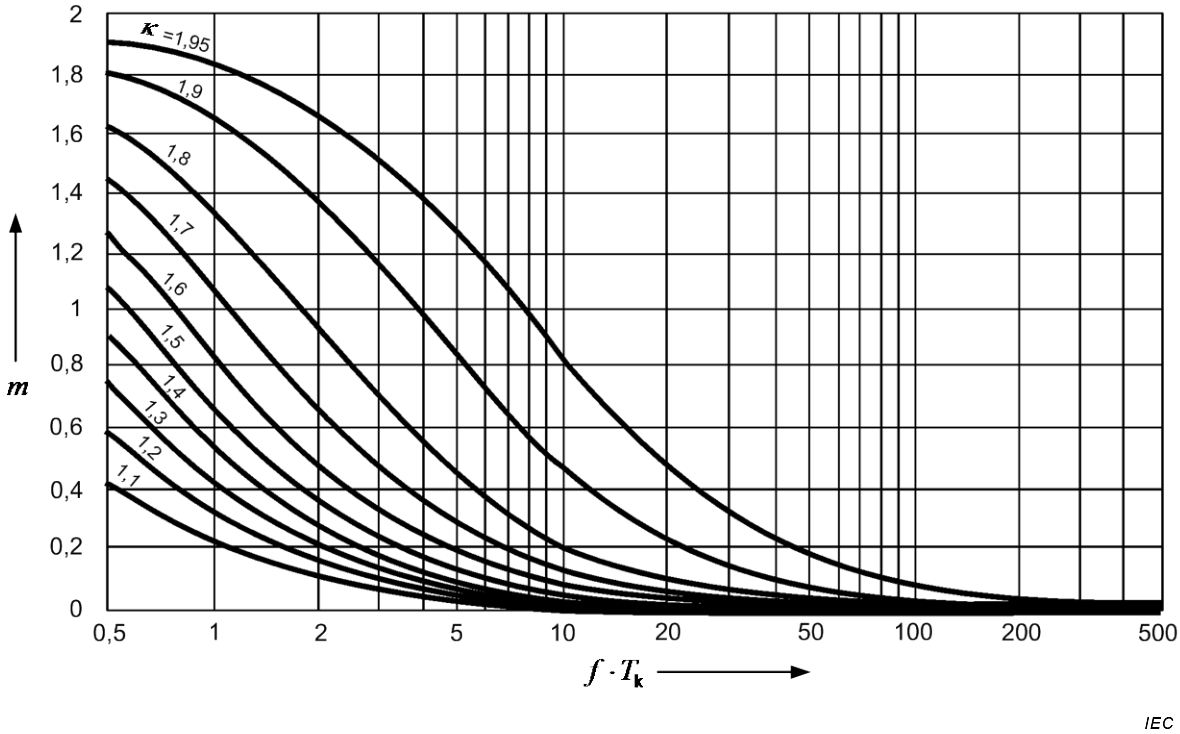


Figure 18 – Factor *m* for the heat effect of the DC component of the short-circuit current (for programming, the formula to calculate *m* is given in Annex A)

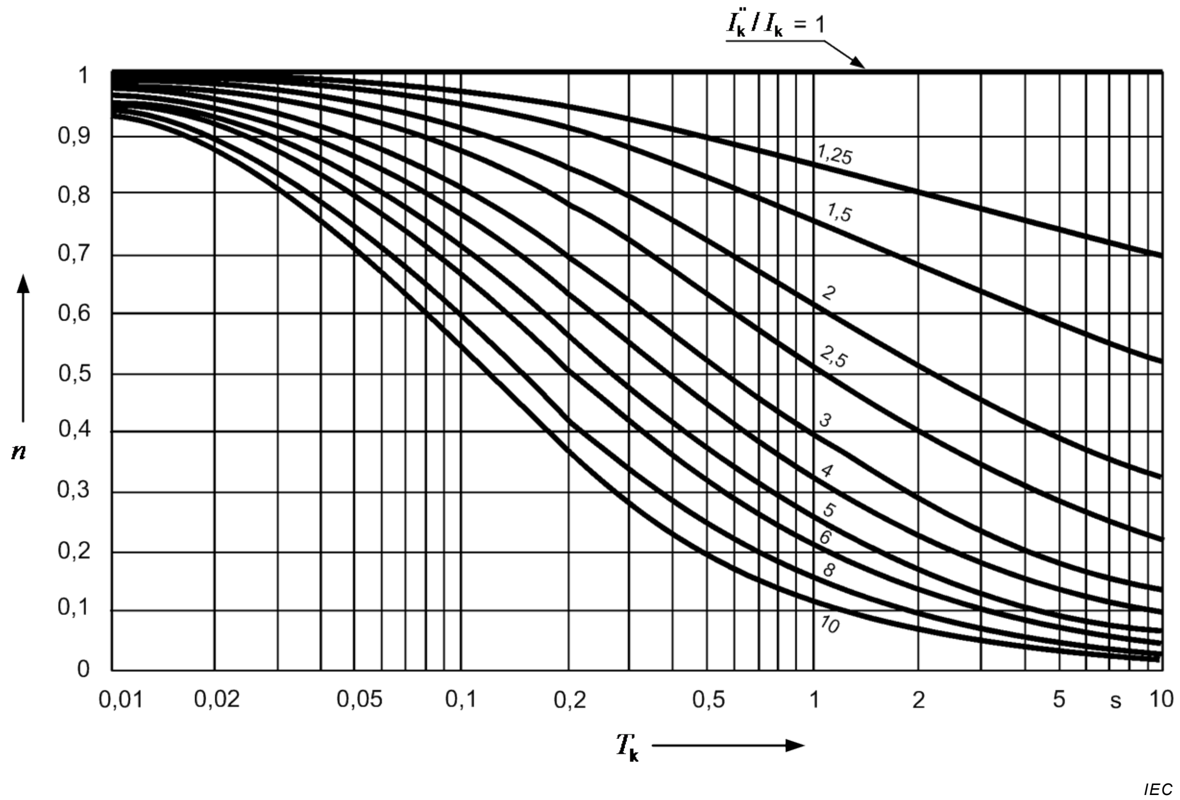


Figure 19 – Factor *n* for the heat effect of the AC component of the short-circuit current (for programming, the formula to calculate *n* is given in Annex A)

The factors m_i are obtained from Figure 18 using $f \cdot T_{ki}$ and the factor κ derived in 8.1. The factors n_i are obtained from Figure 19 using T_{ki} and the quotient I''_{ki} / I_{ki}, where I_{ki} is the steady-state short-circuit current for each short circuit.

When a number of short circuits occur with a short time interval between them, the resulting Joule integral is the sum of the Joule integrals of the individual short-circuit currents, as given in Formula (110).

For distribution networks (far-from-generator short circuits) usually n = 1 can be used.

For far-from-generator short circuits with a rated short-circuit duration of 0,5 s or more, it is permissible to take $m + n$ = 1.

If the Joule integral or the thermal equivalent short-circuit current shall be calculated for unbalanced short circuits, replace I''_{ki} with the appropriate unbalanced short-circuit currents.

NOTE For the calculation of the Joule integral or the thermal equivalent short-circuit current in three-phase AC systems, the three-phase short-circuit current may be decisive.

When a circuit is protected by fuses or current-limiting circuit-breakers, their Joule integral may limit the value below that calculated in accordance with Formula (108) or (110). In this case the Joule integral is determined from the characteristic of the current-limiting device.

Annex A
(normative)

Formulas for the calculation of the factors *m* and *n*

The factor m in Figure 18 is given by:

$$m = \frac{1}{2 f T_k \ln(\kappa - 1)} \cdot \left[e^{4 f T_k \ln(\kappa - 1)} - 1 \right]$$

The factor n in Figure 19 is given by:

$$\frac{I_k''}{I_k} = 1: \qquad n = 1$$

$$\frac{I_k''}{I_k} \geq 1{,}25:$$

$$n = \frac{1}{\left(I_k''/I_k\right)^2} \cdot \left[1 + \frac{T_d'}{20 T_k} \cdot \left(1 - e^{-20 T_k / T_d'}\right) \cdot \left(\frac{I_k''}{I_k} - \frac{I_k'}{I_k}\right)^2 + \frac{T_d'}{2 T_k} \cdot \left(1 - e^{-2 T_k / T_d'}\right) \cdot \left(\frac{I_k'}{I_k} - 1\right)^2 \right.$$
$$+ \frac{T_d'}{5 T_k} \cdot \left(1 - e^{-10 T_k / T_d'}\right) \cdot \left(\frac{I_k''}{I_k} - \frac{I_k'}{I_k}\right) + \frac{2 T_d'}{T_k} \cdot \left(1 - e^{-T_k / T_d'}\right) \cdot \left(\frac{I_k'}{I_k} - 1\right)^2$$
$$\left. + \frac{T_d'}{5{,}5 T_k} \cdot \left(1 - e^{-11 T_k / T_d'}\right) \cdot \left(\frac{I_k''}{I_k} - \frac{I_k'}{I_k}\right) \cdot \left(\frac{I_k'}{I_k} - 1\right) \right]$$

where

$$\frac{I_k'}{I_k} = \frac{I_k''/I_k}{0{,}88 + 0{,}17 \cdot I_k''/I_k}$$

$$T_d' = \frac{3{,}1\,\text{s}}{I_k'/I_k}$$

Annex B
(informative)

Nodal admittance and nodal impedance matrices

The nodal admittance matrix for the positive-sequence system of a network with n nodes has the following $n \times n$ structure.

$$\underline{\mathbf{Y}}_{(1)} = \begin{array}{c} \\ 1 \\ 2 \\ \vdots \\ i \\ \vdots \\ n \end{array} \begin{array}{c} \begin{array}{cccccc} 1 & 2 & \cdots & i & \cdots & n \end{array} \\ \begin{bmatrix} \underline{Y}_{(1)11} & \underline{Y}_{(1)12} & \cdots & \underline{Y}_{(1)1i} & \cdots & \underline{Y}_{(1)1n} \\ \underline{Y}_{(1)21} & \underline{Y}_{(1)22} & \cdots & \underline{Y}_{(1)2i} & \cdots & \underline{Y}_{(1)2n} \\ \vdots & \vdots & \ddots & \vdots & \ddots & \vdots \\ \underline{Y}_{(1)i1} & \underline{Y}_{(1)i2} & \cdots & \underline{Y}_{(1)ii} & \cdots & \underline{Y}_{(1)in} \\ \vdots & \vdots & \ddots & \vdots & \ddots & \vdots \\ \underline{Y}_{(1)n1} & \underline{Y}_{(1)n2} & \cdots & \underline{Y}_{(1)ni} & \cdots & \underline{Y}_{(1)nn} \end{bmatrix} \end{array}$$

The mutual admittance between the nodes i and j is the sum of the short-circuit admittances of the electrical equipment (see Clause 6) between the nodes i and j (see Figure B.1):

$$\underline{Y}_{(1)ij} = \sum_{\ell=1}^{m} \frac{1}{\underline{Z}_{(1)ij,\ell}}$$

The self-admittances of the node i (and analogy for the other nodes) is the negative sum of the admittances in the i^{th} line and the negative sum of the short-circuit admittances of the electrical equipment between the nodes i and the reference node 0 of the positive-sequence system.

$$\underline{Y}_{(1)ii} = -\sum_{j=1,\neq i}^{n} \underline{Y}_{(1)ij} - \sum_{s=1}^{k} \frac{1}{\underline{Z}_{(1)i0,s}}$$

The structure of the nodal matrices for the negative-sequence system and the zero-sequence system are similar.

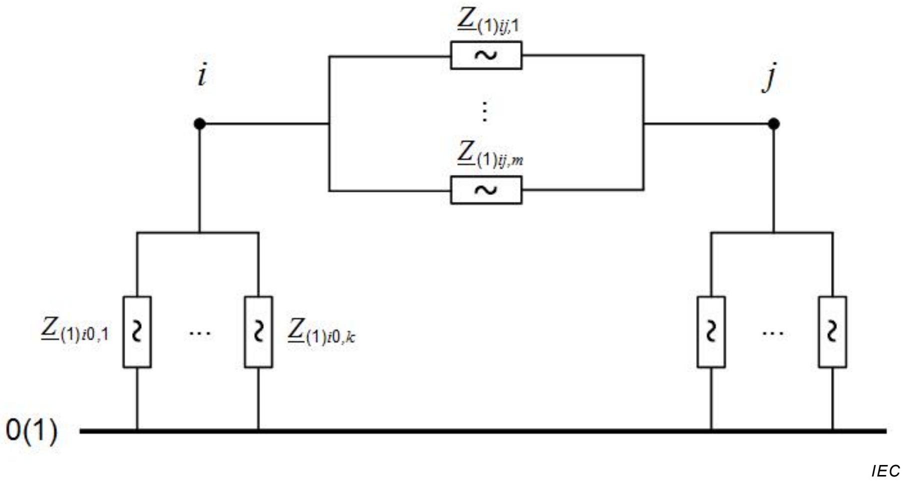


Figure B.1 – Formulation of the nodal admittance matrix

The nodal impedance matrix for the positive-sequence system is the inverse matrix of the nodal admittance matrix for the positive-sequence system with the following $n \times n$ structure.

$$\underline{\mathbf{Z}}_{(1)} = \underline{\mathbf{Y}}_{(1)}^{-1} = \begin{bmatrix} \underline{Z}_{(1)11} & \underline{Z}_{(1)12} & \cdots & \underline{Z}_{(1)1i} & \cdots & \underline{Z}_{(1)1n} \\ \underline{Z}_{(1)21} & \underline{Z}_{(1)22} & \cdots & \underline{Z}_{(1)2i} & \cdots & \underline{Z}_{(1)2n} \\ \vdots & \vdots & \ddots & \vdots & \ddots & \vdots \\ \underline{Z}_{(1)i1} & \underline{Z}_{(1)i2} & \cdots & \underline{Z}_{(1)ii} & \cdots & \underline{Z}_{(1)in} \\ \vdots & \vdots & \ddots & \vdots & \ddots & \vdots \\ \underline{Z}_{(1)n1} & \underline{Z}_{(1)n2} & \cdots & \underline{Z}_{(1)ni} & \cdots & \underline{Z}_{(1)nn} \end{bmatrix}$$

The nodal impedances of the negative-sequence system and the zero-sequence system are found in the same manner:

$$\underline{\mathbf{Z}}_{(2)} = \underline{\mathbf{Y}}_{(2)}^{-1}$$

$$\underline{\mathbf{Z}}_{(0)} = \underline{\mathbf{Y}}_{(0)}^{-1}$$

An example is given by Figure B.2 with the impedances of Table B.1

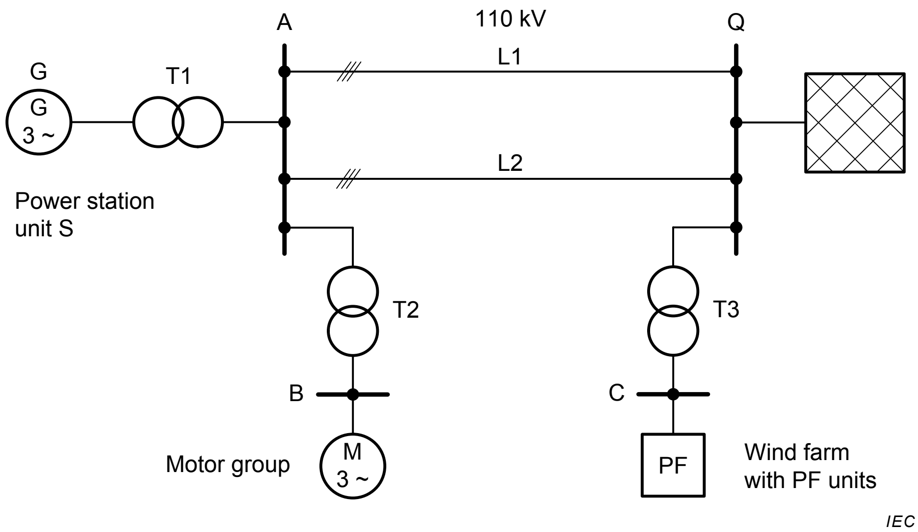


Figure B.2 – Example

Table B.1 – Impedances of electrical equipment referred to the 110 kV side

Equipment	Positive-sequence system	Negative-sequence system	Zero-sequence system
Q	$\underline{Z}_{\mathrm{Q}}$	$\underline{Z}_{(2)\mathrm{Q}} = \underline{Z}_{\mathrm{Q}}$	$\underline{Z}_{(0)\mathrm{Q}}$
S	$\underline{Z}_{\mathrm{SK}} = K_{\mathrm{S}}\left(t_{\mathrm{rT1}}^{2}\underline{Z}_{\mathrm{G}} + \underline{Z}_{\mathrm{T1HV}}\right)$	$\underline{Z}_{(2)\mathrm{SK}} = \underline{Z}_{\mathrm{SK}}$	$\underline{Z}_{(0)\mathrm{SK}} = K_{\mathrm{S}}\underline{Z}_{(0)\mathrm{T1HV}}$
M	$\underline{Z}_{\mathrm{Mt}} = t_{\mathrm{rT2}}^{2}\underline{Z}_{\mathrm{M}}$	$\underline{Z}_{(2)\mathrm{Mt}} = \underline{Z}_{\mathrm{Mt}}$	$\underline{Z}_{(0)\mathrm{Mt}} = \infty$
PF	$\underline{Z}_{\mathrm{PFt}} = \infty$	$\underline{Z}_{(2)\mathrm{PFt}}$	$\underline{Z}_{(0)\mathrm{PFt}}$ [a]
T2	$\underline{Z}_{\mathrm{T2K}} = K_{\mathrm{T}}\underline{Z}_{\mathrm{T2HV}}$	$\underline{Z}_{(2)\mathrm{T2K}} = \underline{Z}_{\mathrm{T2K}}$	$\underline{Z}_{(0)\mathrm{T2K}} = K_{\mathrm{T}}\underline{Z}_{(0)\mathrm{T2}}$
T3	$\underline{Z}_{\mathrm{T3K}} = K_{\mathrm{T}}\underline{Z}_{\mathrm{T3HV}}$	$\underline{Z}_{(2)\mathrm{T3K}} = \underline{Z}_{\mathrm{T3K}}$	$\underline{Z}_{(0)\mathrm{T3K}} = K_{\mathrm{T}}\underline{Z}_{(0)\mathrm{T3}}$
L1	$\underline{Z}_{\mathrm{L1}}$	$\underline{Z}_{(2)\mathrm{L1}} = \underline{Z}_{\mathrm{L1}}$	$\underline{Z}_{(0)\mathrm{L1}}$
L2	$\underline{Z}_{\mathrm{L2}}$	$\underline{Z}_{(2)\mathrm{L2}} = \underline{Z}_{\mathrm{L2}}$	$\underline{Z}_{(0)\mathrm{L2}}$
[a] Depends on the vector group of the transformer.			

Nodal admittance matrix for the positive-sequence system:

$$\underline{\mathbf{Y}}_{(1)} = \begin{bmatrix} -\dfrac{1}{\underline{Z}_{\mathrm{L1}}}-\dfrac{1}{\underline{Z}_{\mathrm{L2}}}-\dfrac{1}{\underline{Z}_{\mathrm{T2K}}}-\dfrac{1}{\underline{Z}_{\mathrm{SK}}} & \dfrac{1}{\underline{Z}_{\mathrm{L1}}}+\dfrac{1}{\underline{Z}_{\mathrm{L2}}} & \dfrac{1}{\underline{Z}_{\mathrm{T2K}}} & 0 \\ \dfrac{1}{\underline{Z}_{\mathrm{L1}}}+\dfrac{1}{\underline{Z}_{\mathrm{L2}}} & -\dfrac{1}{\underline{Z}_{\mathrm{L1}}}-\dfrac{1}{\underline{Z}_{\mathrm{L2}}}-\dfrac{1}{\underline{Z}_{\mathrm{T3K}}}-\dfrac{1}{\underline{Z}_{\mathrm{Q}}} & 0 & \dfrac{1}{\underline{Z}_{\mathrm{T3K}}} \\ \dfrac{1}{\underline{Z}_{\mathrm{T2K}}} & 0 & -\dfrac{1}{\underline{Z}_{\mathrm{T2K}}}-\dfrac{1}{\underline{Z}_{\mathrm{Mt}}} & 0 \\ 0 & \dfrac{1}{\underline{Z}_{\mathrm{T3K}}} & 0 & -\dfrac{1}{\underline{Z}_{\mathrm{T3K}}} \end{bmatrix}$$

Nodal admittance matrix for the negative-sequence system:

$$\underline{\mathbf{Y}}_{(2)}=\begin{bmatrix} -\frac{1}{\underline{Z}_{(2)\mathrm{L1}}}-\frac{1}{\underline{Z}_{(2)\mathrm{L2}}}-\frac{1}{\underline{Z}_{(2)\mathrm{T2K}}}-\frac{1}{\underline{Z}_{(2)\mathrm{SK}}} & \frac{1}{\underline{Z}_{(2)\mathrm{L1}}}+\frac{1}{\underline{Z}_{(2)\mathrm{L2}}} & \frac{1}{\underline{Z}_{(2)\mathrm{T2K}}} & 0 \\ \frac{1}{\underline{Z}_{(2)\mathrm{L1}}}+\frac{1}{\underline{Z}_{(2)\mathrm{L2}}} & -\frac{1}{\underline{Z}_{(2)\mathrm{L1}}}-\frac{1}{\underline{Z}_{(2)\mathrm{L2}}}-\frac{1}{\underline{Z}_{(2)\mathrm{T3K}}}-\frac{1}{\underline{Z}_{(2)\mathrm{Q}}} & 0 & \frac{1}{\underline{Z}_{(2)\mathrm{T3K}}} \\ \frac{1}{\underline{Z}_{(2)\mathrm{T2K}}} & 0 & -\frac{1}{\underline{Z}_{(2)\mathrm{T2K}}}-\frac{1}{\underline{Z}_{(2)\mathrm{Mt}}} & 0 \\ 0 & \frac{1}{\underline{Z}_{(2)\mathrm{T3K}}} & 0 & -\frac{1}{\underline{Z}_{(2)\mathrm{T3K}}}-\frac{1}{\underline{Z}_{(2)\mathrm{PFt}}} \end{bmatrix}$$

Nodal admittance matrix for the zero-sequence system:

$$\underline{\mathbf{Y}}_{(0)}=\begin{bmatrix} -\frac{1}{\underline{Z}_{(0)\mathrm{L1}}}-\frac{1}{\underline{Z}_{(0)\mathrm{L2}}}-\frac{1}{\underline{Z}_{(0)\mathrm{T2K}}}-\frac{1}{\underline{Z}_{(0)\mathrm{SK}}} & \frac{1}{\underline{Z}_{(0)\mathrm{L1}}}+\frac{1}{\underline{Z}_{(0)\mathrm{L2}}} & \frac{1}{\underline{Z}_{(0)\mathrm{T2K}}} & 0 \\ \frac{1}{\underline{Z}_{(0)\mathrm{L1}}}+\frac{1}{\underline{Z}_{(0)\mathrm{L2}}} & -\frac{1}{\underline{Z}_{(0)\mathrm{L1}}}-\frac{1}{\underline{Z}_{(0)\mathrm{L2}}}-\frac{1}{\underline{Z}_{(0)\mathrm{T3K}}}-\frac{1}{\underline{Z}_{(0)\mathrm{Q}}} & 0 & \frac{1}{\underline{Z}_{(0)\mathrm{T3K}}} \\ \frac{1}{\underline{Z}_{(0)\mathrm{T2K}}} & 0 & -\frac{1}{\underline{Z}_{(0)\mathrm{T2K}}} & 0 \\ 0 & \frac{1}{\underline{Z}_{(0)\mathrm{T3K}}} & 0 & -\frac{1}{\underline{Z}_{(0)\mathrm{T3K}}}-\frac{1}{\underline{Z}_{(0)\mathrm{PFt}}} \end{bmatrix}$$

The short-circuit impedances of the positive-sequence, negative-sequence and zero-sequence systems are the negative diagonal elements $\underline{Z}_{(1)ii}$, $\underline{Z}_{(2)ii}$, and $\underline{Z}_{(0)ii}$ of the nodal impedance matrices:

$$\underline{Z}_{(1)} = -\underline{Z}_{(1)ii}$$

$$\underline{Z}_{(2)} = -\underline{Z}_{(2)ii}$$

$$\underline{Z}_{(0)} = -\underline{Z}_{(0)ii}$$

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