

INTERNATIONAL STANDARD

NORME INTERNATIONALE

**Short-circuit currents – Calculation of effects –
Part 1: Definitions and calculation methods**

**Courants de court-circuit – Calcul des effects –
Partie 1: Définitions et méthodes de calcul**



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INTERNATIONAL ELECTROTECHNICAL COMMISSION

**SHORT-CIRCUIT CURRENTS –
CALCULATION OF EFFECTS –****Part 1: Definitions and calculation methods**

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International Standard IEC 60865-1 has been prepared by IEC technical committee 73: Short-circuit currents.

This third edition cancels and replaces the second edition published in 1993. This edition constitutes a technical revision.

The main changes with respect to the previous edition are listed below:

- 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 IEC 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.

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

CDV	Report on voting
73/152/CDV	73/153/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 of the IEC 60865 series, under the general title, *Short-circuit currents – Calculation of effects* can be found on the IEC website.

The committee has decided that the contents of this publication will remain unchanged until the stability date indicated on the IEC web site 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- withdrawn,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 – 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, including among 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	$\text{m}^4/(\text{A}^2\text{s})$
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	N/m

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_{om}	Ratio of dynamic and static contribution of main conductor stress	1
V_{os}	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
$\varepsilon_{pi}, \varepsilon_{st}$	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

$\nu_e, \nu_1, \nu_2,$ $\nu_3, \nu_4,$	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:

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

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:

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

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

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

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:

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

- 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

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

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

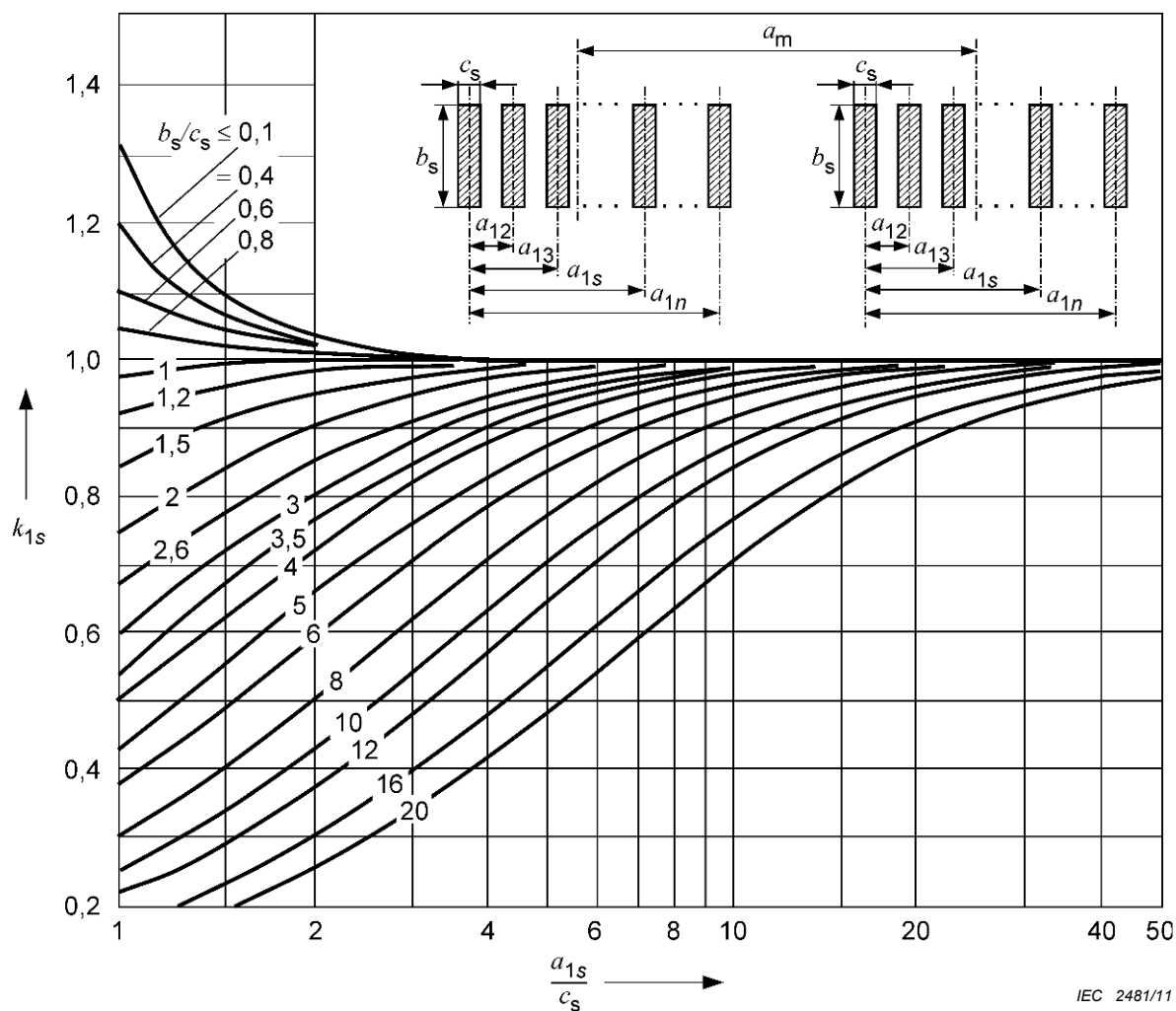
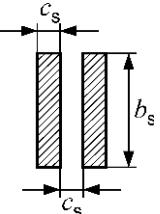
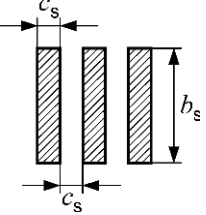
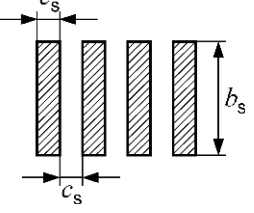
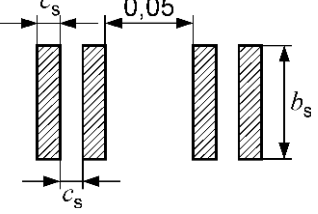


Figure 1 – Factor k_{1s} for calculating the effective conductor distance

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	b_s c_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:

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

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:

$$\sigma_{s,d} = V_{os} V_{rs} \frac{F_s l_s}{16 W_s} \quad (10)$$

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_{om} , V_{os} , 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_{om} , V_{rm} and V_{os} , 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.

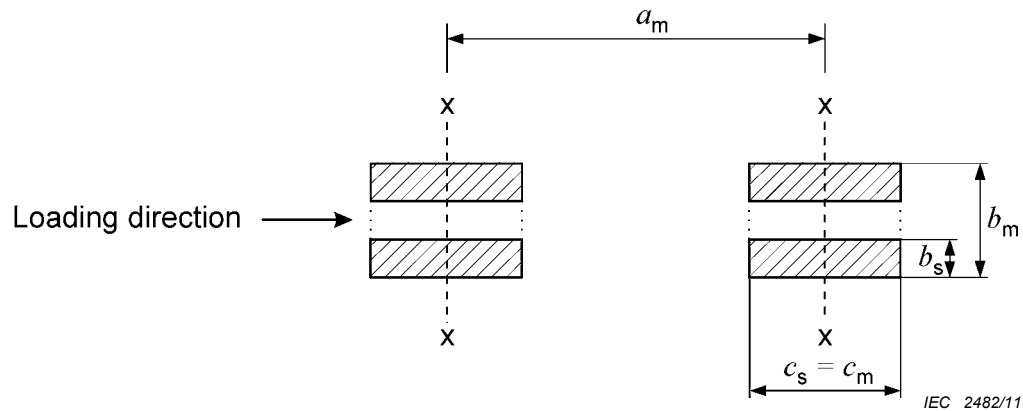


Figure 2a – Loading along the surface

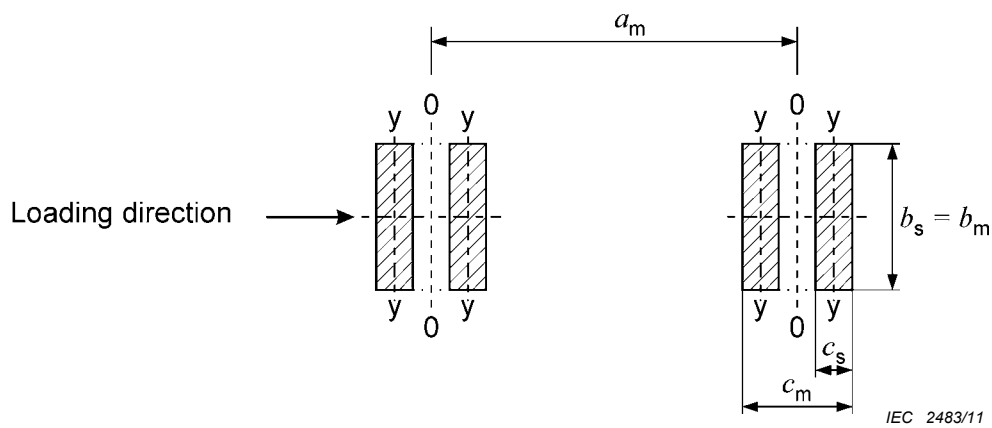


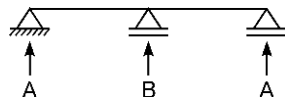
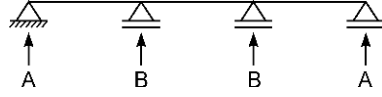
Figure 2b – Loading perpendicular to the surface

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	$2,0$ for $\frac{\sigma_{tot,d}}{0,8 f_y} \leq 0,5$ $\frac{0,8 f_y}{\sigma_{tot,d}}$ for $0,5 < \frac{\sigma_{tot,d}}{0,8 f_y} < 1,0$ $1,0$ for $1,0 \leq \frac{\sigma_{tot,d}}{0,8 f_y}$ range 1 2 3
Three-phase	1,0	1,0	1,8	$2,7$ for $\frac{\sigma_{tot,d}}{0,8 f_y} \leq 0,37$ $\frac{0,8 f_y}{\sigma_{tot,d}}$ for $0,37 < \frac{\sigma_{tot,d}}{0,8 f_y} < 1,0$ $1,0$ for $1,0 \leq \frac{\sigma_{tot,d}}{0,8 f_y}$ range 1 2 3

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

Type of beam and support			α	$\beta^*)$	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:

$$\sigma_{m,d} \leq q f_y \quad (11)$$

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:

$$\sigma_{tot,d} = \sigma_{m,d} + \sigma_{s,d} \quad (12)$$

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

$$\sigma_{tot,d} \leq q f_y \quad (13)$$

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

$$\sigma_{s,d} \leq f_y \quad (14)$$

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:

$$F_{r,d} = V_F V_{rm} \alpha F_m \quad (15)$$

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

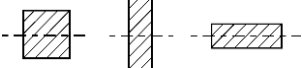
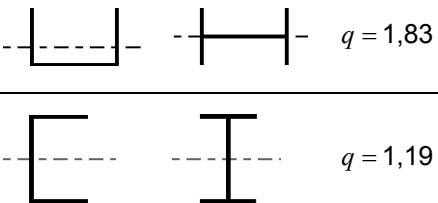
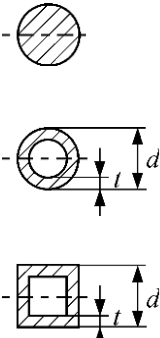
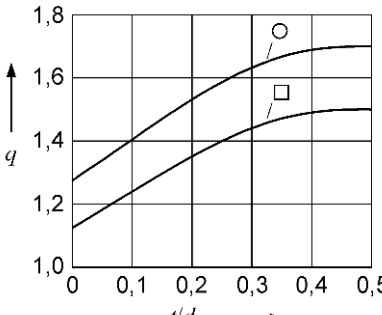
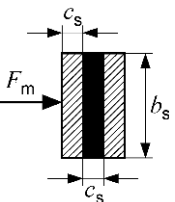
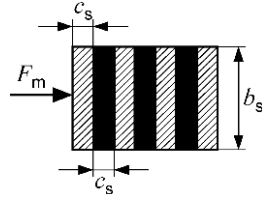
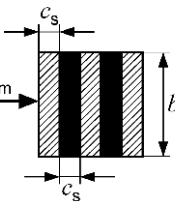
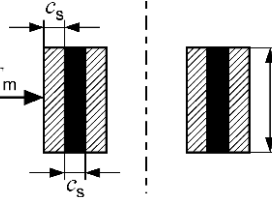
Cross section	Cross section
 $q = 1,5$	 $q = 1,83$ $q = 1,19$
 $q = 1,7$ $q = 1,7 \frac{1 - (1 - 2t/d)^3}{1 - (1 - 2t/d)^4}$ $q = 1,5 \frac{1 - (1 - 2t/d)^3}{1 - (1 - 2t/d)^4}$	
q is valid for the dotted bending axis. The forces are perpendicular to it.	

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:

$$f_{cm} = \frac{\gamma}{l^2} \sqrt{\frac{E J_m}{m'_m}} \quad (16)$$

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:

$$f_{cm} = e \frac{\gamma}{l^2} \sqrt{\frac{E J_s}{m'_s}} \quad (17)$$

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

$$f_{cs} = \frac{3,56}{l_s^2} \sqrt{\frac{E J_s}{m'_s}} \quad (18)$$

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 , $V_{\sigma m}$, $V_{\sigma s}$, V_{rm} and V_{rs}

The factors V_F , $V_{\sigma m}$, $V_{\sigma s}$, 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 $T_{k1} \leq 0,1$ s can cause an appreciable reduction of the stress in structures with $f_{cm}/f \leq 1$.

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 $f_{cm}/f > 2,4$.

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

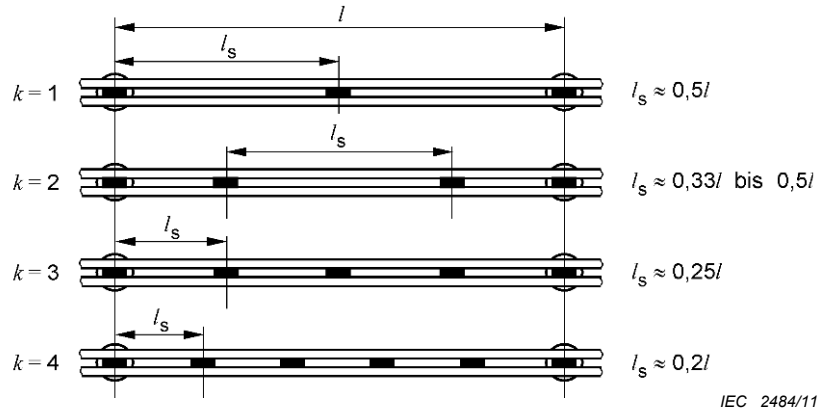


Figure 3a – Arrangement of connecting pieces within the span

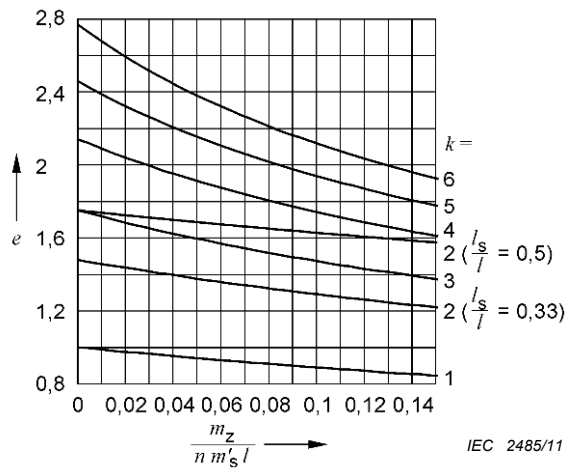


Figure 3b – Connecting pieces are stiffening elements

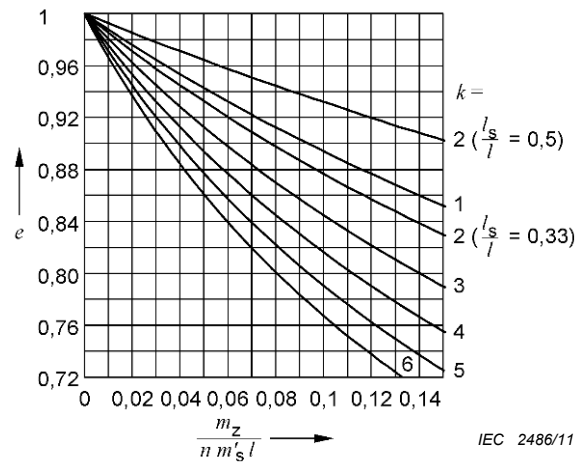


Figure 3c – Connecting pieces are, or operate as, spacers

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.

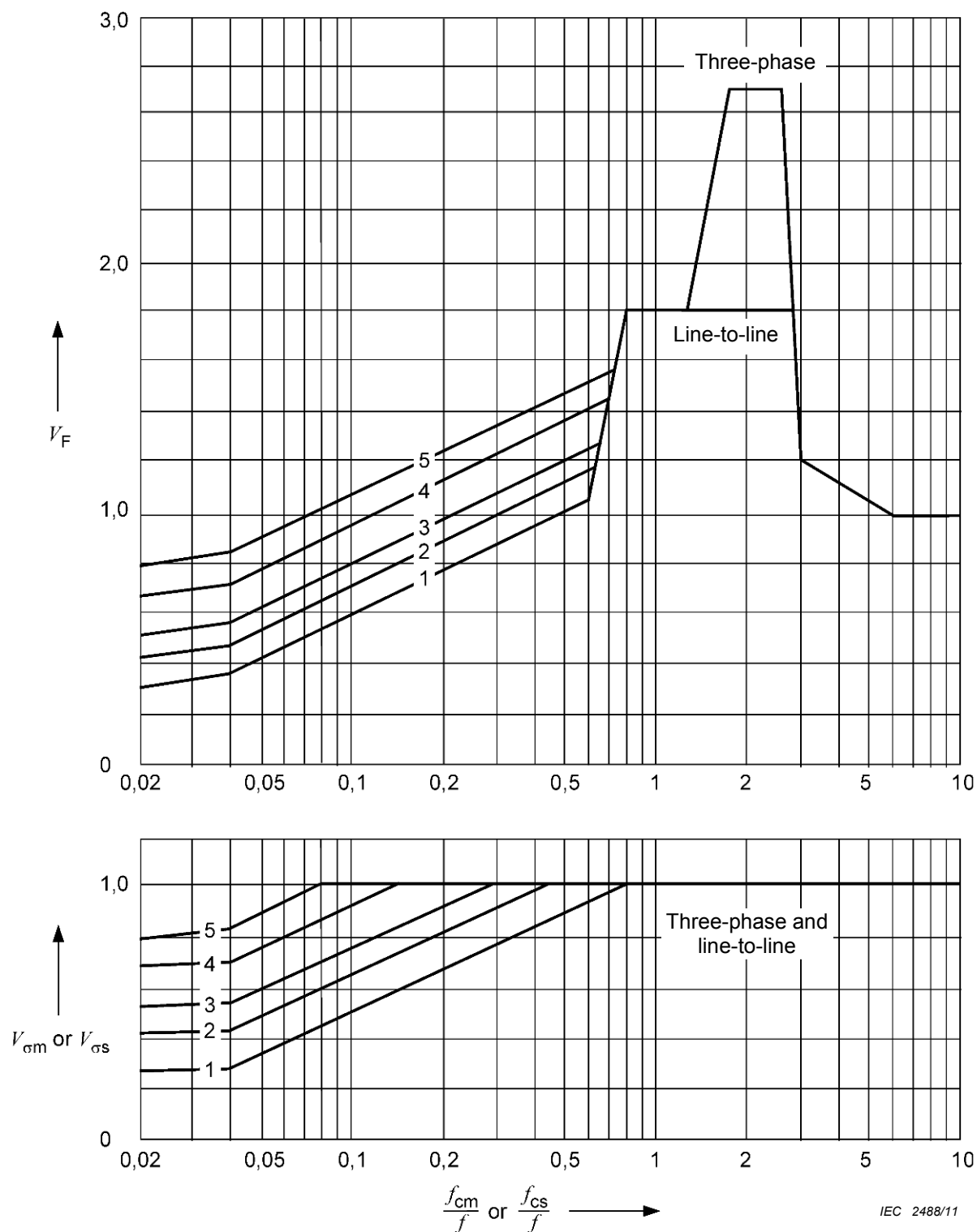


Figure 4 – Factors V_F , $V_{\sigma m}$ and $V_{\sigma s}$ to be used with the three-phase and line-to-line short-circuits

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

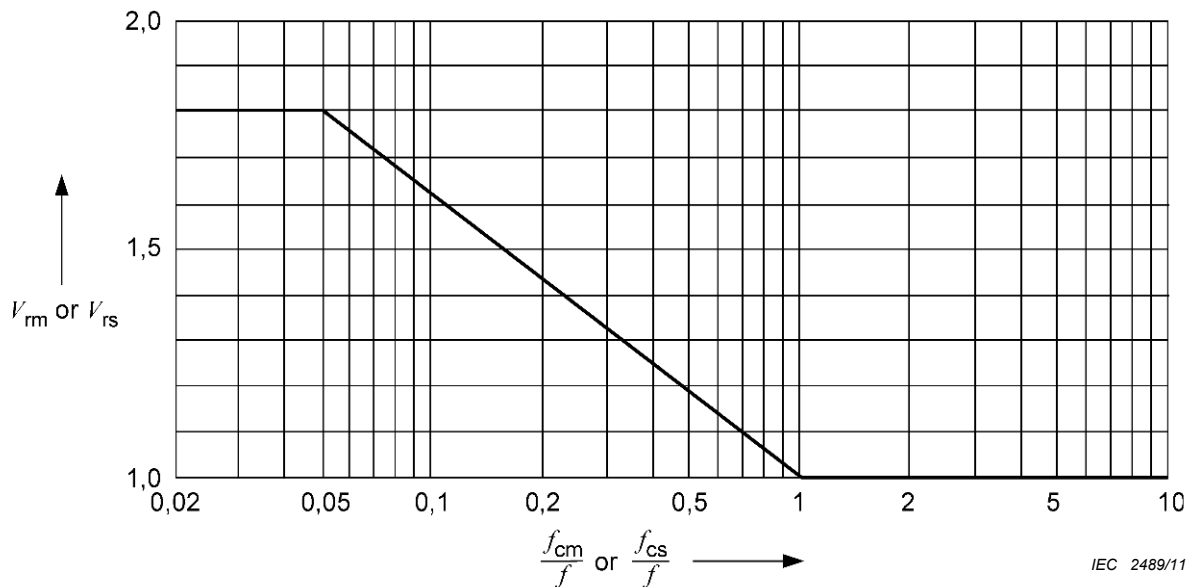


Figure 5 – Factors V_{rm} and V_{rs} to be used with three-phase automatic reclosing

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. $-20\text{ }^{\circ}\text{C}$, and also on the basis of the static tensile force F_{st} existing at the maximum operating temperature, e.g. $60\text{ }^{\circ}\text{C}$. 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:

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

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

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

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 $0,75 (I_k'')^2$ in Equation (19) by $(I_{k2}'')^2$.

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

$$r = \frac{F'}{n m'_s g} \quad (20)$$

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

$$\delta_1 = \arctan r \quad (21)$$

The equivalent static conductor sag at midspan is given by

$$f_{es} = \frac{n m'_s g l^2}{8 F_{st}} \quad (22)$$

The period T of the conductor oscillations is given by

$$T = 2\pi \sqrt{0,8 \frac{f_{es}}{g}} \quad (23)$$

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:

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

where δ_1 shall be given in degrees.

The stiffness norm is given by:

$$N = \frac{1}{S l} + \frac{1}{n E_{eff} A_s} \quad (25)$$

NOTE 2 If the exact value of S is not known in Equation (25), the value $S = 100 \times 10^3$ 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:

- 150×10^3 N/m to $1\,300 \times 10^3$ N/m at a rated voltage of 123 kV;
- 400×10^3 N/m to $2\,000 \times 10^3$ N/m at a rated voltage of 245 kV;
- 600×10^3 N/m to $3\,000 \times 10^3$ 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

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

where

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

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:

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

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:

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

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:

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

from:

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

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} .

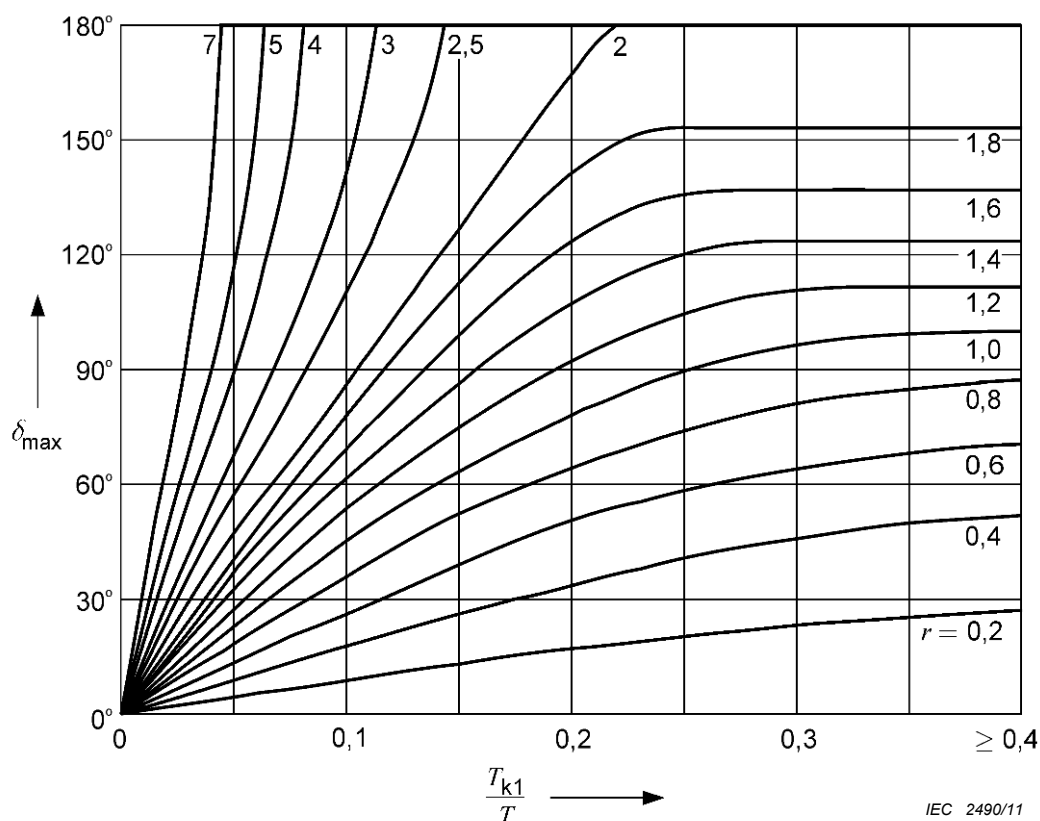


Figure 6 – Maximum swing out angle $\delta_{\max}$ for a given maximum short-circuit duration T_{k1}

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:

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

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

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

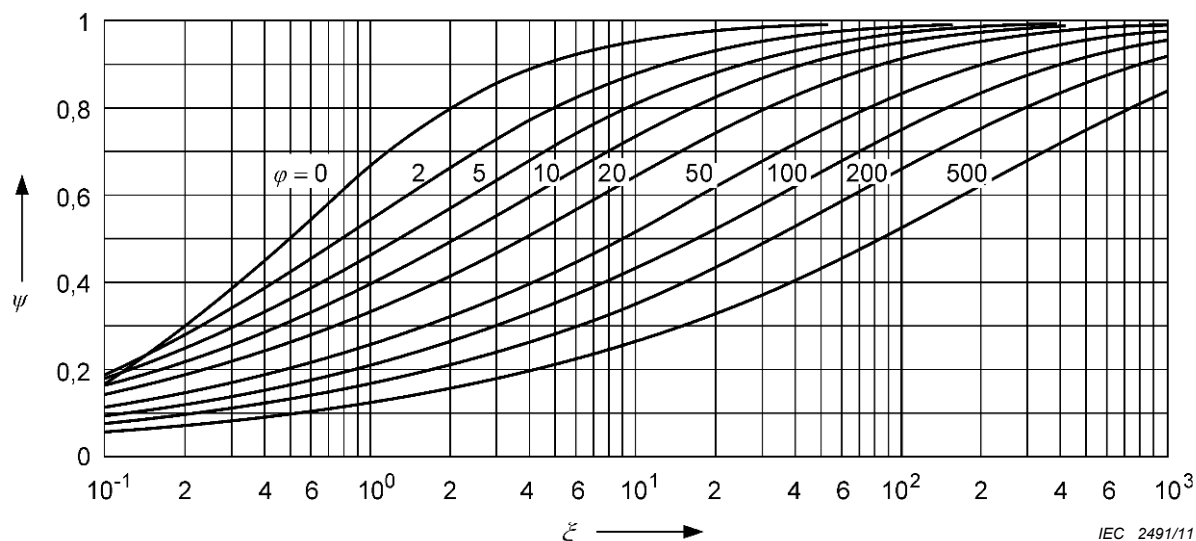


Figure 7 – Factor ψ for tensile force in flexible conductors

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:

$$\varepsilon_{\text{ela}} = N(F_{t,d} - F_{st}) \quad (34)$$

The short-circuit tensile force $F_{t,d}$ 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 $F_{t,d}$ according to Equation (33).

The thermal expansion is given by:

$$\varepsilon_{\text{th}} = \begin{cases} c_{\text{th}} \left(\frac{I_k''}{n A_s} \right)^2 T_{\text{res}} / 4 & \text{for } T_{k1} \geq T_{\text{res}} / 4 \\ c_{\text{th}} \left(\frac{I_k''}{n A_s} \right)^2 T_{k1} & \text{for } T_{k1} < T_{\text{res}} / 4 \end{cases} \quad (35)$$

For c_{th} use:

- $0,27 \times 10^{-18} \text{ m}^4/(\text{A}^2\text{s})$ for aluminium, aluminium alloy and aluminium/steel conductors with a cross section ratio of Al/St >6 ;
- $0,17 \times 10^{-18} \text{ m}^4/(\text{A}^2\text{s})$ for aluminium/steel conductors with a cross section ratio of Al/St ≤ 6 ;
- $0,088 \times 10^{-18} \text{ m}^4/(\text{A}^2\text{s})$ 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