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BSI Standards Publication

Short-circuit currents — Calculation of effects

Part 1: Definitions and calculation methods

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National foreword

This British Standard is the UK implementation of EN 60865-1:2012. It is identical to IEC 60865-1:2011. It supersedes BS EN 60865-1:1994 which is withdrawn.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.

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EN 60865-1

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Supersedes EN 60865-1:1993

English version

Short-circuit currents - Calculation of effects - Part 1: Definitions and calculation methods (IEC 60865-1:2011)

Courants de court-circuit -
Calcul des effets -
Partie 1: Définitions et méthodes de calcul
(CEI 60865-1:2011)

Kurzschlussströme -
Berechnung der Wirkung -
Teil 1: Begriffe und Berechnungsverfahren
(IEC 60865-1:2011)

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

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Foreword

The text of document 73/152/CDV, future edition 3 of IEC 60865-1, prepared by IEC/TC 73 "Short-circuit currents" was submitted to the IEC-CENELEC parallel vote and approved by CENELEC as EN 60865-1:2012.

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)	2012-09-23
• latest date by which the national standards conflicting with the document have to be withdrawn	(dow)	2014-11-28

This document supersedes EN 60865-1:1993.

EN 60865-1:2012 includes the following significant technical changes with respect to EN 60865-1:1993:

— The determinations for automatic reclosure together with rigid conductors have been revised.

— The influence of mid-span droppers to the span has been included.

— For vertical cable-connection the displacement and the tensile force onto the lower fixing point may now be calculated.

— Additional recommendations for foundation loads due to tensile forces have been added.

— The subclause for determination of the thermal equivalent short-circuits current has been deleted (it is now part of EN 60909-0).

— The regulations for thermal effects of electrical equipment have been deleted.

— The standard has been reorganized and some of the symbols have been changed to follow the conceptual characteristic of international standards.

Attention is drawn to the possibility that some of the elements of this document may be the subject of patent rights. CENELEC [and/or CEN] shall not be held responsible for identifying any or all such patent rights.

Endorsement notice

The text of the International Standard IEC 60865-1:2011 was approved by CENELEC as a European Standard without any modification.

In the official version, for Bibliography, the following note has to be added for the standard indicated:

IEC 61936-1 NOTE Harmonized as EN 61936-1.

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 When an international publication has been modified by common modifications, indicated by (mod), the relevant EN/HD applies.

Publication	Year	Title	EN/HD	Year
IEC 60909	Series	Short-circuit currents calculation in three-phase a.c. systems	EN 60909	Series
IEC 60909-0	-	Short-circuit currents in three-phase a.c. systems - Part 0: Calculation of currents	EN 60909-0	-
IEC 60949	-	Calculation of thermally permissible short-circuit currents, taking into account non-adiabatic heating effects	-	-
IEC 60986	-	Short-circuit temperature limits of electric cables with rated voltages from 6 kV (U_m = 7,2 kV) up to 30 kV (U_m = 36 kV)	-	-
IEC 61660-2	-	Short-circuit currents in d.c. auxiliary installations in power plants and substations - Part 2: Calculation of effects	EN 61660-2	-

CONTENTS

SHORT-CIRCUIT CURRENTS – CALCULATION OF EFFECTS –

Part 1: Definitions and calculation methods

1 Scope

This part of IEC 60865 is applicable to the mechanical and thermal effects of short-circuit currents. It contains procedures for the calculation of

– the electromagnetic effect on rigid conductors and flexible conductors,

– the thermal effect on bare conductors.

For cables and insulated conductors, reference is made, for example, to IEC 60949 and IEC 60986. For the electromagnetic and thermal effects in d.c. auxiliary installations of power plants and substations reference is made to IEC 61660-2.

Only a.c. systems are dealt with in this standard.

The following points should, in particular, be noted:

a) The calculation of short-circuit currents should be based on IEC 60909. For the determination of the greatest possible short-circuit current, additional information from other IEC standards may be referred to, e.g. details about the underlying circuitry of the calculation or details about current-limiting devices, if this leads to a reduction of the mechanical stress.

b) Short-circuit duration used in this standard depends on the protection concept and should be considered in that sense.

c) These standardized procedures are adjusted to practical requirements and contain simplifications which are conservative. Testing or more detailed methods of calculation or both may be used.

d) In Clause 5 of this standard, for arrangements with rigid conductors, only the stresses caused by short-circuit currents are calculated. Furthermore, other stresses can exist, e.g. caused by dead-load, wind, ice, operating forces or earthquakes. The combination of these loads with the short-circuit loading should be part of an agreement and/or be given by standards, e.g. erection-codes.

   The tensile forces in arrangements with flexible conductors include the effects of dead-load. With respect to the combination of other loads the considerations given above are valid.

e) The calculated loads are design loads and should be used as exceptional loads without any additional partial safety factor according to installation codes of, for example, IEC 61936-1 [1][1].

2 Normative references

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

IEC 60909 (all parts) *Short-circuit current calculation in three-phase a.c. systems*

[1] Figures in square brackets refer to the bibliography.

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

IEC 60949, *Calculation of thermally permissible short-circuit currents, taking into account non-adiabatic heating effects*

IEC 60986, *Short-circuit temperature limits of electric cables with rated voltages from 6 kV (U_m = 7,2 kV) up to 30 kV (U_m = 36 kV)*

IEC 61660-2, *Short-circuit currents in d.c. auxiliary installations in power plants and substations – Part 2: Calculation of effects*

3 Terms, definitions, symbols and units

3.1 Terms and definitions

For the purposes of this document the following terms and definitions apply.

3.1.1
main conductor
conductor or arrangement composed of a number of conductors which carries the total current in one phase

3.1.2
sub-conductor
single conductor which carries a certain part of the total current in one phase and is a part of the main conductor

3.1.3
fixed support
support of a rigid conductor in which moments are imposed in the regarded plane

3.1.4
simple support
support of a rigid conductor in which no moments are imposed in the regarded plane

3.1.5
connecting piece
any additional mass within a span which does not belong to the uniform conductor material, includingamong others, spacers, stiffening elements, bar overlappings, branchings, etc.

3.1.6
spacer
mechanical element between sub-conductors, rigid or flexible, which, at the point of installation, maintains the clearance between sub-conductors

3.1.7
stiffening element
special spacer intended to reduce the mechanical stress of rigid conductors

3.1.8
relevant natural frequency
f_{cm}
first natural frequency of the free vibration of a single span beam without damping and natural frequency of order ν of beams with ν spans without damping

3.1.9
short-circuit tensile force
$F_{t,d}$
maximum tensile force (design value) in a flexible main conductor due to swing out reached during the short-circuit

3.1.10
drop force
$F_{f,d}$
maximum tensile force (design value) in a flexible main conductor which occurs when the span drops down after swing out

3.1.11
pinch force
$F_{pi,d}$
maximum tensile force (design value) in a bundled flexible conductor during the short-circuit due to the attraction of the sub-conductors in the bundle

3.1.12
duration of the first short-circuit current flow
T_{k1}
time interval between the initiation of the short-circuit and the first breaking of the current

3.1.13
thermal equivalent short-circuit current
I_{th}
r.m.s. value of current having the same thermal effect and the same duration as the actual short-circuit current, which can contain d.c. component and can subside in time

3.1.14
thermal equivalent short-circuit current density
S_{th}
ratio of the thermal equivalent short-circuit current and the cross-section area of the conductor

3.1.15
rated short-time withstand current density, S_{thr}, for conductors
r.m.s. value of the current density which a conductor is able to withstand for the rated short time

3.1.16
duration of short-circuit current
T_k
sum of the time durations of the short-circuit current flow from the initiation of the first short-circuit to the final breaking of the current in all phases

3.1.17
rated short-time
T_{kr}
time duration for which a conductor can withstand a current density equal to its rated short-time withstand current density

3.2 Symbols and units

All equations used in this standard are quantity equations in which quantity symbols represent physical quantities possessing both numerical values and dimensions.

The symbols used in this standard and the SI-units concerned are given in the following lists.

A	Cross-section of one main-conductor	m^2
A_s	Cross-section of one sub-conductor	m^2
a	Centre-line distance between conductors	m
a_m	Effective distance between main conductors	m
a_{min}	Minimum air clearance	m
a_s	Effective distance between sub-conductors	m
a_{1n}	Centre-line distance between sub-conductor 1 and sub-conductor n	m
a_{1s}	Centre-line distance between sub-conductors	m
b_h	Maximum horizontal displacement	m
b_m	Dimension of a main conductor perpendicular to the direction of the force	m
b_s	Dimension of a sub-conductor perpendicular to the direction of the force	m
C_D	Dilatation factor	1
C_F	Form factor	1
c_m	Dimension of a main conductor in the direction of the force	m
c_s	Dimension of a sub-conductor in the direction of the force	m
c_{th}	Material constant	$m^4/(A^2s)$
d	Outer diameter of a tubular or flexible conductor	m
E	Young's modulus	N/m^2
E_{eff}	Actual Young's modulus	N/m^2
e	Factor for the influence of connecting pieces	1
F	Force acting between two parallel long conductors during a short-circuit	N
F'	Characteristic electromagnetic force per unit length on flexible main conductors	N/m
F_m	Force between main conductors during a short-circuit	N
F_{m2}	Force between main conductors during a line-to-line short-circuit	N
F_{m3}	Force on the central main conductor during a balanced three-phase short-circuit	N
$F_{r,d}$	Force on support of rigid conductors (peak value, design value)	N
$F_{f,d}$	Drop force of one main conductor (design value)	N
$F_{pi,d}$	Pinch force of one main conductor (design value)	N
F_s	Force between sub-conductors during a short-circuit	N
F_{st}	Static tensile force of one flexible main conductor	N
$F_{t,d}$	Short-circuit tensile force of one main conductor (design value)	N

F_v	Short-circuit current force between the sub-conductors in a bundle	N
f	System frequency	Hz
f_{cm}	Relevant natural frequency of a main conductor	Hz
f_{cs}	Relevant natural frequency of a sub-conductor	Hz
f_{ed}	Dynamic conductor sag at midspan	m
f_{es}	Equivalent static conductor sag at midspan	m
f_{st}	Static conductor sag at midspan	m
f_y	Stress corresponding to the yield point	N/m^2
g	Conventional value of acceleration of gravity	m/s^2
h	Height of the dropper	m
I''_k	Initial symmetrical three-phase short-circuit current (r.m.s.)	A
I''_{k1}	Initial line-to-earth short-circuit current (r.m.s.)	A
I''_{k2}	Initial symmetrical line-to-line short-circuit current (r.m.s.)	A
I_{th}	Thermal equivalent short-circuit current	A
i_p	Peak short-circuit current	A
i_{p2}	Peak short-circuit current in case of a line-to-line short-circuit	A
i_1, i_2	Instantaneous values of the currents in the conductors	A
J_m	Second moment of main conductor area	m^4
J_s	Second moment of sub-conductor area	m^4
j	Parameter determining the bundle configuration during short-circuit current flow	1
k	Number of sets of spacers or stiffening elements	1
k_{1n}	Factor for the effective distance between sub-conductor 1 and sub-conductor, n	1
k_{1s}	Factor for effective conductor distance	1
l	Centre-line distance between supports	m
l_c	Cord length of a flexible main conductor in the span	m
l_i	Length of one insulator chain	m
l_s	Centre-line distance between connecting pieces or between one connecting piece and the adjacent support	m
l_v	Cord length of a dropper	m
m'_m	Mass per unit length of main conductor	kg/m
m'_s	Mass per unit length of one sub-conductor	kg/m
m_z	Total mass of one set of connecting pieces	kg
N	Stiffness norm of an installation with flexible conductors	1/N
n	Number of sub-conductors of a main conductor	1
q	Factor of plasticity	1
r	The ratio of electromechanic force on a conductor under short-circuit conditions to gravity	1
S	Resultant spring constant of both supports of one span	N/m
S_{th}	Thermal equivalent short-circuit current density	A/mm^2

S_{thr}	Rated short-time withstand current density	A/mm^2
T	Period of conductor oscillation	s
T_k	Duration of short-circuit current	s
T_{ki}	Duration of short-circuit i at repeating short-circuits	s
T_{kr}	Rated short-time	s
T_{k1}	Duration of the first short-circuit current flow	s
T_{res}	Resulting period of the conductor oscillation during the short-circuit current flow	s
t	Wall thickness of tubes	m
V_F	Ratio of dynamic and static force on supports	1
V_{rm}	Ratio of dynamic stress (forces on the supports, contribution of main conductor bending stress) caused by forces between main conductors with unsuccessful three-phase automatic reclosing and dynamic stress with successful three-phase automatic reclosing	1
V_{rs}	Ratio of contribution of dynamic stress caused by forces between sub-conductors with unsuccessful three-phase automatic reclosing and contribution of dynamic stress with successful three-phase automatic reclosing	1
$V_{\sigma m}$	Ratio of dynamic and static contribution of main conductor stress	1
$V_{\sigma s}$	Ratio of dynamic and static contribution of sub-conductor stress	1
W_m	Section modulus of main conductor	m^3
W_s	Section modulus of sub-conductor	m^3
w	Width of dropper	m
α	Factor for force on support	1
β	Factor for main conductor stress	1
γ	Factor for relevant natural frequency estimation	1
δ	Actual maximum swing-out angle due to the limitation of the swing-out movement by the dropper	degrees
δ_{end}	Swing-out angle at the end of the short-circuit current flow	degrees
δ_{max}	Maximum swing-out angle	degrees
δ_1	Angular direction of the force	degrees
ε_{ela}	Elastic expansion	1
ε_{pi}, ε_{st}	Strain factor of the bundle contraction	1
ε_{th}	Thermal expansion	1
ζ	Stress factor of the flexible main conductor	1
η	Factor for calculating $F_{pi,d}$ in the case of non-clashing sub-conductors	1
θ_b	Conductor temperature of the beginning of a short-circuit	°C
θ_e	Conductor temperature at the end of a short-circuit	°C
κ	Factor for the calculation of the peak short-circuit current	1
μ_0	Magnetic constant, permeability of vacuum	H/m
ν	Number of spans of a continuous beam	1

ν_e, ν_1, ν_2, ν_3, ν_4,	Factors for calculating $F_{pi,d}$	1
ξ	Factor for calculating $F_{pi,d}$ in the case of clashing sub-conductors	1
σ_{fin}	Lowest value of cable stress when Young's modulus becomes constant	N/m^2
$\sigma_{m,d}$	Bending stress caused by the forces between main conductors (design value)	N/m^2
$\sigma_{s,d}$	Bending stress caused by the forces between sub-conductors (design value)	N/m^2
$\sigma_{tot,d}$	Total conductor stress (design value)	N/m^2
χ	Quantity for the maximum swing-out angle	1
φ, ψ	Factors for the tensile force in a flexible conductor	1

4 General

With the calculation methods presented in this standard

- stresses in rigid conductors,
- tensile forces in flexible conductors,
- forces on insulators and substructures, which might expose them to bending, tension and/or compression,
- span displacements of flexible conductors and
- heating of conductors

can be estimated.

Electromagnetic forces are induced in conductors by the currents flowing through them. Where such electromagnetic forces interact on parallel conductors, they cause stresses that have to be taken into account at the substations. For this reason:

- the forces between parallel conductors are set forth in the following clauses;
- the electromagnetic force components set up by conductors with bends and/or cross-overs may normally be disregarded.

In the case of metal-clad systems, the change of the electromagnetic forces between the conductors due to magnetic shielding can be taken into account. In addition, however, the forces acting between each conductor and its enclosure and between the enclosures shall be considered.

When parallel conductors are long compared to the distance between them, the forces will be evenly distributed along the conductors and are given by Equation (1)

$$F = \frac{\mu_0}{2\pi} i_1 i_2 \frac{l}{a} \quad (1)$$

where

i_1 and i_2	are the instantaneous values of the currents in the conductors;
l	is the centre-line distance between the supports;
a	is the centre-line distance between the conductors.

When the currents in the two conductors have the same direction, the forces are attractive. When the directions of the currents are opposite, the forces are repulsive.

5 Rigid conductor arrangements

5.1 General

Rigid conductors can be supported in different ways, either fixed or simple or in a combination of both. Depending on the type of support and the number of supports, the stresses in the conductors and the forces on the supports will be different for the same short-circuit current. The equations given also include the elasticity of the supports.

The stresses in the conductors and the forces on the supports also depend on the ratio between the relevant natural frequency of the mechanical system and the electrical system frequency. For example, in the case of resonance or near to resonance, the stresses and forces in the system can be amplified. If $f_{cm} / f < 0,5$ the response of the system decreases and the maximum stresses are in the outer phases.

5.2 Calculation of electromagnetic forces

5.2.1 Calculation of peak force between the main conductors during a three-phase short-circuit

In a three-phase system with the main conductors arranged with the same centre-line distances on the same plane, the maximum force acts on the central main conductor during a three-phase short-circuit and is given by:

$$F_{m3} = \frac{\mu_0}{2\pi} \frac{\sqrt{3}}{2} i_p^2 \frac{l}{a_m} \quad (2)$$

where

i_p is the peak value of the short-circuit current in the case of a balanced three-phase short-circuit. For the calculation, see the IEC 60909 series;

l is the maximum centre-line distance between adjacent supports;

a_m is the effective distance between main conductors in 5.3.

NOTE Equation (2) can also be used for calculating the resulting peak force when conductors with circular cross-sections are in the corners of an equilateral triangle and where a_m is the length of the side of the triangle.

5.2.2 Calculation of peak force between the main conductors during a line-to-line short-circuit

The maximum force acting between the conductors carrying the short-circuit current during a line-to-line short-circuit in a three-phase system or in a two-line single-phase-system is given by:

$$F_{m2} = \frac{\mu_0}{2\pi} i_{p2}^2 \frac{l}{a_m} \quad (3)$$

where

i_{p2} is the peak short-circuit current in the case of a line-to-line short-circuit;

l is the maximum centre-line distance between adjacent supports;

a_m is the effective distance between main conductors in 5.3.

5.2.3 Calculation of peak value of force between coplanar sub-conductors

The maximum force acts on the outer sub-conductors and is between two adjacent connecting pieces given by:

$$F_s = \frac{\mu_0}{2\pi}\left(\frac{i_p}{n}\right)^2 \frac{l_s}{a_s} \qquad (4)$$

where

n is the number of sub-conductors;

l_s is the maximum existing centre-line distance between two adjacent connecting pieces;

a_s is the effective distance between sub-conductors;

i_p is equal to i_p for a three-phase system or to i_{p2} for a two-line single-phase system.

5.3 Effective distance between main conductors and between sub-conductors

The forces between conductors carrying short-circuit currents depend on the geometrical configuration and the profile of the conductors. For this reason the effective distance a_m between main conductors has been introduced in 5.2.1 and 5.2.2 and the effective distance a_s between sub-conductors in 5.2.3. They shall be taken as follows:

Effective distance a_m between coplanar main conductors with the centre-line distance a:

- Main conductors consisting of single circular cross-sections:

$$a_m = a \qquad (5)$$

- Main conductors consisting of single rectangular cross-sections and main conductors composed of sub-conductors with rectangular cross-sections:

$$a_m = \frac{a}{k_{12}} \qquad (6)$$

  k_{12} shall be taken from Figure 1, with $a_{1s} = a$, $b_s = b_m$ and $c_s = c_m$.

Effective distance a_s between the n coplanar sub-conductors of a main conductor:

- Sub-conductors with circular cross-sections:

$$\frac{1}{a_s} = \frac{1}{a_{12}} + \frac{1}{a_{13}} + \frac{1}{a_{14}} + \cdots + \frac{1}{a_{1s}} + \cdots + \frac{1}{a_{1n}} \qquad (7)$$

- Sub-conductors with rectangular cross-sections:

  Some values for a_s are given in Table 1. For other distances and sub-conductor dimensions the equation

$$\frac{1}{a_s} = \frac{k_{12}}{a_{12}} + \frac{k_{13}}{a_{13}} + \frac{k_{14}}{a_{14}} + \cdots + \frac{k_{1s}}{a_{1s}} + \cdots + \frac{k_{1n}}{a_{1n}} \qquad (8)$$

  can be used. The values for k_{12},.......k_{1n} shall be taken from Figure 1.

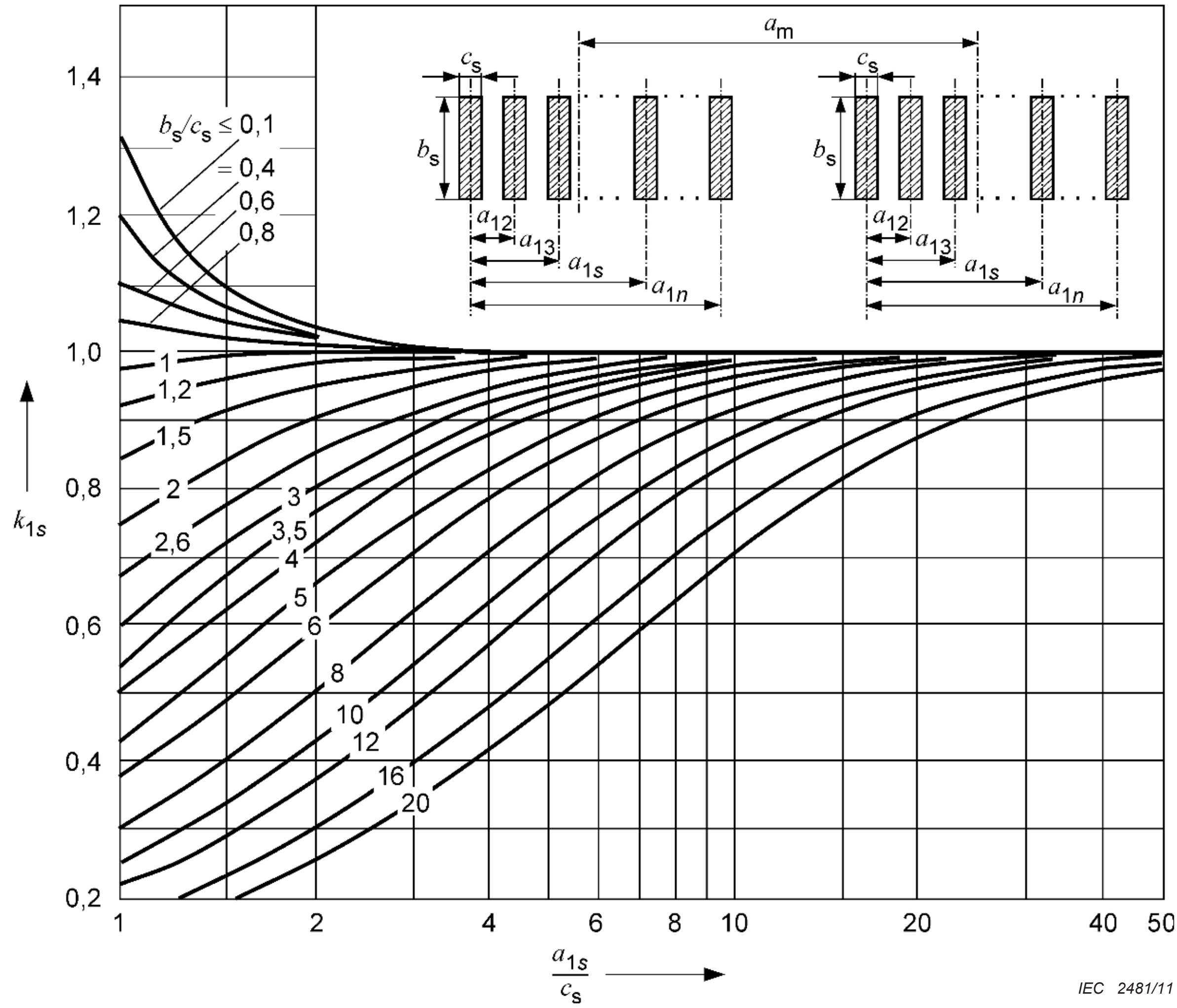
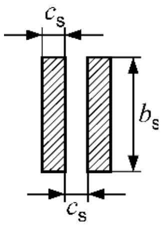
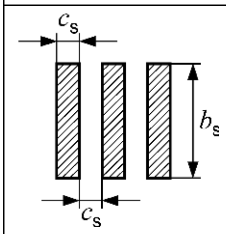
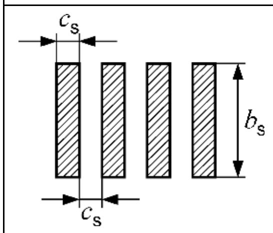
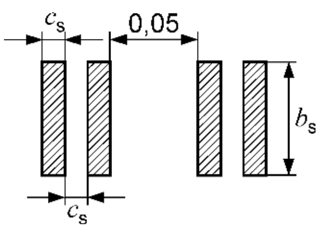


Figure 1 – Factor k_{1s} for calculating the effective conductor distance

For programming, the Equation is given in Clause A.2.

Table 1 – Effective distance a_s between sub-conductors for rectangular cross-section dimensions[a]

Rectangular cross sections	c_s \ b_s	0,04	0,05	0,06	0,08	0,10	0,12	0,16	0,20
	0,005	0,020	0,024	0,027	0,033	0,040	–	–	–
	0,010	0,028	0,031	0,034	0,041	0,047	0,054	0,067	0,080
	0,005	–	0,013	0,015	0,018	0,022	–	–	–
	0,010	0,017	0,019	0,020	0,023	0,027	0,030	0,037	0,043
	0,005	–	–	–	–	–	–	–	–
	0,010	0,014	0,015	0,016	0,018	0,020	0,022	0,026	0,031
	0,005	–	0,014	0,015	0,018	0,020	–	–	–
	0,010	0,017	0,018	0,020	0,022	0,025	0,027	0,032	–

[a] All dimensions are given in metres.

5.4 Calculation of stresses in rigid conductors

5.4.1 Calculation of stresses

Conductors have to be fixed in a way that axial forces can be disregarded. Under this assumption the forces acting are bending forces and the general equation for the bending stress caused by the forces between main conductors is given by:

$$\sigma_{m,d} = V_{\sigma m} V_{rm} \beta \frac{F_m l}{8 W_m} \tag{9}$$

where

F_m is either the value F_{m3} of three-phase systems according to Equation (2) or F_{m2} of two-line single-phase systems according to Equation (3);

W_m is the section modulus of the main conductor and shall be calculated with respect to the direction of forces between main conductors.

The bending stress caused by the forces between sub-conductors is given by:

$$\sigma_{s,d} = V_{\sigma s} V_{rs} \frac{F_s l_s}{16 W_s} \tag{10}$$

where

F_s according to Equation (4) shall be used;

W_s is the section modulus of the sub-conductor and shall be calculated with respect to the direction of forces between sub-conductors.

$V_{\sigma m}$, $V_{\sigma s}$, V_{rm} and V_{rs} are factors which take into account the dynamic phenomena, and β is a factor depending on the type and the number of supports. The maximum possible values of $V_{\sigma m}$ V_{rm} and $V_{\sigma s}$ V_{rs} shall be taken from Table 2 and the factor β shall be taken from Table 3.

NOTE The factor β describes the reduction of the bending stress at the place of its supports, taking into account the plastic deformation of the conductor (see Table 3).

Non-uniform spans in continuous beams may be treated, with sufficient degree of accuracy by assuming the maximum span applied throughout. This means that

- the end supports are not subjected to greater stress than the inner ones,
- span lengths less than 20 % of the adjacent ones shall be avoided. If that does not prove to be possible, the conductors shall be decoupled using flexible joints at the supports. If there is a flexible joint within a span, the length of this span should be less than 70 % of the lengths of the adjacent spans.

If it is not evident whether a beam is supported or fixed, the worst case shall be taken into account.

For further consideration, see 5.7

5.4.2 Section modulus and factor q of main conductor composed of sub-conductors

The bending stress and, consequently, the mechanical withstand of the conductor, depends on the section modulus.

If the stress occurs in accordance with Figure 2a, the section modulus W_m is independent of the number of connecting pieces and is equal to the sum of the section moduli W_s of the sub-conductors (W_s with respect to the axis x-x). The factor q has then the value 1,5 for rectangular cross-sections and 1,19 for U and I sections.

If the stress occurs in accordance with Figure 2b and in the case there is only one or no stiffening element within a supported distance, the section modulus W_m is equal to the sum of the section moduli W_s of the sub-conductors (W_s with respect to the axis y-y). The factor q has then the value 1,5 for rectangular cross-sections and 1,83 for U and I sections.

When, within a supported distance, there are two or more stiffening elements, higher values of section moduli may be used:

- for main conductors composed of sub-conductors of rectangular cross-sections with a space between the bars equal to the bar thickness, the section moduli are given in Table 5;
- for conductor groups having U and I cross-sections, 50 % of the section moduli with respect to the axis 0-0 should be used.

The factor q then has a value of 1,5 for rectangular cross-section and 1,83 for U and I sections.

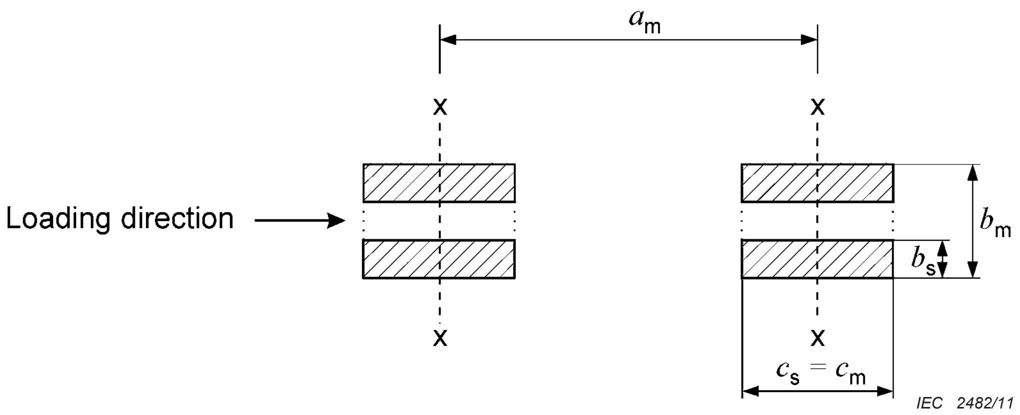


Figure 2a – Loading along the surface

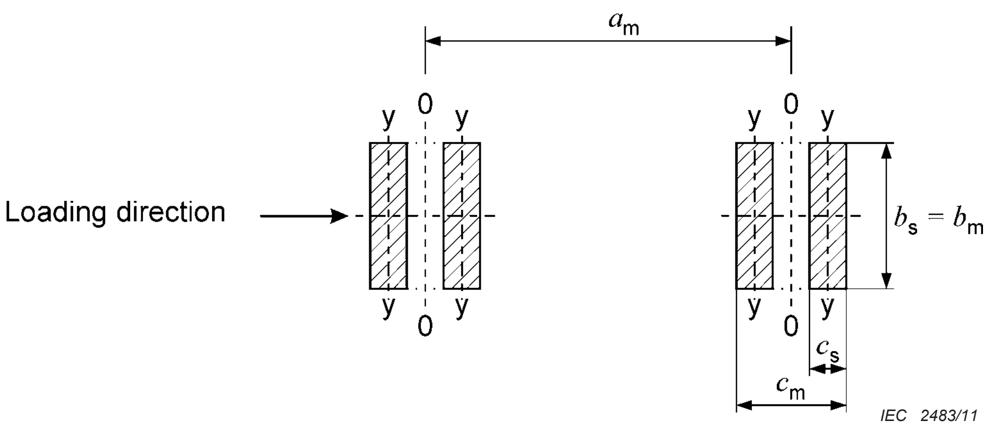


Figure 2b – Loading perpendicular to the surface

Figure 2 – Loading direction and bending axis for multiple conductor arrangements

Table 2 – Maximum possible values of $V_{\sigma m}V_{rm}$, $V_{\sigma s}V_{rs}$, $V_F V_{rm}$

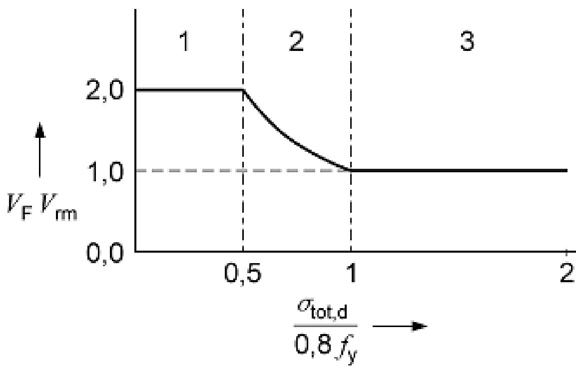
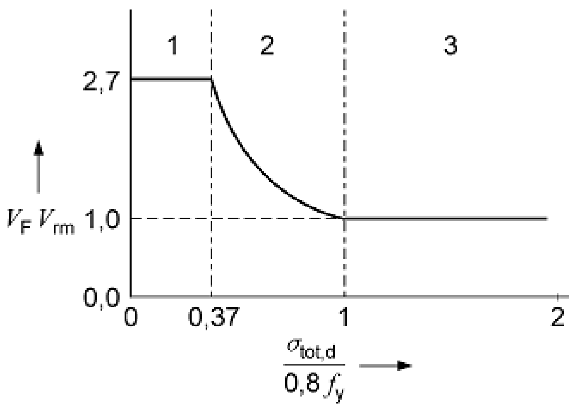
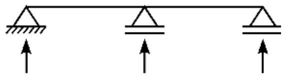
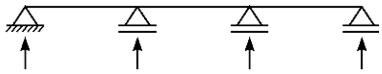
Type of short-circuit	System			
	Without three-phase automatic reclosing	**With three-phase automatic reclosing**		**With and without three-phase automatic reclosing**
	$V_{\sigma m}V_{rm}, V_{\sigma s}V_{rs}$	$V_{\sigma m}V_{rm}$, $V_{\sigma s}V_{rs}$		$V_F V_{rm}$
		First current flow	Second current flow	
Line-to-line	1,0	1,0	1,8	range 2,0 for $\frac{\sigma_{tot,d}}{0,8 f_y} \le 0,5$ 1 $\frac{0,8 f_y}{\sigma_{tot,d}}$ for $0,5 < \frac{\sigma_{tot,d}}{0,8 f_y} < 1,0$ 2 1,0 for $1,0 \le \frac{\sigma_{tot,d}}{0,8 f_y}$ 3 
Three-phase	1,0	1,0	1,8	range 2,7 for $\frac{\sigma_{tot,d}}{0,8 f_y} \le 0,37$ 1 $\frac{0,8 f_y}{\sigma_{tot,d}}$ for $0,37 < \frac{\sigma_{tot,d}}{0,8 f_y} < 1,0$ 2 1,0 for $1,0 \le \frac{\sigma_{tot,d}}{0,8 f_y}$ 3 

Table 3 – Factors α, β, γ for different busbar support arrangements

Type of beam and support			α	β *)	γ
Single span beam	A and B: simple supports		A: 0,5 B: 0,5	1,0	1,57
	A: fixed support B: simple support		A: 0,625 B: 0,375	$\frac{8}{11} = 0{,}73$	2,45
	A and B: fixed supports		A: 0,5 B: 0,5	$\frac{8}{16} = 0{,}5$	3,56
Continuous beam with equidistant simple supports	Two spans		A: 0,375 B: 1,25	$\frac{8}{11} = 0{,}73$	2,45
	Three or more spans		A: 0,4 B: 1,1	$\frac{8}{11} = 0{,}73$	3,56
* Plasticity effects included.					

5.4.3 Permitted conductor stress

A single conductor is assumed to withstand the short-circuit forces when:

$$\sigma_{\mathrm{m,d}} \leq q\, f_{\mathrm{y}} \tag{11}$$

where f_{y} is the stress corresponding to the yield point.

The factor q shall be taken from Table 4, see also 5.4.2.

NOTE The factor q as given in Table 4 and in 5.4.2 describes the increase of the permitted stress of the conductor due to its plastic behaviour at places outside of its supports taking into account the shape of the conductor.

When a main conductor consists of two or more sub-conductors the total stress in the conductor is given by:

$$\sigma_{\mathrm{tot,d}} = \sigma_{\mathrm{m,d}} + \sigma_{\mathrm{s,d}} \tag{12}$$

The conductor is assumed to withstand the short-circuit forces when:

$$\sigma_{\mathrm{tot,d}} \leq q\, f_{\mathrm{y}} \tag{13}$$

It is necessary to verify that the short-circuit does not affect the distance between sub-conductors too much, therefore a value

$$\sigma_{s,d} \leq f_y \tag{14}$$

is recommended.

In Table 4 the highest acceptable values for q for different cross-sections are given. For $\sigma_{m,d} = q\,f_y$ respectively $\sigma_{tot,d} = q\,f_y$ small permanent deformations can occur, approximately 1 % of the distance between supports for q-values according to Table 4, which do not jeopardize the safety of operation as long as by this the minimum clearances between main conductors or between a main conductor and the earthed structure are not violated.

For the yield point of conductor materials, f_y, the standards often state ranges with minimum and maximum values. If only such limit values rather than actual readings are available, the minimum value should be used in 5.4.3 and the maximum value in Table 2.

NOTE A possible static stress in the conductor (e.g. due to its dead load) is not regarded in Equations (11) to (14). If applicable, it should be combined with the stress due to short-circuit corresponding to the direction of action.

5.5 Structure loads due to rigid conductors

The equivalent static force $F_{r,d}$ on supports of rigid conductors shall be calculated from:

$$F_{r,d} = V_F\,V_{rm}\,\alpha\,F_m \tag{15}$$

where F_m is either the value F_{m3} of three-phase systems according to Equation (2) or F_{m2} of two-line single-phase systems according to Equation (3) shall be used.

The maximum possible values of $V_F\,V_{rm}$ shall be taken from Table 2.

The factor α is dependent on the type and the number of supports and shall be taken from Table 3.

For further consideration, see 5.7 .

The force $F_{r,d}$ shall not be greater than the withstand value given by the manufacturer of supports and insulators. For an insulator stressed by a bending force, the rated withstand value is given as a force acting at the insulator head.

NOTE For a force acting at a point higher than the insulator head, a withstand value lower than the rated withstand value should be used, based on the withstand bending moment at the critical insulator cross-section.

5.6 Consideration of automatic reclosing

At rigid conductors, automatic reclosing has to be regarded if three-phase automatic reclosing is used.

In networks with three-phase automatic reclosing different mechanical stresses occur during the first and the second current flow duration. Thus, different forces can result on the supports during the two current flow durations. That's why the force $F_{r,d}$ shall be calculated as follows:

- calculation of $\sigma_{tot,d}$ according to 5.4 with $V_{\sigma m}V_{rm}$, $V_{\sigma s}V_{rs}$ from Table 2 for the first current flow duration and determination of $V_F\,V_{rm}$ from Table 2;
- calculation of $\sigma_{tot,d}$ according to 5.4 with $V_{\sigma m}V_{rm}$, $V_{\sigma s}V_{rs}$ from Table 2 for the second current flow duration and determination of $V_F\,V_{rm}$ from Table 2;
- calculation of $F_{r,d}$ according to Equation (15) with the maximum value of $V_F\,V_{rm}$ out of the two current flow durations.

Table 4 – Factor q

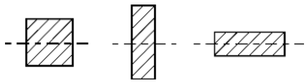
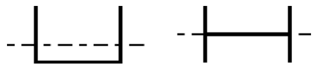
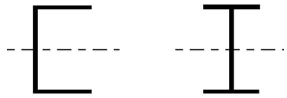
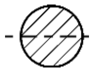
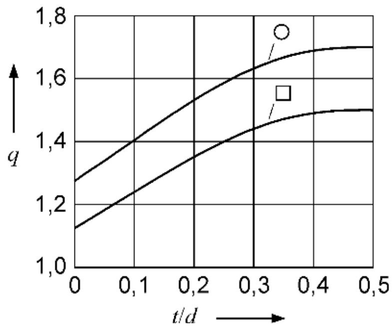
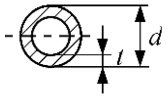
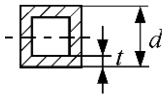
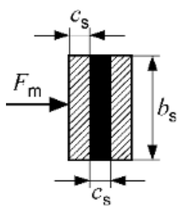
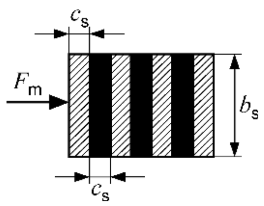
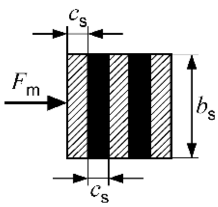
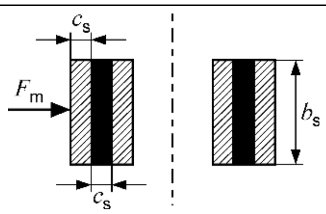
Cross section		Cross section	
	$q = 1{,}5$		$q = 1{,}83$
			$q = 1{,}19$
	$q = 1{,}7$		
	$q = 1{,}7\,\dfrac{1-(1-2t/d)^3}{1-(1-2t/d)^4}$		
	$q = 1{,}5\,\dfrac{1-(1-2t/d)^3}{1-(1-2t/d)^4}$		
q is valid for the dotted bending axis. The forces are perpendicular to it.			

Table 5 – Section moduli W_m of main conductors with two or more stiffening elements between two adjacent supports

Rectangular sections	W_m	Rectangular sections	W_m
	$0{,}867\, c_s^2\, b_s$		$3{,}48\, c_s^2\, b_s$
	$1{,}98\, c_s^2\, b_s$		$1{,}73\, c_s^2\, b_s$
The stiffening elements are black.			

5.7 Calculation with special regard to conductor oscillation

5.7.1 General

The equations in 5.4.1 and 5.5 contain factors $V_{\sigma m}$, $V_{\sigma s}$, V_F, V_{rm} and V_{rs} which take into account oscillatory nature of the stresses and forces.

The upper limits of these factors are given in Table 2. Lower values than these are permitted, if they are estimated by this subclause. It is necessary to calculate the relevant natural frequency f_{cm} taking into account the accuracy of the data.

5.7.2 Determination of relevant natural frequency

The relevant natural frequency of a conductor can be calculated from:

$$f_{\text{cm}} = \frac{\gamma}{l^2}\sqrt{\frac{E\,J_{\text{m}}}{m'_{\text{m}}}} \quad (16)$$

Equation (16) is directly applicable to main conductors consisting of single cross-sections.

The factor γ is dependent on the type and number of supports and is given in Table 3.

NOTE 1 The relevant natural frequency is calculated slightly too high with Equation (16) for continuous beam having three or more spans. A more exact calculation can be made with additional effort only. That's why it is recommended to use Equation (16).

If the main conductor is composed of sub-conductors of rectangular cross-section, the relevant natural frequency of the main conductor shall be calculated from:

$$f_{\text{cm}} = e\,\frac{\gamma}{l^2}\sqrt{\frac{E\,J_{\text{s}}}{m'_{\text{s}}}} \quad (17)$$

The factor e shall be taken from Figure 3b or Figure 3c. In the case of no connecting pieces e = 1.

For a main conductor composed of sub-conductors of U and I sections f_{cm} is calculated from Equation (16): J_{m} and m'_{m} shall apply to the main conductor design.

For the calculation of sub-conductor stress, taking the relevant natural frequency into account, the equation

$$f_{\text{cs}} = \frac{3{,}56}{l_{\text{s}}^2}\sqrt{\frac{E\,J_{\text{s}}}{m'_{\text{s}}}} \quad (18)$$

shall be used.

NOTE 2 The second moments of area J_{m} and J_{s} are calculated according to Figures 2a or 2b.

5.7.3 The factors V_{F}, $V_{\sigma\text{m}}$, $V_{\sigma\text{s}}$, V_{rm} and V_{rs}

The factors V_{F}, $V_{\sigma\text{m}}$, $V_{\sigma\text{s}}$, V_{rm} and V_{rs} as functions of the ratio f_{cm}/f and f_{cs}/f, where f is the system frequency, are a little different if a three-phase short-circuit or a line-to-line short-circuit is to be concerned, and they are also dependent on the mechanical damping of the conductor system. For practical calculations, these factors shall be taken from Figure 4.

NOTE 1 Short-circuit duration $T_{\text{k1}} \le 0{,}1$ s can cause an appreciable reduction of the stress in structures with $f_{\text{cm}}/f \le 1$.

NOTE 2 In the case of elastic supports, the relevant natural frequency is lower than calculated with Equation (16). This is to be considered when using Figure 4, if the value of $f_{\text{cm}}/f > 2{,}4$.

For three-phase automatic reclosing, the factors V_{rm} and V_{rs} shall be taken from Figure 5; in other cases $V_{\text{rm}} = 1$, $V_{\text{rs}} = 1$.

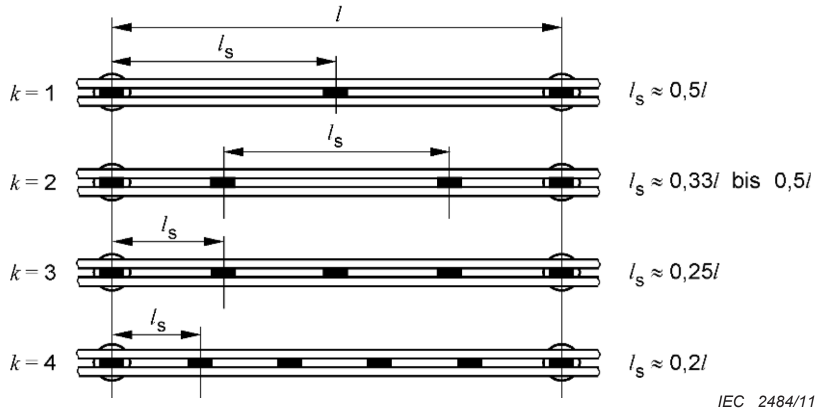


Figure 3a – Arrangement of connecting pieces within the span

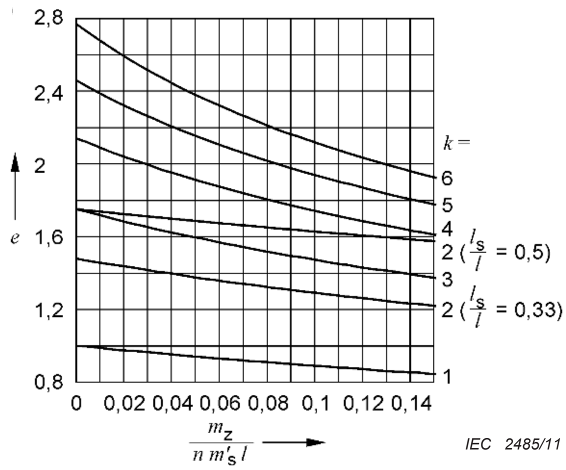


Figure 3b – Connecting pieces are stiffening elements

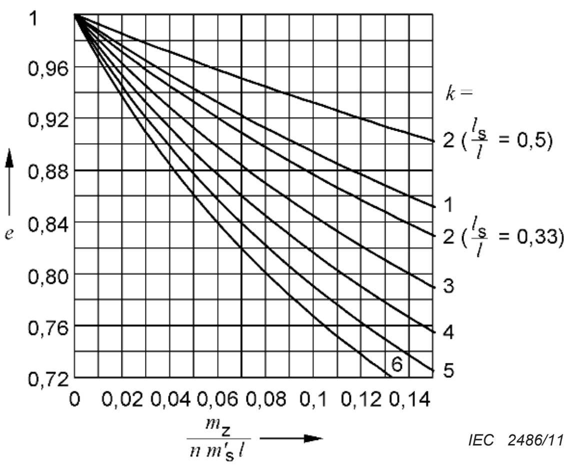
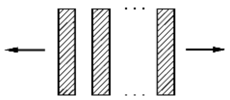
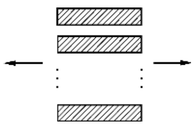


Figure 3c – Connecting pieces are, or operate as, spacers

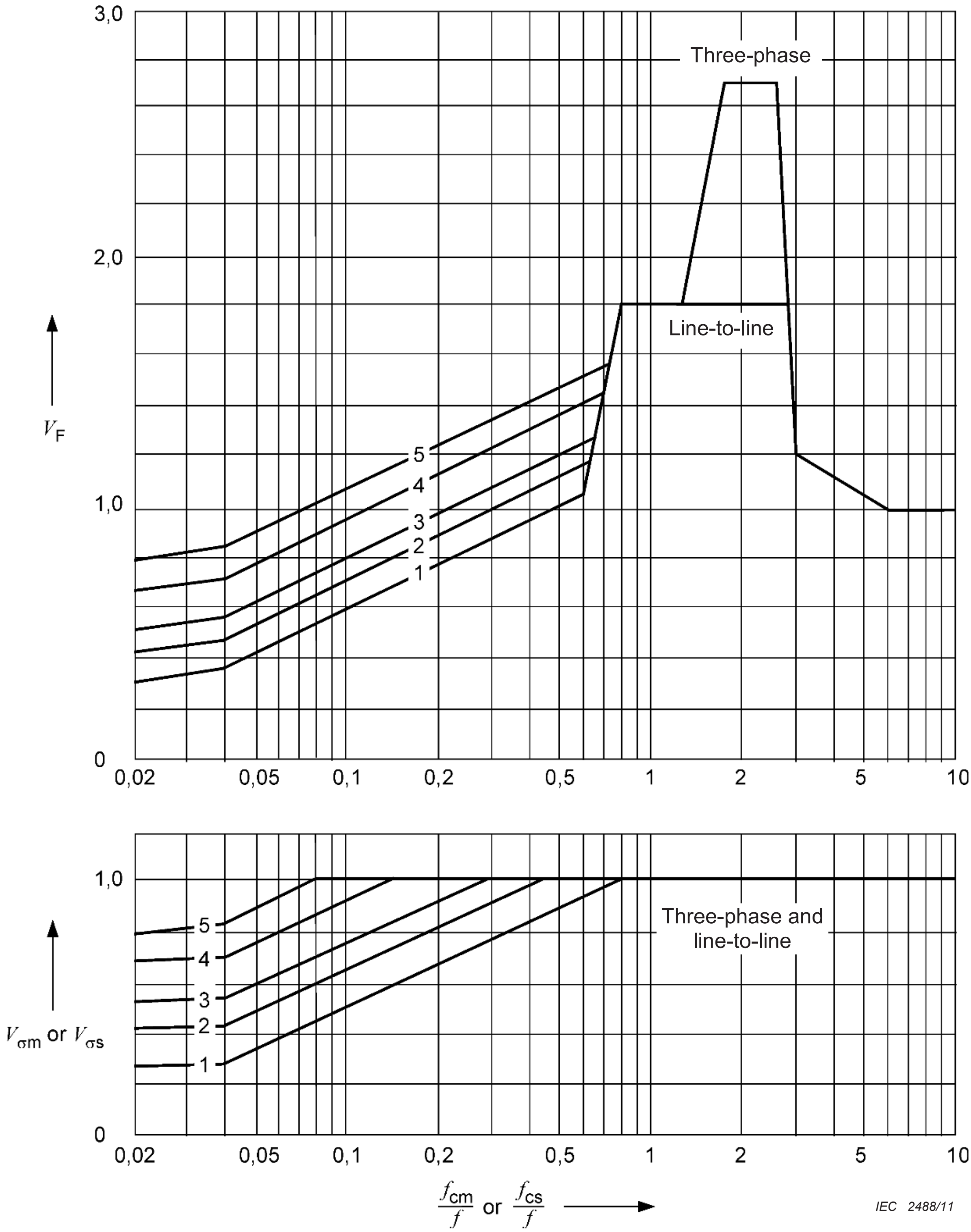
Factor e shall be taken from the Figure 3b or Figure 3c as shown:

		Within a span there are	
		k **stiffening elements**	k **spacers**
Direction of oscillation perpendicular to the surface		Factor e from Figure 3b	Factor e from Figure 3c
Direction of oscillation along the surface		Factor e from Figure 3c	Factor e from Figure 3c

IEC 2487/11

Figure 3 – Factor e for the influence of connecting pieces in Equation (17)

For programming, the equation is given in Clause A.3.



Key

1 $\kappa \geq 1{,}60$ 2 $\kappa = 1{,}40$ 3 $\kappa = 1{,}25$
4 $\kappa = 1{,}10$ 5 $\kappa = 1{,}00$

Figure 4 – Factors V_F, $V_{\sigma m}$ and $V_{\sigma s}$ to be used with the three-phase and line-to-line short-circuits

For programming, the equations are given in Clause A.4.

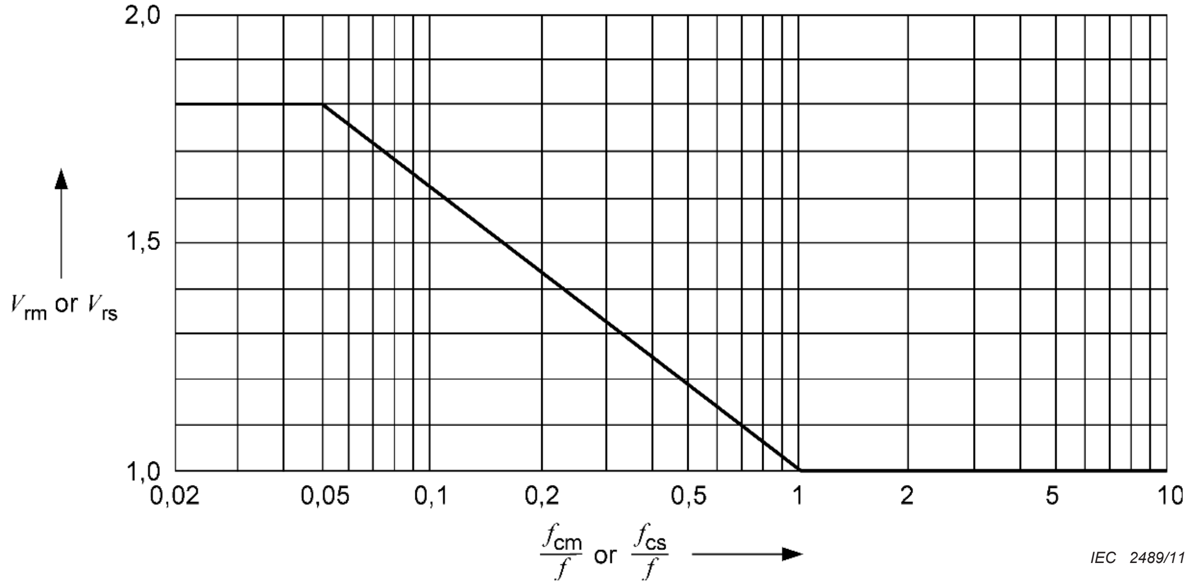


Figure 5 – Factors V_{rm} and V_{rs} to be used with three-phase automatic reclosing

For programming, the equation is given in Clause A.5.

6 Flexible conductor arrangements

6.1 General

In a span, there is a difference between the tensile force $F_{t,d}$ due to the swing-out of the conductor during the short-circuit, the tensile force $F_{f,d}$ after the short-circuit when the conductor drops back and the tensile force $F_{pi,d}$ caused by the pinch effect in the conductor bundle. The effects on horizontal main conductors are calculated in 6.2. After calculation of the characteristic parameters for the configuration and type of short-circuit in 6.2.2, the tensile force $F_{t,d}$ without dropper in the span is calculated in 6.2.3. The dynamic change of sag due to elongation of conductor and change of shape of the conductor curve is determined in 6.2.4 and afterwards the tensile force $F_{t,d}$ with droppers in the span in 6.2.5. The tensile force $F_{f,d}$ after the short-circuit follows in 6.2.6. The horizontal displacement of the span b_h and the minimum air clearance between conductors a_{min} during the swing-out of the conductors is calculated in 6.2.7. The effects on vertical main conductors are determined in 6.3. The tensile force $F_{pi,d}$ is calculated in 6.4. Design loads are given with 6.5.

In installations with flexible conductors, the stresses occurring in line-to-line short-circuits and balanced three-phase short-circuits are approximately equal. However, for line-to-line short-circuits, conductor swing out typically results in decreasing minimum clearances, (i.e. when adjacent conductors carrying short-circuit current move towards one another after the short-circuit). In the case of balanced three-phase short-circuit, the centre conductor moves only slightly because of its inertia and the alternating bidirectional forces which act on it. Consequently $F_{t,d}$, $F_{f,d}$ and b_h are therefore calculated for a line-to-line short-circuit.

The tensile forces $F_{t,d}$, $F_{f,d}$ and $F_{pi,d}$ include the tensile forces caused by the dead-load.

The following calculations shall be carried out on the basis of the static tensile force F_{st} existing at the local minimum winter temperature, e.g. –20 °C, and also on the basis of the static tensile force F_{st} existing at the maximum operating temperature, e.g. 60 °C. For each tensile force, the worst case shall be taken into account for design purposes.

6.2 Effects on horizontal main conductors

6.2.1 General

The following subclauses apply to single conductors and to bundle configurations.

In addition to the stresses calculated here, the stresses due to the sub-conductors according to 6.4 have to be calculated. Arrangements with and without droppers within the span are regarded.

The following sections are valid for horizontal, side by side arranged cables. In other arrangements, smaller tensile forces can occur. Due to the effort of such calculations, it is recommended to use the given equation in these cases as well. If the difference in the height of fixing points is more than 25 % of the span, the calculation shall be made according to 6.3.

The following equations apply for span lengths up to approximately 120 m and ratios of sag to span-length to approximately 8 %. For longer spans, the movement of the conductor can result in lower stresses than calculated using the equations. If this can be proved by computation or measurement, lower loads may be taken into account.

NOTE Droppers near to the fixing point of the main conductor have little effect on the tensile forces and the movement of the main conductor. In this case, it is recommended to calculate according to 6.2 without regarding the droppers.

The share of concentrated masses in the span e.g. by clamps, droppers or connectors should be regarded when calculating the static tensile force F_{st} and the static sag f_{st}. For the dropper, half of its mass should be estimated in this case.

The sum of existing concentrated masses shall be converted to an additional mass per unit length across the span when calculating for the tensile forces $F_{t,d}$ and $F_{f,d}$. However, the mass of the dropper in the middle of span and its clamp shall not be regarded.

6.2.2 Characteristic dimensions and parameter

The characteristic electromagnetic load per unit length on flexible main conductors in three-phase systems is given

- if the current flows along the whole length of the main conductor span with and without dropper by:

$$F' = \frac{\mu_0}{2\pi} 0{,}75 \frac{(I''_k)^2}{a} \frac{l_c}{l} \tag{19a}$$

- if the current flows along half of the length of the main conductor span and along the dropper by:

$$F' = \frac{\mu_0}{2\pi} 0{,}75 \frac{(I''_k)^2}{a} \frac{l_c/2 + l_v/2}{l} \tag{19b}$$

where

I''_k is the three-phase initial symmetrical short-circuit current (r.m.s.);

a is the centre-line distance between main conductor mid-points;

l_c is the cord length of the main conductor in the span;

l_v is the cord length of the dropper.

For slack conductors which exert bending forces on the support insulators $l_c = l$. For spans with strained conductors $l_c = l - 2l_i$, where l_i is the length of one insulator chain.

In the case of two-line single-phase systems replace $0{,}75\ \left(I''_{\text{k}}\right)^2$ in Equation (19) by $\left(I''_{\text{k2}}\right)^2$.

NOTE 1 The calculation procedure does not consider the contribution of the aperiodic component of the short-circuit current. This will, however, significantly influence the result only if the duration of the short-circuit current flow is less than 0,1 s. In this case reference is made to [2].

The ratio of electromagnetic force under short-circuit conditions to the gravitational force on a conductor is an important parameter given by

$$r = \frac{F'}{n\, m'_{\text{s}}\, g} \tag{20}$$

and gives the direction of the resulting force exerted on the conductor:

$$\delta_1 = \arctan r \tag{21}$$

The equivalent static conductor sag at midspan is given by

$$f_{\text{es}} = \frac{n\, m'_{\text{s}}\, g\, l^2}{8\, F_{\text{st}}} \tag{22}$$

The period T of the conductor oscillations is given by

$$T = 2\pi \sqrt{0{,}8\, \frac{f_{\text{es}}}{g}} \tag{23}$$

and applies for small swing-out angles without current flow in the conductor.

The resulting period T_{res} of the conductor oscillation during the short-circuit current flow is given by:

$$T_{\text{res}} = \frac{T}{\sqrt[4]{1+r^2}\left[1 - \frac{\pi^2}{64}\left(\frac{\delta_1}{90°}\right)^2\right]} \tag{24}$$

where δ_1 shall be given in degrees.

The stiffness norm is given by:

$$N = \frac{1}{S\, l} + \frac{1}{n\, E_{\text{eff}}\, A_{\text{s}}} \tag{25}$$

NOTE 2 If the exact value of S is not known in Equation (25), the value S = 100×10³ N/m may be used for slack conductors which exert bending forces on support insulators.

NOTE 3 If the exact value of S for spans with strained conductors is not known, the value of **one** structure in following ranges may be used:

– 150×10³ N/m to 1 300×10³ N/m at a rated voltage of 123 kV;

– 400×10³ N/m to 2 000×10³ N/m at a rated voltage of 245 kV;

– 600×10³ N/m to 3 000×10³ N/m at a rated voltage of 420 kV.

S in Equation (25) is the resulting spring constant of both fixing points.

E_{eff} is the actual Young's modulus

$$E_{eff} = \begin{cases} E \left[0,3 + 0,7 \sin\left(\frac{F_{st}}{n\, A_s\, \sigma_{fin}} 90° \right) \right] & \text{for } \frac{F_{st}}{n\, A_s} \le \sigma_{fin} \\ E & \text{for } \frac{F_{st}}{n\, A_s} > \sigma_{fin} \end{cases} \quad (26)$$

where

$$\sigma_{fin} = 50 \cdot 10^6 \frac{\text{N}}{\text{m}^2} \quad (27)$$

σ_{fin} is the lowest value of the cable stress when Young's modulus becomes constant. The final Young's modulus E for stranded conductors shall be used.

The stress factor ζ of the main conductor is given by:

$$\zeta = \frac{\left(n\, g\, m'_s\, l\right)^2}{24\, F_{st}^3\, N} \quad (28)$$

During or at the end of the short-circuit current flow, the span will have oscillated out of the steady-state position to the angle given by:

$$\delta_{end} = \begin{cases} \delta_1 \left[1 - \cos\left(360° \frac{T_{k1}}{T_{res}} \right) \right] & \text{for } 0 \le \frac{T_{k1}}{T_{res}} \le 0,5 \\ 2\, \delta_1 & \text{for } \frac{T_{k1}}{T_{res}} > 0,5 \end{cases} \quad (29)$$

Insofar as the duration of the first short-circuit current flow T_{k1} as defined in 3.1.12 is known, the maximum swing-out angle δ_{max} may be determined as per Figure 6 or calculated as given below. Otherwise, or if T_{k1} is greater than the value 0,4 T, then the value 0,4 T shall be used for T_{k1} in Equations (29), (32) and (35).

During or after the short-circuit current flow, the span without dropper in midspan will have oscillated to the maximum swing-out angle δ_{max} which is obtained with:

$$\chi = \begin{cases} 1 - r \sin \delta_{end} & \text{for } 0 \le \delta_{end} \le 90° \\ 1 - r & \text{for } \delta_{end} > 90° \end{cases} \quad (30)$$

from:

$$\delta_{max} = \begin{cases} 1,25 \arccos \chi & \text{for } 0,766 \le \chi \le 1 \\ 10° + \arccos \chi & \text{for } -0,985 \le \chi \le 0,766 \\ 180° & \text{for } \chi < -0,985 \end{cases} \quad (31)$$

NOTE 4 The calculated swing-out angle δ_{max} is the maximum value which can occur for the "worst case" which is a short-circuit duration less than or equal to the stated short-circuit duration T_{k1}.

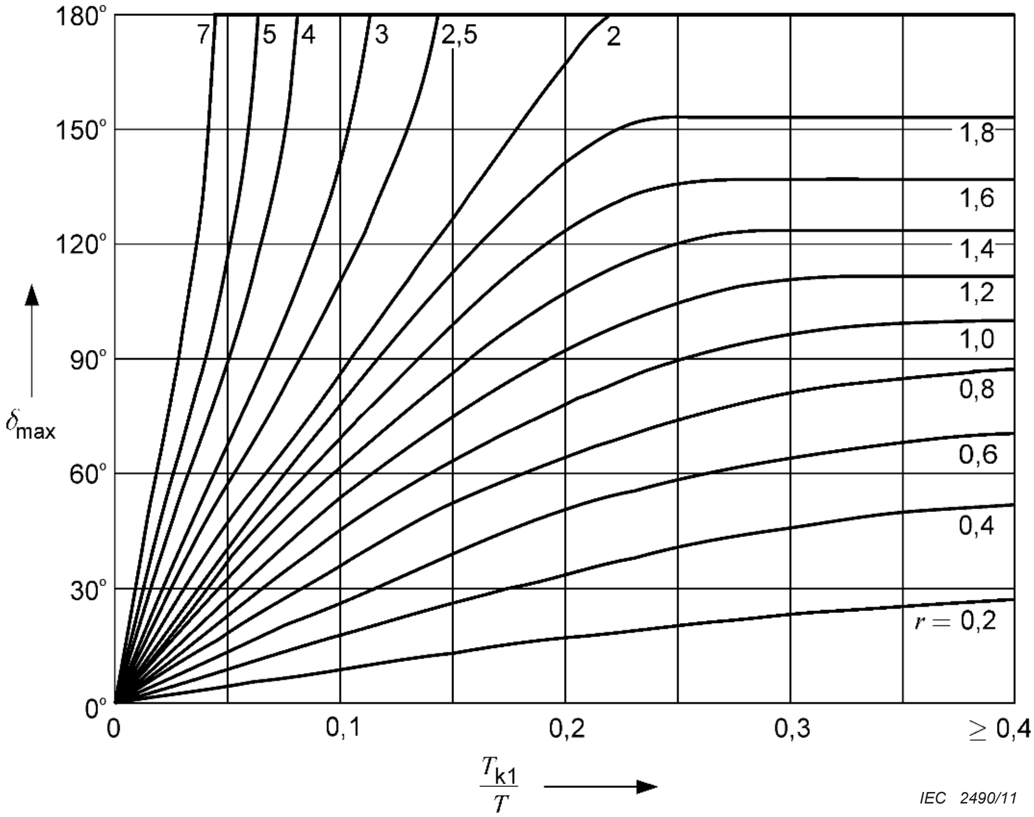


Figure 6 – Maximum swing out angle δ_{max} for a given maximum short-circuit duration T_{k1}

For programming, refer to Equations (31) and (19) to (30).

6.2.3 Tensile force $F_{t,d}$ during short-circuit caused by swing out (short-circuit tensile force) without dropper in midspan

The load parameter φ is obtained as follows:

$$\varphi = \begin{cases} 3\left(\sqrt{1+r^2}-1\right) & \text{for} \quad T_{k1} \geq T_{res}/4 \\ 3\left(r \sin\delta_{end} + \cos\delta_{end} - 1\right) & \text{for} \quad T_{k1} < T_{res}/4 \end{cases} \tag{32}$$

The factor ψ is a function of ζ and φ and is determined in Figure 7.

The tensile force $F_{t,d}$ is given by

$$F_{t,d} = F_{st}\left(1+\varphi\psi\right) \tag{33}$$

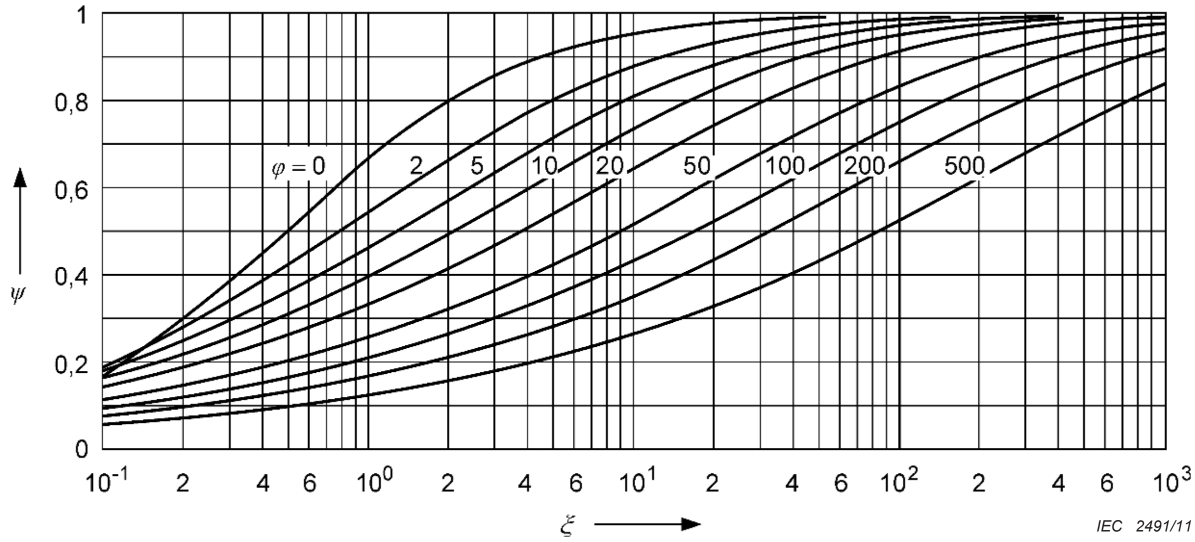


Figure 7 – Factor ψ for tensile force in flexible conductors

For programming, the equation is given in Clause A.6.

6.2.4 Dynamic change of sag due to elongation of conductor and change of shape of the conductor curve

The elastic expansion is given by:

$$\varepsilon_{\mathrm{ela}} = N\left(F_{\mathrm{t,d}} - F_{\mathrm{st}}\right) \tag{34}$$

The short-circuit tensile force $F_{\mathrm{t,d}}$ shall always be calculated with Equation (33) for spans without dropper in the middle of the span. For arrangements with dropper in the middle of the span, the actual swing-out angle δ shall be determined in 6.2.5. For this purpose, the elastic expansion for a span without dropper in the middle of the span shall be calculated with $F_{\mathrm{t,d}}$ according to Equation (33).

The thermal expansion is given by:

$$\varepsilon_{\mathrm{th}} = \begin{cases} c_{\mathrm{th}}\left(\dfrac{I''_{\mathrm{k}}}{n\,A_{\mathrm{s}}}\right)^2 T_{\mathrm{res}}/4 & \text{for} \quad T_{\mathrm{k1}} \geq T_{\mathrm{res}}/4 \\ c_{\mathrm{th}}\left(\dfrac{I''_{\mathrm{k}}}{n\,A_{\mathrm{s}}}\right)^2 T_{\mathrm{k1}} & \text{for} \quad T_{\mathrm{k1}} < T_{\mathrm{res}}/4 \end{cases} \tag{35}$$

For c_{th} use:

$0{,}27\times10^{-18}$ m^4/(A^{2}s)	for aluminium, aluminium alloy and aluminium/steel conductors with a cross section ratio of Al/St >6;
$0{,}17\times10^{-18}$ m^4/(A^{2}s)	for aluminium/steel conductors with a cross section ratio of Al/St ≤6;
$0{,}088\times10^{-18}$ m^4/(A^{2}s)	for copper.

In the case of two-line, single-phase systems, replace I''_{k} in Equation (35) by I''_{k2}.

The factor C_{D} allows for sag increases caused by elastic and thermal elongation of the conductor and is given by

$$C_D = \sqrt{1 + \frac{3}{8}\left[\frac{l}{f_{es}}\right]^2 (\varepsilon_{ela} + \varepsilon_{th})} \quad (36)$$

The factor C_F allows for a possible increase in the dynamic sag of the conductor caused by a change in shape of the conductor curve and is given by:

$$C_F = \begin{cases} 1{,}05 & \text{for} \quad r \le 0{,}8 \\ 0{,}97 + 0{,}1\,r & \text{for} \quad 0{,}8 < r < 1{,}8 \\ 1{,}15 & \text{for} \quad r \ge 1{,}8 \end{cases} \quad (37)$$

The dynamic sag results with

$$f_{ed} = C_F\, C_D\, f_{es} \quad (38)$$

6.2.5 Tensile force $F_{t,d}$ during short-circuit caused by swing out (short-circuit tensile force) with dropper in the middle of the span

Droppers within a span have an effect to the movement of the main-conductor. Adequate short droppers hinder the swing-out of the main conductor and the maximum swing-out angle δ_{max} of a similar main conductor without dropper will not be reached.

NOTE 1 The equations may also be used if the upper fixing point of the dropper is apart from the middle up to 10 % of the main conductor length.

NOTE 2 As an alternative to the following equations, it may be calculated with 6.2.3.

The plane of the dropper in Figure 8 can be parallel or perpendicular to the main conductors. The actual swing-out angle due to the limitation of the swing-out movement by the dropper is given by:

$$\delta = \begin{cases} \arccos \dfrac{(h + f_{es})^2 + f_{ed}^2 - (l_v^2 - w^2)}{2 f_{ed}(h + f_{es})} & \text{plane parallel} \\ \arccos \dfrac{(h + f_{es})^2 + f_{ed}^2 - (l_v^2 - w^2)}{2 f_{ed}\sqrt{(h + f_{es})^2 + w^2}} + \arccos \dfrac{h + f_{es}}{\sqrt{(h + f_{es})^2 + w^2}} & \text{plane perpendicular} \end{cases} \quad (39)$$

with

h, w height of dropper, width of dropper according to Figure 8;

l_v cord length of the dropper.

If $l_v \ge \sqrt{(h + f_{es} + f_{ed})^2 + w^2}$ in the case of parallel plane or if $l_v \ge \sqrt{(h + f_{es})^2 + w^2} + f_{ed}$ in the case of perpendicular plane, the calculation has to be done with 6.2.2.

At the calculation of load parameter φ a distinction has to be made between the following cases:

- $\delta \ge \delta_1$:

  The swing-out of the main conductor is not influenced within T_{res} / 4 by the dropper. The load parameter φ is calculated with

$$\varphi = \begin{cases} 3\left(\sqrt{1+r^2}-1\right) & \text{for} \quad T_{k1} \geq T_{res}/4 \\ 3\left(r \sin\delta_{end} + \cos\delta_{end} - 1\right) & \text{for} \quad T_{k1} < T_{res}/4 \end{cases} \tag{40}$$

- $\delta < \delta_1$:

  The swing-out of the main conductor is influenced within T_{res} / 4 by the dropper. The load parameter φ is calculated with

$$\varphi = \begin{cases} 3\left(r \sin\delta + \cos\delta - 1\right) & \text{for} \quad \delta_{end} \geq \delta \\ 3\left(r \sin\delta_{end} + \cos\delta_{end} - 1\right) & \text{for} \quad \delta_{end} < \delta \end{cases} \tag{41}$$

The factor ψ is a function of ζ and φ and given in Figure 7. The short-circuit tensile force $F_{t,d}$ is calculated with:

$$F_{t,d} = F_{st}\left(1+\varphi\psi\right) \tag{42}$$

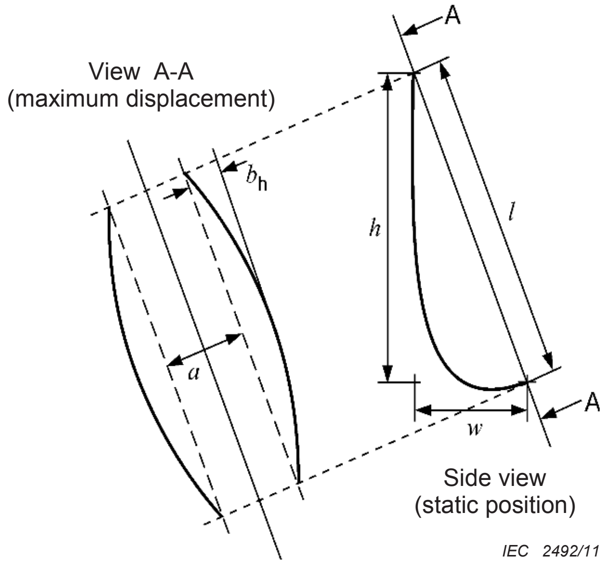


Figure 8 – Geometry of a dropper

6.2.6 Tensile force $F_{f,d}$ after short-circuit caused by drop (drop force)

On termination of the short-circuit the span oscillates or drops back. The maximum value $F_{f,d}$ for a span on termination of the drop is only significant for $r > 0{,}6$ if $\delta_{max} \geq 70°$ and with a dropper in the middle of the span additionally $\delta \geq 60°$. In this case, the drop force is given by:

$$F_{f,d} = 1{,}2\, F_{st} \sqrt{1 + 8\,\zeta\,\frac{\delta_{max}}{180°}} \tag{43}$$

NOTE In short spans the bending stiffness of the span reduces the span drop, which means that the span drop is calculated to be too large if the span length is less than approximately 100 times the diameter of the single conductor, i.e. $l < 100\, d$.

6.2.7 Horizontal span displacement b_h and minimum air clearance a_{min}

The maximum horizontal displacement in midspan, b_h, due to a short-circuit is given by the following for spans with slack conductors $l_c = l$ connected to support insulators and equipment:

$$b_h = \begin{cases} f_{ed} & \text{for} \quad \delta_{max} \geq 90° \\ f_{ed} \sin \delta_{max} & \text{for} \quad \delta_{max} < 90° \end{cases} \quad \text{for} \quad l_c = l \tag{44}$$

The maximum horizontal displacement in midspan, b_h, due to a short-circuit is given by the following for spans with strained conductors $l_c = l - 2l_i$ connected to portals with tension insulator strings:

$$b_h = \begin{cases} f_{ed} \sin\delta_1 & \text{for} \quad \delta_{max} \geq \delta_1 \\ f_{ed} \sin\delta_{max} & \text{for} \quad \delta_{max} < \delta_1 \end{cases} \quad \text{for} \quad l_c = l - 2l_i \tag{45}$$

δ_{max}, and δ_1 are defined in 6.2.2 and f_{ed} in 6.2.4.

The maximum horizontal displacement in midspan, b_h, due to a short-circuit for spans with strained conductors $l_c = l - 2l_i$ connected to portals with tension insulator strings and which have a dropper in midspan, is depending to the length of the dropper. It is calculated for the two cases:

- $\delta \geq \delta_{max}$:

  The dropper has no influence to the movement of the cable and the maximum horizontal displacement is calculated with:

$$b_h = \begin{cases} f_{ed} \sin\delta_1 & \text{for} \quad \delta_{max} \geq \delta_1 \\ f_{ed} \sin\delta_{max} & \text{for} \quad \delta_{max} < \delta_1 \end{cases} \quad \text{for} \quad l_c = l - 2l_i \tag{46}$$

- $\delta < \delta_{max}$:

  The dropper has influence to the movement of the cable and the maximum horizontal displacement is calculated with:

$$b_h = \begin{cases} f_{ed} \sin\delta_1 & \text{for} \quad \delta \geq \delta_1 \\ f_{ed} \sin\delta & \text{for} \quad \delta < \delta_1 \end{cases} \quad \text{for} \quad l_c = l - 2l_i \tag{47}$$

δ_1, f_{ed} and δ has to be determined according to 6.2.2, 6.2.4 and 6.2.5, respectively.

NOTE Alternatively to Equations (46) and (47), calculation may be done with Equation (45).

Due to a short-circuit, conductors in a single plane configuration are displaced at the midpoint of the span in the worst case in a circle of radius b_h about straight line connection of the two adjacent anchor points. The distance between the midpoints of the two main conductors during a line-to-line two-phase short-circuit is given in the worst case by:

$$a_{min} = a - 2b_h \tag{48}$$

6.3 Effects on vertical main conductors (droppers)

Droppers according to this subclause are mainly cable connections running vertically which are normally used between differently high equipment or insulators. Precondition for the application of this subclause is that the resulting spring coefficient of the lower and upper fixing point does not stride fundamentally under the value $S = 100\times10^3$ N/m recommended in 6.2.2.

At bundle configuration, 6.4 shall be taken into account additionally.

Unlike the calculation of the conductors running horizontally according to 6.2 the height of the maximum short-circuit force at the lower fixing point and the cable deflection are independent of cable mass, static cable tension and short-circuit duration. For the behaviour during the short-circuit, cable geometry consisting of width and height of the connection as well as the cable length l_v are relevant only.

Besides the geometry the bending force at the lower fixing point is, in addition, dependent on the short-circuit current and the centre line distance of conductors and is calculated for cable length 1,4 $w \le l_v \le 3{,}3\ w$ to:

$$F_{t,d} = \frac{5}{3} l_v \frac{\mu_0}{2\pi} \frac{\left(I''_k\right)^2}{a} \frac{l_v}{w} \tag{49}$$

with sizes according Figure 8

where

l_v is the length of cable;

a is the centre line distance between conductors;

w is the width of dropper.

The displacement depends on geometry only and is calculated for cable length $l_v \le 2\ l$ to:

$$b_h = \left[0{,}60\sqrt{\frac{l_v}{l} - 1} + 0{,}44\left(\frac{l_v}{l} - 1\right) - 0{,}32 \ln\frac{l_v}{l}\right]\frac{l^2}{l_v} \tag{50}$$

with the diagonal distance l between two fixing points according to Figure 8.

6.4 Effects on bundled conductors

6.4.1 Characteristic dimensions and parameter

The following applies to regular bundle configurations, where the midpoints of the sub-conductors are located on a circle with equal distances a_s between adjacent sub-conductors.

For regular bundle configurations up to four subconductors, the tensile force is calculated by

$$F_{pi,d} = 1{,}1\ F_{t,d} \tag{51}$$

if the clearance between sub-conductors and the configuration of the spacers are such that the sub-conductors of the bundle clash effectively during a short-circuit. $F_{t,d}$ is calculated in 6.2.

Sub-conductors are considered to clash effectively if the clearance a_s between the midpoints of adjacent sub-conductors, as well as the distance l_s between two adjacent spacers fulfil either Equations (52) or (53):

$$a_s / d \le 2{,}0 \quad \text{and} \quad l_s \ge 50\,a_s \tag{52}$$

$$a_s / d \le 2{,}5 \quad \text{and} \quad l_s \ge 70\,a_s \tag{53}$$

If the regular bundle configuration does not fulfil the conditions stated above, the following equations apply to calculating $F_{pi,d}$.

The short-circuit current force is given by:

$$F_\mathrm{v} = (n-1)\ \frac{\mu_0}{2\pi}\ \left(\frac{I''_\mathrm{k}}{n}\right)^2\ \frac{l_\mathrm{s}}{a_\mathrm{s}}\ \frac{\nu_2}{\nu_3} \tag{54}$$

In single-phase a.c. systems, I''_k in Equations (54), (55), (60) and (63) shall be replaced by I''_k2. If the line-to-earth initial short-circuit current I''_k1 is greater than the three-phase initial symmetrical short-circuit current I''_k, the latter shall be replaced by I''_k1 in Equations (54), (55), (60) and (63).

The factor ν_2 is given by Figure 9, as a function of

$$\nu_1 = f\ \frac{1}{\sin\dfrac{180°}{n}}\sqrt{\frac{(a_\mathrm{s}-d)\,m'_\mathrm{s}}{\dfrac{\mu_0}{2\pi}\left(\dfrac{I''_\mathrm{k}}{n}\right)^2\dfrac{n-1}{a_\mathrm{s}}}} \tag{55}$$

where f is the system frequency. The factor ν_3 is given by Figure 10.

The strain factors characterizing the contraction of the bundle shall be calculated from

$$\varepsilon_\mathrm{st} = 1{,}5\ \frac{F_\mathrm{st}\ l_\mathrm{s}^2\ N}{(a_\mathrm{s}-d)^2}\left(\sin\frac{180°}{n}\right)^2 \tag{56}$$

$$\varepsilon_\mathrm{pi} = 0{,}375\ n\ \frac{F_\mathrm{v}\ l_\mathrm{s}^3\ N}{(a_\mathrm{s}-d)^3}\ \left(\sin\frac{180°}{n}\right)^3 \tag{57}$$

The parameter

$$j = \sqrt{\frac{\varepsilon_\mathrm{pi}}{1+\varepsilon_\mathrm{st}}} \tag{58}$$

determines the bundle configuration during short-circuit current flow as follows:

$j \geq 1$ The sub-conductors clash. The tensile force $F_\mathrm{pi,d}$ is calculated in 6.4.2;

$j < 1$ The sub-conductors reduce their distance but do not clash. The tensile force $F_\mathrm{pi,d}$ is calculated in 6.4.3.

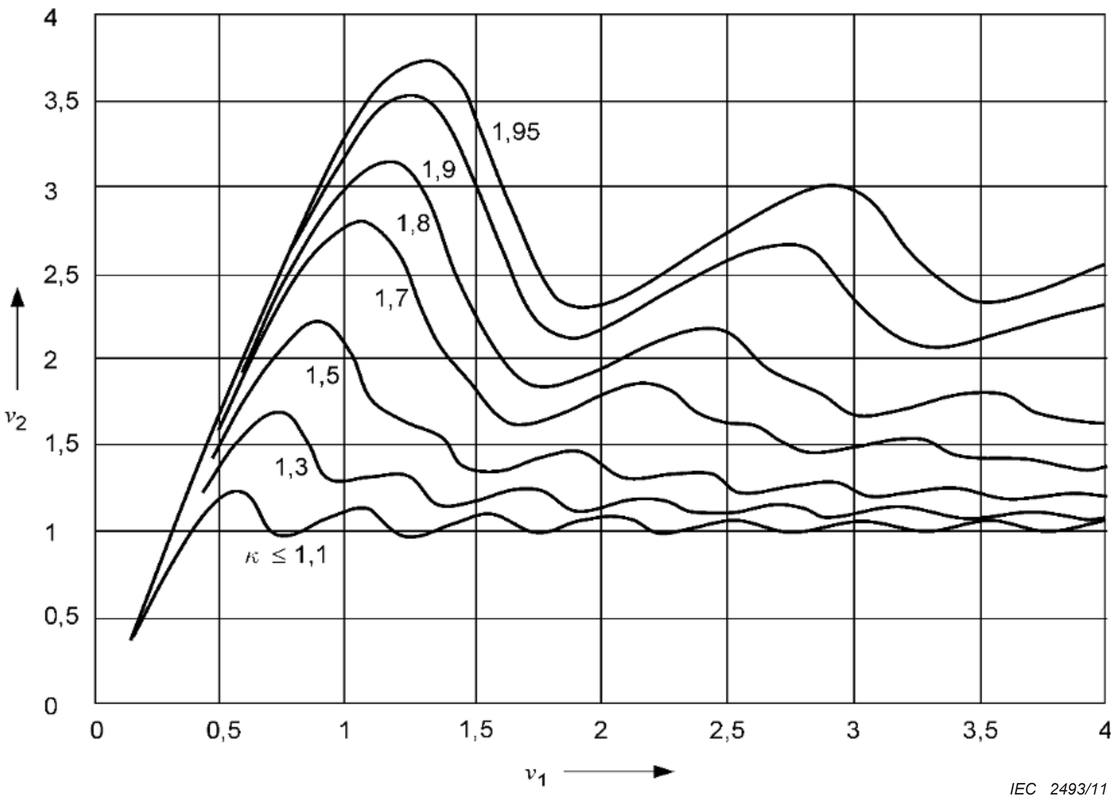


Figure 9 – v_2 as a function of v_1

For programming, the equation is given in Clause A.7.

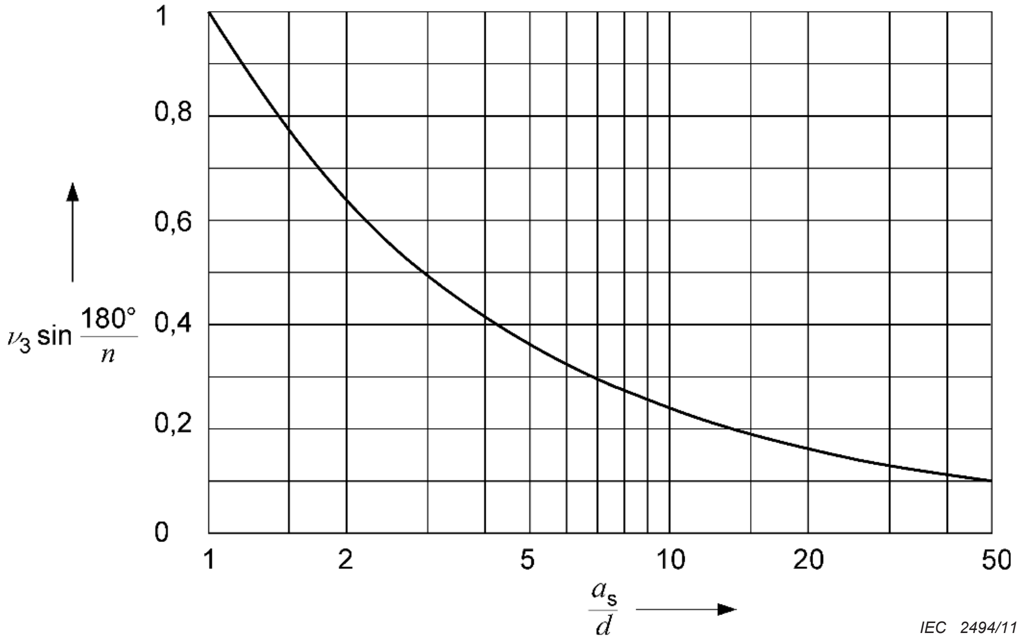


Figure 10 – $v_3 \times \sin \frac{180^\circ}{n}$ as a function of a_s/d

For programming, the equation is given in Clause A.8.

6.4.2 Tensile force $F_{\mathrm{pi,d}}$ in the case of clashing sub-conductors

If $j \geq 1$, the tensile force $F_{\mathrm{pi,d}}$ is obtained from

$$F_{\mathrm{pi,d}} = F_{\mathrm{st}}\left(1+\frac{\nu_{\mathrm{e}}}{\varepsilon_{\mathrm{st}}}\xi\right); \tag{59}$$

ξ is given by Figure 11.

ν_{e} is given by

$$\nu_{\mathrm{e}} = \frac{1}{2}+\left[\frac{9}{8}n\,(n-1)\,\frac{\mu_0}{2\pi}\left(\frac{I''_{\mathrm{k}}}{n}\right)^2 N\,\nu_2\left(\frac{l_{\mathrm{s}}}{a_{\mathrm{s}}-d}\right)^4 \frac{\left(\sin\frac{180^\circ}{n}\right)^4}{\xi^3}\left\{1-\frac{\arctan\sqrt{\nu_4}}{\sqrt{\nu_4}}\right\}-\frac{1}{4}\right]^{1/2} \tag{60}$$

with

$$\nu_4 = \frac{a_{\mathrm{s}}-d}{d} \tag{61}$$

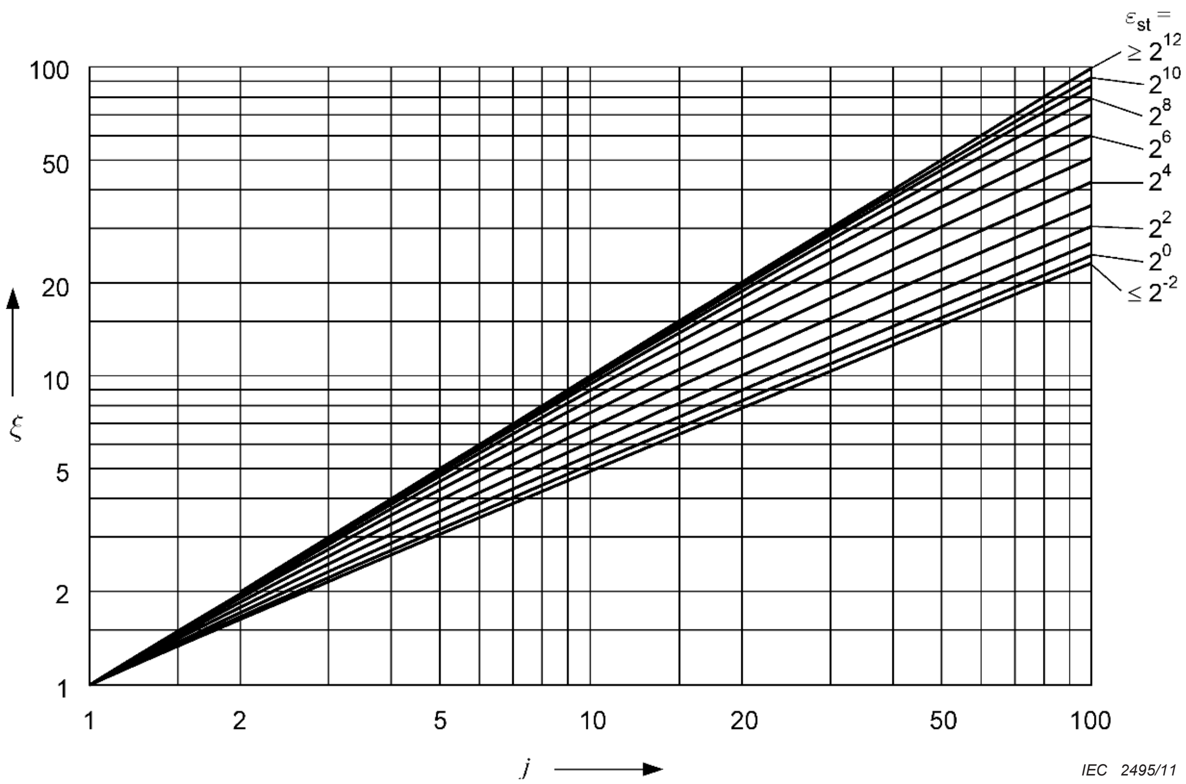


Figure 11 – ξ as a function of j and $\varepsilon_{\mathrm{st}}$

For programming, the equation is given in Clause A.9.

6.4.3 Tensile force $F_{\mathrm{pi,d}}$ in the case of non-clashing sub-conductors

If $j < 1$, the tensile force $F_{\mathrm{pi,d}}$ is obtained from

$$F_{\text{pi,d}} = F_{\text{st}}\left(1+\frac{\nu_{\text{e}}}{\varepsilon_{\text{st}}}\eta^2\right) \qquad (62)$$

η is then given by one of the diagrams in Figure 12, depending on the parameter a_{s}/d.

ν_{e} is given by

$$\nu_{\text{e}} = \frac{1}{2}+\left[\frac{9}{8}n\,(n-1)\,\frac{\mu_0}{2\,\pi}\left(\frac{I''_{\text{k}}}{n}\right)^2 N\,\nu_2\left(\frac{l_{\text{s}}}{a_{\text{s}}-d}\right)^4 \frac{\left(\sin\frac{180°}{n}\right)^4}{\eta^4}\left\{1-\frac{\arctan\sqrt{\nu_4}}{\sqrt{\nu_4}}\right\}-\frac{1}{4}\right]^{1/2} \qquad (63)$$

with

$$\nu_4 = \eta\,\frac{a_{\text{s}}-d}{a_{\text{s}}-\eta\left(a_{\text{s}}-d\right)} \qquad (64)$$

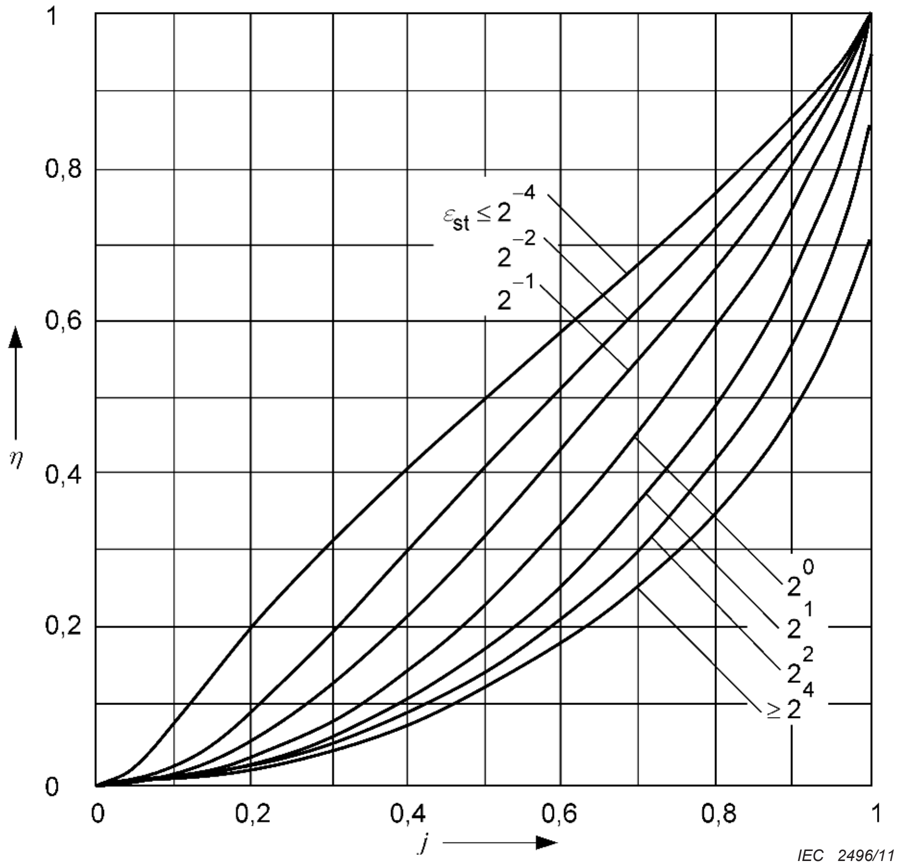


Figure 12a – 2,5 < a_{s}/d ≤5,0

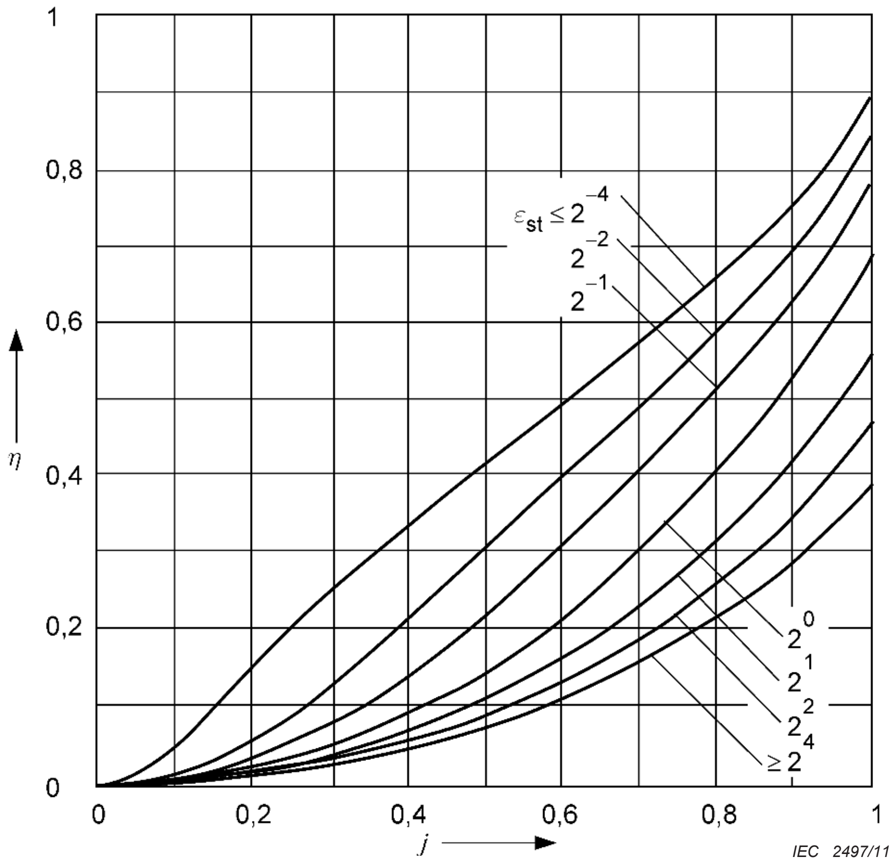


Figure 12b – 5,0 < a_s/d **≤10,0**

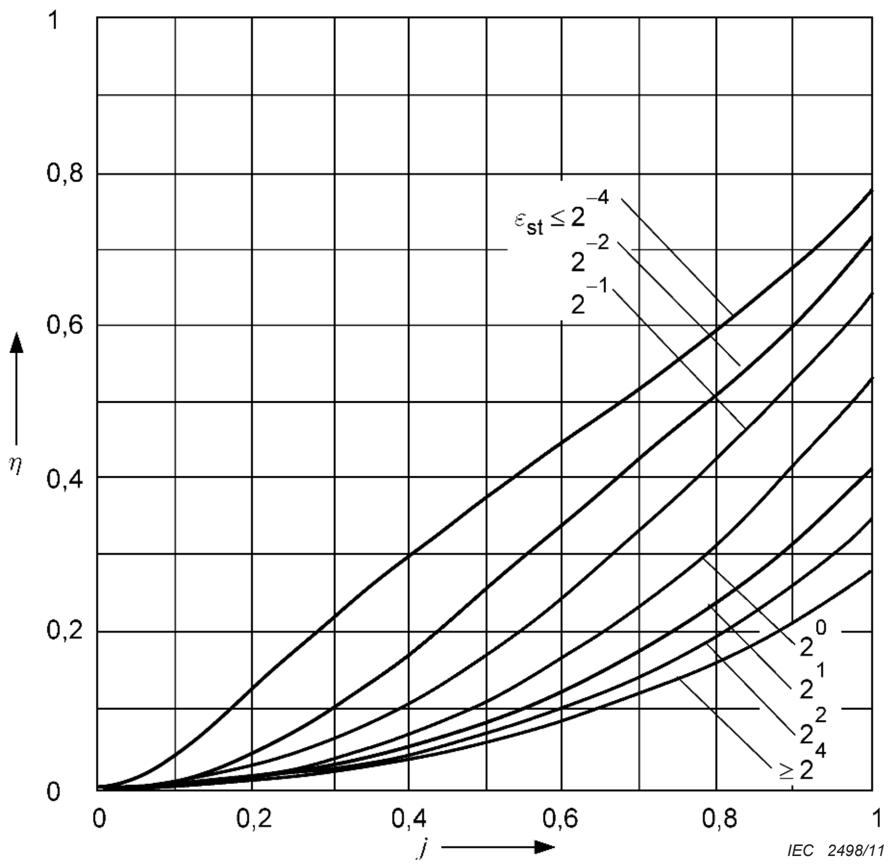


Figure 12c – 10,0 < a_s/d ≤15,0

Figure 12 – η as a function of j and ε_{st}

For programming, the equation is given in Clause A.10.

6.5 Structure loads due to flexible conductors

6.5.1 Design load for post insulators, their supports and connectors

The maximum value of $F_{t,d}$, $F_{f,d}$ or $F_{pi,d}$ for flexible conductor arrangements shall not be greater than the withstand value given by the manufacturer of supports and insulators. For an insulator stressed by a bending force, the rated withstand value is given as a force acting at the insulator head.

NOTE 1 For a force acting at a point higher than the insulator head, a withstand value lower than the rated withstand value should be used, based on the withstand bending moment at the critical insulator cross-section.

Connectors for flexible conductors shall be rated on the basis of the maximum value of 1,5 $F_{t,d}$, 1,0 $F_{f,d}$ or 1,0 $F_{pi,d}$.

NOTE 2 The factor 1,5 takes into account that the energy of oscillations is absorbed by the mass of the insulators.

6.5.2 Design load for structures, insulators and connectors with tensile forces transmitted by insulator chains

The maximum value of $F_{t,d}$, $F_{f,d}$ or $F_{pi,d}$ of flexible conductor spans shall be applied to the structure, the insulators and the connectors as a static load.

NOTE 1 In the design of three-phase structures for three-phase short-circuits it should be remembered that the maximum value of $F_{t,d}$ or $F_{f,d}$ will appear in two phases, and the third phase will be subjected only to the static tension.

NOTE 2 In the design of three-phase structures for three-phase short-circuits, different maximum values of $F_{pi,d}$ can occur at different times in the three phases. This effect is met approximately by applying the calculated $F_{pi,d}$ to two phases of the structure.

6.5.3 Design load for foundations

For the design of foundations, 6.5.1 and 6.5.2 apply accordingly.

NOTE Due to inertia and the dynamic character of a short-circuit, effects of instability need not be regarded at the design stage of monolithic foundations (monobloc foundations). It may be assumed that stability is given if a design according to other load cases and loads such as static tensile force or wind load has taken place.

7 The thermal effect on bare conductors

7.1 General

The heating of conductors due to short-circuit currents involves several phenomena of a non-linear character and other factors that have been either neglected or approximated in order to make the mathematical approach possible.

For the purpose of this clause the following assumptions have been made:

- skin-effect (magnetic influence of a conductor itself) and proximity-effect (magnetic influence of nearby parallel conductors) are disregarded;
- resistance-temperature characteristic is assumed linear;
- the specific heat of the conductor is considered constant;
- the heating is considered adiabatic.

When repeated short-circuits occur with a short-time interval between them (e.g. rapid automatic reclosing) the cooling in the short dead-time is of relatively little importance, and the heating can still be considered adiabatic. In cases where the dead-time interval is of longer duration (e.g. delayed automatic reclosing), the heat loss may be taken into account.

The calculation does not take into account the skin effect or the proximity effect, i.e. the current is regarded as evenly distributed over the conductor cross-section area. For large cross sections above 600 mm^2, the skin effect shall be taken into account. For such calculations, reference should be made to the literature.

NOTE If the main conductor is composed of sub-conductors, uneven current distribution between the sub-conductors will influence the temperature rise of sub-conductors.

7.2 Calculation of thermal equivalent short-circuit current

The thermal equivalent short-circuit current shall be calculated according to IEC 60909-0 using the short-circuit current r.m.s. value and the factors for the time-dependent heat effects of the d.c. and a.c. components of the short-circuit current. If by automatic reclosure a number of short-circuits occur, a resulting thermal equivalent short-circuit current has to be calculated.

For the calculation of the thermal equivalent short-circuit current I_{th} in a three-phase system, the three-phase balanced short-circuit is normally decisive. For single-phase systems, the thermal equivalent short-circuit current should be calculated according to IEC 60909-0 in the same way.

For current-limiting devices the thermal equivalent short-circuit current I_{th} and the associated duration of short-circuit current T_k are given by the manufacturer.

7.3 Calculation of temperature rise and rated short-time withstand current density for conductors

The temperature rise of a conductor caused by a short-circuit is a function of the duration of the short-circuit current, the thermal equivalent short-circuit current and the conductor material.

By use of the graphs in Figure 13, it is possible to calculate the temperature rise of a conductor when the rated short-time withstand current density is known, or vice versa.

The recommended highest temperatures during a short-circuit for different conductors are given in Table 6. If they are reached, a negligible decrease in strength can occur which does not empirically jeopardize the safety in operation. The maximum permitted temperature of the support shall be taken into account.

Table 6 – Recommended highest temperatures for mechanically stressed conductors during a short-circuit

Type of conductor	Recommended highest conductor temperature during a short-circuit °C
Bare conductors, solid or stranded: Cu, Al or Al alloy	200
Bare conductors, solid or stranded: steel	300

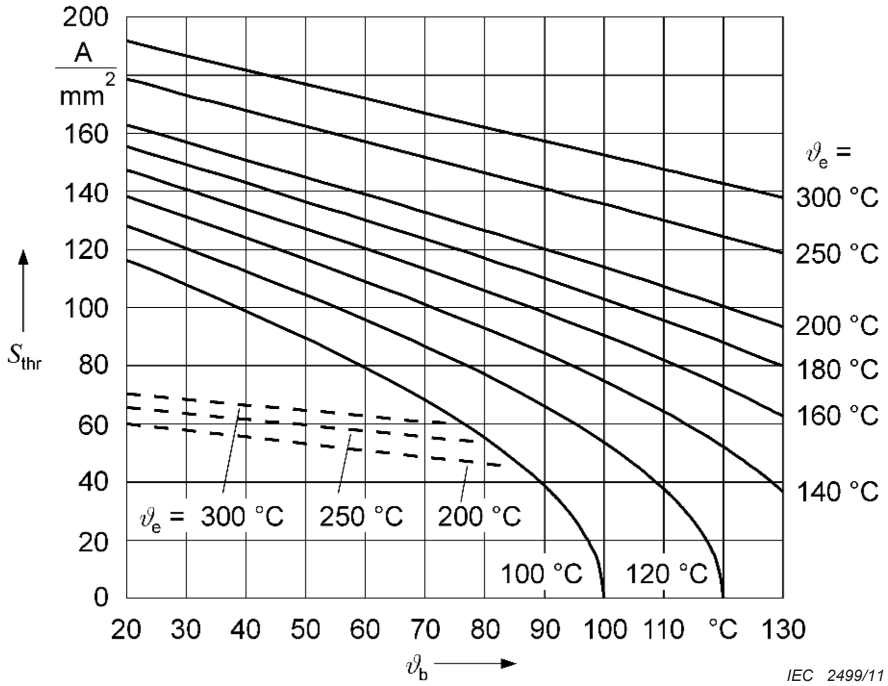


Figure 13a – Full lines, copper; dotted lines, low-alloyed steel

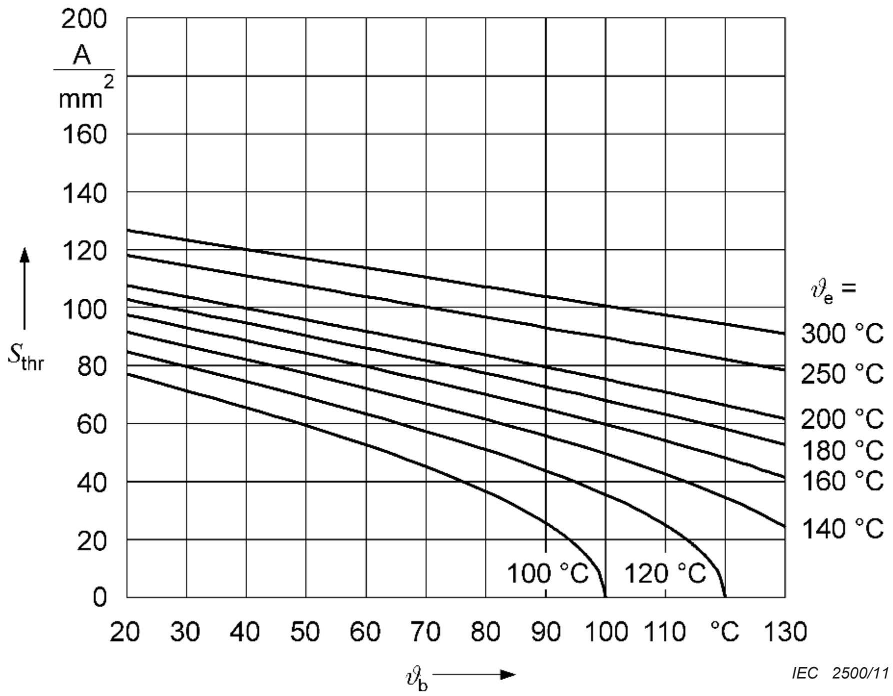


Figure 13b – Aluminium, aluminium alloy, aluminium conductor steel reinforced (ACSR)

Figure 13 – Relation between rated short-circuit withstand current density (T_{kr} = 1 s) and conductor temperature

For programming, the equations are given in Clause A.11.

7.4 Calculation of thermal short-time strength for different durations of the short-circuit

Bare conductors have sufficient thermal short-time strength as long as the following relation holds for the thermal equivalent short-circuit current density S_{th} for all T_k values:

$$S_{\mathrm{th}} \le S_{\mathrm{thr}} \sqrt{\frac{T_{\mathrm{kr}}}{T_{\mathrm{k}}}} \tag{65}$$

The rated short-time withstand current density S_{thr} is shown in Figure 13, for T_{kr} = 1 s.

The steel core of the steel reinforced aluminium conductor (ACSR) shall not be taken into account when calculating the cross-section area for the estimation of the current density.

When a number of short-circuits occur with a short time interval between them, the resulting short-circuit duration is

$$T_{\mathrm{k}} = \sum_{i=1}^{n} T_{\mathrm{k}i} \tag{66}$$

Annex A
(normative)

Equations for calculation of diagrams

A.1 Symbols

In addition to 3.2 the following symbols are used:

a_{sw}	Effective distance between the sub-conductor of a bundle	m
c	Specific thermal capacity	J/(kg K)
c_c	Factor for the stiffening of connecting pieces	1
f_η	Factor to describe the approach of the sub-conductor in the bundle	1
T_{pi}	Time from the start of the short-circuit up to the arriving of $F_{pi,d}$	s
y_a	Clearance of non-clashing bundles during the short-circuit	m
α_{20}	Temperature coefficient	1/K
ξ_m	Factor for the influence of the mass of connecting pieces on the relevant natural frequency	1
κ_{20}	Specific conductivity at 20 °C	1/(Ωm)
ρ	Specific mass	kg/m³

A.2 Figure 1

The factor k_{1s} is given by the following equation:

$$
\begin{aligned}
k_{1s} = \Bigg\{ & -\left(\frac{(a_{1s}/c_s)+1}{b_s/c_s}\right)^3 \ln \frac{\left[(a_{1s}/c_s)+1\right]^2+(b_s/c_s)^2}{\left[(a_{1s}/c_s)+1\right]^2} + 2\left(\frac{a_{1s}/c_s}{b_s/c_s}\right)^3 \ln \frac{(a_{1s}/c_s)^2+(b_s/c_s)^2}{(a_{1s}/c_s)^2} \\
& -\left(\frac{(a_{1s}/c_s)-1}{b_s/c_s}\right)^3 \ln \frac{\left[(a_{1s}/c_s)-1\right]^2+(b_s/c_s)^2}{\left[(a_{1s}/c_s)-1\right]^2} \\
& +3\left[\frac{a_{1s}/c_s}{b_s/c_s} \ln \frac{\left[(a_{1s}/c_s)+1\right]^2+(b_s/c_s)^2}{(a_{1s}/c_s)^2+(b_s/c_s)^2} + \frac{1}{b_s/c_s} \ln \frac{\left[(a_{1s}/c_s)+1\right]^2+(b_s/c_s)^2}{\left[(a_{1s}/c_s)-1\right]^2+(b_s/c_s)^2} \right. \\
& \left. -\frac{a_{1s}/c_s}{b_s/c_s} \ln \frac{(a_{1s}/c_s)^2+(b_s/c_s)^2}{\left[(a_{1s}/c_s)-1\right]^2+(b_s/c_s)^2}\right] \\
& +6\left[\left(\frac{(a_{1s}/c_s)+1}{b_s/c_s}\right)^2 \arctan\frac{b_s/c_s}{(a_{1s}/c_s)+1} - 2\left(\frac{a_{1s}/c_s}{b_s/c_s}\right)^2 \arctan\frac{b_s/c_s}{a_{1s}/c_s} \right. \\
& \left. +\left(\frac{(a_{1s}/c_s)-1}{b_s/c_s}\right)^2 \arctan\frac{b_s/c_s}{(a_{1s}/c_s)-1}\right] \\
& +2\left[\arctan\frac{(a_{1s}/c_s)+1}{b_s/c_s} - 2\arctan\frac{a_{1s}/c_s}{b_s/c_s} + \arctan\frac{(a_{1s}/c_s)-1}{b_s/c_s}\right]\Bigg\} \frac{a_{1s}/c_s \cdot b_s/c_s}{6}
\end{aligned}
$$

A.3 Figure 3

The factor e is given by the equation:

$$e = \frac{c_\mathrm{c}}{\sqrt{1 + \xi_\mathrm{m} \dfrac{m_\mathrm{Z}}{n\, m'_\mathrm{s}\, l}}}$$

with

k	l_s / l	ξ_m	c_c	
			Figure 3b	Figure 3c
0	–	0,0	1,0	1,0
1	0,5	2,5	1,0	1,0
2	0,33	3,0	1,48	1,0
2	0,5	1,5	1,75	1,0
3	0,25	4,0	1,75	1,0
4	0,2	5,0	2,14	1,0
5	0,17	6,0	2,46	1,0
6	0,14	7,0	2,77	1,0

A.4 Figure 4

The factor V_F is given by:

<table>
<tr><th rowspan="2">f_cm/f</th><th colspan="2">Factor V_F</th></tr>
<tr><th>Three-phase short-circuit</th><th>Line-to-line-short-circuit</th></tr>
<tr><td><0,04</td><td colspan="2">$0{,}232 + 3{,}52\,\mathrm{e}^{-1{,}45\kappa} + 0{,}166\,\lg(f_\mathrm{cm}/f)$ [a]</td></tr>
<tr><td>0,04 … 0,8</td><td colspan="2">maximum value of V_F1 or V_F2
$V_\mathrm{F1} = 0{,}839 + 3{,}52\,\mathrm{e}^{-1{,}45\kappa} + 0{,}6\,\lg(f_\mathrm{cm}/f)$ [a]
$V_\mathrm{F2} = 2{,}38 + 6{,}00\,\lg(f_\mathrm{cm}/f)$</td></tr>
<tr><td>0,8 … 1,2</td><td colspan="2">1,8</td></tr>
<tr><td>1,2 … 1,6</td><td>$1{,}23 + 7{,}2\,\lg(f_\mathrm{cm}/f)$</td><td>1,8</td></tr>
<tr><td>1,6 … 2,4</td><td>2,7</td><td>1,8</td></tr>
<tr><td>2,4 … 2,74</td><td>$8{,}59 - 15{,}5\,\lg(f_\mathrm{cm}/f)$</td><td>1,8</td></tr>
<tr><td>2,74 … 3,0</td><td colspan="2">$8{,}59 - 15{,}5\,\lg(f_\mathrm{cm}/f)$</td></tr>
<tr><td>3,0 … 6,0</td><td colspan="2">$1{,}50 - 0{,}646\,\lg(f_\mathrm{cm}/f)$</td></tr>
<tr><td>>6,0</td><td colspan="2">1,0</td></tr>
<tr><td colspan="3">[a] If κ >1,6 then κ = 1,6 shall be used.</td></tr>
</table>

The factor $V_{\sigma m}$ is given by:

f_{cm}/f	Factor $V_{\sigma m}$
<0,04	$0{,}0929 + 4{,}49\,e^{-1{,}68\kappa} + 0{,}0664\lg(f_{cm}/f)$ [a]
0,04 … 0,8	minimum value of $V_{\sigma 1}$ or $V_{\sigma 2}$ $V_{\sigma 1} = 0{,}756 + 4{,}49\,e^{-1{,}68\kappa} + 0{,}54\lg(f_{cm}/f)$ [a] $V_{\sigma 2} = 1{,}0$
>0,8	1
[a] If κ >1,6 then κ = 1,6 shall be used.	

In the case of $V_{\sigma s}$, the same equations shall be used as for $V_{\sigma m}$, but f_{cm}/f shall be replaced by f_{cs}/f.

A.5 Figure 5

The factors V_{rm} and V_{rs} are given by:

$$V_{rm} = \begin{cases} 1{,}8 & \text{for} \quad f_{cm}/f \le 0{,}05 \\ 1{,}0 - 0{,}615\lg(f_{cm}/f) & \text{for} \quad 0{,}05 < f_{cm}/f < 1{,}0 \\ 1{,}0 & \text{for} \quad f_{cm}/f \ge 1{,}0 \end{cases}$$

$$V_{rs} = \begin{cases} 1{,}8 & \text{for} \quad f_{cs}/f \le 0{,}05 \\ 1{,}0 - 0{,}615\lg(f_{cs}/f) & \text{for} \quad 0{,}05 < f_{cs}/f < 1{,}0 \\ 1{,}0 & \text{for} \quad f_{cs}/f \ge 1{,}0 \end{cases}$$

A.6 Figure 7

Factor ψ is a function of ζ and φ. It can be calculated as the real solution of the equation:

$$\varphi^2\psi^3 + \varphi(2+\zeta)\psi^2 + (1+2\zeta)\psi - \zeta(2+\varphi) = 0$$

with $0 < \psi \le 1$.

A.7 Figure 9

The factor ν_2 is given by:

$$\nu_2 = 1 - \frac{\sin(4\pi f T_{pi} - 2\gamma) + \sin 2\gamma}{4\pi f T_{pi}} + \frac{f\tau}{f T_{pi}}\left(1 - e^{-\frac{2 f T_{pi}}{f\tau}}\right)\sin^2\gamma$$
$$- \frac{8\pi f\tau\sin\gamma}{1 + (2\pi f\tau)^2}\left\{\left(2\pi f\tau\,\frac{\cos(2\pi f T_{pi} - \gamma)}{2\pi f T_{pi}} + \frac{\sin(2\pi f T_{pi} - \gamma)}{2\pi f T_{pi}}\right) e^{-\frac{f T_{pi}}{f\tau}} + \frac{\sin\gamma - 2\pi f\tau\cos\gamma}{2\pi f T_{pi}}\right\}$$

where τ is the time constant of the network and can be calculated according to IEC 60909-0:

$$\frac{1}{\tau} = -\frac{2\pi f}{3} \ln \frac{\kappa - 1{,}02}{0{,}98} \qquad \text{with} \qquad \kappa \geq 1{,}1 \qquad \text{and} \qquad \gamma = \arctan(2\pi f \tau)$$

If κ <1,1 then κ = 1,1 shall be used.

$f\,T_{pi}$ is the solution of the equation:

$$\nu_1 = f\,T_{pi}\sqrt{\nu_2}$$

A.8 Figure 10

The factor ν_3 is given by:

$$\nu_3 = \frac{d/a_s}{\sin\dfrac{180°}{n}} \; \frac{\sqrt{(a_s/d) - 1}}{\arctan\sqrt{(a_s/d) - 1}}$$

A.9 Figure 11

ξ is the real solution of the equation:

$$\xi^3 + \varepsilon_{st}\,\xi^2 - j^2(1 + \varepsilon_{st}) = 0$$

with $j^{2/3} \leq \xi \leq j$

A.10 Figure 12

The function η in Figure 12 may be calculated numerically by solving the cubic equation with non-linear coefficients:

$$\eta^3 + \varepsilon_{st}\,\eta - j^2(1 + \varepsilon_{st})\,f_\eta = 0$$

with $0 < \eta \leq 1$, and

$$f_\eta = \frac{\nu_3}{a_{sw}/a_s}$$

$$a_{sw}/a_s = \frac{2\,y_a/a_s}{\sin\dfrac{180°}{n}} \; \frac{\sqrt{\dfrac{1 - 2\,y_a/a_s}{2\,y_a/a_s}}}{\arctan\sqrt{\dfrac{1 - 2\,y_a/a_s}{2\,y_a/a_s}}}$$

$$2\,y_a/a_s = 1 - \eta\,(1 - d/a_s)$$

A.11 Figure 13

The rated short-circuit withstand current density S_{thr} is given by:

$$S_{\text{thr}} = \frac{1}{\sqrt{T_{\text{kr}}}} \sqrt{\frac{\kappa_{20}\, c\, \rho}{\alpha_{20}} \ \ln \frac{1+\alpha_{20}\left(\vartheta_{\text{e}} - 20\ ^{\circ}\text{C}\right)}{1+\alpha_{20}\left(\vartheta_{\text{b}} - 20\ ^{\circ}\text{C}\right)}}$$

with the following data of material:

Symbol	**SI-unit**	**Copper**	**Aluminium alloy, aluminium conductor Steel reinforced (ACSR)**	**Steel**
c	J(kg K)	390	910	480
ρ	kg/m^3	8 900	2 700	7 850
κ_{20}	1/(Ωm)	56 × 10^6	34,8 × 10^6	7,25 × 10^6
α_{20}	1/K	0,003 9	0,004	0,004 5

If base-temperatures other than 20 °C are used, the equation for S_{thr} has to be changed.

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