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Overhead electrical conductors - Calculation methods for stranded bare conductors

Conducteurs pour lignes électriques aériennes - Méthodes de calcul applicables aux conducteurs câblés

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Overhead electrical conductors – Calculation methods for stranded bare conductors

International Electrotechnical Commission, 3, rue de Varembé, PO Box 131, CH-1211 Geneva 20, Switzerland
Telephone: +41 22 919 02 11 Telefax: +41 22 919 03 00 E-mail: inmail@iec.ch Web: www.iec.ch

Commission Electrotechnique Internationale
International Electrotechnical Commission
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CONTENTS

Clause Page

Annexes

INTERNATIONAL ELECTROTECHNICAL COMMISSION

OVERHEAD ELECTRICAL CONDUCTORS – CALCULATION METHODS FOR STRANDED BARE CONDUCTORS

FOREWORD

1) The IEC (International Electrotechnical Commission) is a worldwide organization for standardization comprising all national electrotechnical committees (IEC National Committees). The object of the IEC is to promote international cooperation on all questions concerning standardization in the electrical and electronic fields. To this end and in addition to other activities, the IEC publishes International Standards. Their preparation is entrusted to technical committees; any IEC National Committee interested in the subject dealt with may participate in this preparatory work. International, governmental and non-governmental organizations liaising with the IEC also participate in this preparation. The IEC collaborates closely with the International Organization for Standardization (ISO) in accordance with conditions determined by agreement between the two organizations.

2) The formal decisions or agreements of the IEC on technical matters, prepared by technical committees on which all the National Committees having a special interest therein are represented, express, as nearly as possible, an international consensus of opinion on the subjects dealt with.

3) They have the form of recommendations for international use published in the form of standards, technical reports or guides and they are accepted by the National Committees in that sense.

4) In order to promote international unification, IEC National Committees undertake to apply IEC International Standards transparently to the maximum extent possible in their national and regional standards. Any divergence between the IEC Standard and the corresponding national or regional standard shall be clearly indicated in the latter.

The main task of IEC technical committees is to prepare International Standards. In exceptional circumstances, a technical committee may propose the publication of a technical report of one of the following types:

- type 1, when the required support cannot be obtained for the publication of an International Standard, despite repeated efforts;
- type 2, when the subject is still under technical development or where for any other reason there is the future but not immediate possibility of an agreement on an International Standard;
- type 3, when a technical committee has collected data of a different kind from that which is normally published as an International Standard, for example "state of the art".

Technical reports of types 1 and 2 are subject to review within three years of publication to decide whether they can be transformed into International Standards. Technical reports of type 3 do not necessarily have to be reviewed until the data they provide are considered to be no longer valid or useful.

IEC 1597, which is a technical report of type 3, has been prepared by IEC technical committee 7: Overhead electrical conductors.

The text of this technical report is based on the following documents:

Committee draft	Report on voting
7(SEC)466	7(SEC)471

Full information on the voting for the approval of this technical report can be found in the report on voting indicated in the above table.

This technical report is an informative companion to IEC 1089: *Round wire concentric lay overhead electrical conductors*.

This document is a Technical Report of type 3. It is intended to provide additional technical information on conductors specified in IEC 1089.

Various conductor properties and calculation methods are given in this document. These are normally found in a number of references, but rarely condensed in a single document.

It is noted that all definitions given in IEC 1089 apply equally to this document.

Annexes A, B and C are for information only.

OVERHEAD ELECTRICAL CONDUCTORS – CALCULATION METHODS FOR STRANDED BARE CONDUCTORS

1 Scope

This document provides information with regard to conductors specified in IEC 1089. Such information includes properties of conductors and useful methods of calculation.

The following chapters are included in this document:

- current carrying capacity of conductors: Calculation method and typical example
- alternating current resistance, inductive and capacitive reactances
- elongation of conductors: Thermal and stress-strain data
- conductor creep
- loss of strength of aluminium wires due to high temperatures
- calculation of maximum conductor length in a drum

It is noted that this document does not discuss all theories and available methods for calculating conductor properties, but provides users with simple methods that provide acceptable accuracies.

2 Symbols and abbreviations

2.1 *Symbols and units*

A		cross-sectional area of the conductor (mm^2)
	A_a	aluminium wires
	A_s	steel wires
B		Internal width of a drum (m)
D		conductor diameter (m)
d_1, d_2		outside and inside diameter of a drum (m)
E		modulus of elasticity of complete conductor (MPa)
	E_a	aluminium wires
	E_s	steel wires
f		frequency (Hz)
F		tensile force in the complete conductor (kN)
	F_a	in the aluminium wires
	F_s	in steel wires
I		conductor current (A)
K_1		relative rigidity of steel to aluminum wires
K_c		creep coefficient
K_e		emissivity coefficient in respect to black body

K_g		layer factor
k_p		factor due to packing a conductor in a drum
k_s		factor due to void between conductor and planking
L		maximum conductor length in a drum (m)
Nu		Nusselt number
P_{conv}		convection heat loss (W/m)
P_j		Joule losses (W/m)
P_{rad}		radiation heat loss (W/m)
P_{sol}		solar radiation heat gain (W/m)
r		conductor radius (m)
Re		Reynolds number
R_T		electrical resistance of conductor at a temperature T (Ω/m)
s		Stefan-Boltzmann constant ($5{,}67 \times 10^{-8}$ W.m^{-2}.K^{-4})
S_i		intensity of solar radiation (W/m^2)
t		time (h)
T		temperature (K)
	T_1	ambient temperature (K)
	T_2	final equilibrium temperature (K)
v		wind speed in m/s
V_{dr}		coiling volume in a drum (m^3)
X_c		capacitive reactance, calculated for 0,3 m spacing (MΩ .km)
X_i		inductive reactance calculated for a radius of 0,3 m (Ω/km)
α		temperature coefficient of electrical resistance (K^{-1})
α_a		ratio of aluminium area to total conductor area
α_s		ratio of steel area to total conductor area
β		coefficient of linear expansion of conductor in K^{-1}
	β_a	for aluminum
	β_s	for steel
Δx		general expression used to express the increment of variable x
ε		general expression of strain (unit elongation)
	ε_a	elastic strain of aluminium wires
	ε_c	creep and settlement strain
	ε_s	elastic strain of steel wires
	ε_T	thermal strain
ϕ		coefficient for temperature (T) dependence in creep calculations
γ		solar radiation absorption coefficient
λ		thermal conductivity of air film in contact with the conductor (W.m^{-1}.K^{-1})
μ		coefficient for time (t) dependence in creep calculations
σ		stress (MPa)
ψ		coefficient for stress (σ) dependence in creep calculations

2.2 *Abbreviations*

CCC	current carrying capacity (A)
GMR	geometric mean radius of the conductor (m)

3 Current carrying capacity

3.1 *General*

The current carrying capacity (CCC) of a conductor is the maximum steady-state current inducing a given temperature rise in the conductor, for given ambient conditions.

The CCC depends on the type of conductor, its electrical resistance, the maximum allowable temperature rise and the ambient conditions.

3.2 *Heat balance equation*

The steady-state temperature rise of a conductor is reached whenever the heat gained by the conductor from various sources is equal to the heat losses. This is expressed by equation (1) as follows:

$$P_j + P_{sol} = P_{rad} + P_{conv} \qquad (1)$$

where

P_j is the heat generated by Joule effect

P_{sol} is the solar heat gain by the conductor surface

P_{rad} is the heat loss by radiation of the conductor

P_{conv} is the convection heat loss

Note that magnetic heat gain (see 4.1, 4.2 and 4.3), corona heat gain, or evaporative heat loss are not taken into account in equation (1).

3.3 *Calculation method*

In the technical literature there are many methods of calculating each component of equation (1). However, for steady-state conditions, there is reasonable agreement between the currently available methods[1] and they all lead to current carrying capacities within approximately 10 %.

Technical Report IEC 943 provides a detailed and general method to compute temperature rise in electrical equipment. This method is used for calculating the current carrying capacity of conductors included in this document. Note that CIGRÉ has published a detailed method for calculating CCC in *Electra* No. 144, October 1992.

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[1] Various methods were compared to IEC 943, IEEE, practices in Germany, Japan, France, etc.

3.4 *Joule effect*

Power losses P_j (W), due to Joule effect are given by equation (2):

$$P_j = R_T I^2 \tag{2}$$

where

R_T is the electrical resistance of conductor at a temperature T (Ω/m)

I is the conductor current (A)

3.5 *Solar heat gain*

Solar heat gain, P_{sol} (W/m), is given by equation (3):

$$P_{sol} = \gamma D S_i \tag{3}$$

where

γ is the solar radiation absorption coefficient

D is the conductor diameter (m)

S_i is the intensity of solar radiation (W/m^2)

3.6 *Radiated heat loss*

Heat loss by radiation, P_{rad} (W), is given by equation (4):

$$P_{rad} = s \pi D K_e (T_2^4 - T_1^4) \tag{4}$$

where

s is the Stefan-Boltzmann constant ($5{,}67 \times 10^{-8}$ W.m^{-2}.K^{-4})

D is the conductor diameter (m)

K_e is the emissivity coefficient in respect to black body

T is the temperature (K)

  T_1 ambient temperature (K)

  T_2 final equilibrium temperature (K)

3.7 *Convection heat loss*

Only forced convection heat loss, P_{conv} (W), is taken into account and is given by equation (5):

$$P_{conv} = \lambda \, \mathrm{Nu} \, (T_2 - T_1) \, \pi \tag{5}$$

where

λ is the thermal conductivity of the air film in contact with the conductor, assumed constant and equal to: 0,02585 W.m^{-1}.K^{-1}

Nu is the Nusselt number, given by equation (6):

$$\mathrm{Nu} = 0{,}65 \, \mathrm{Re}^{0{,}2} + 0{,}23 \, \mathrm{Re}^{0{,}61} \tag{6}$$

Re is the Reynolds number given by equation (7):

$$\mathrm{Re} = 1{,}644 \times 10^{9}\, v\, D\, [(T_1 + 0{,}5(T_2 - T_1)]^{-1{,}78} \qquad (7)$$

v is the wind speed in m/s

D is the conductor diameter (m)

T is the temperature (K)

  T_1 ambient temperature (K)

  T_2 final equilibrium temperature (K)

3.8 *Method to calculate current carrying capacity (CCC)*

From equation (1), the steady-state current carrying capacity can be calculated:

$$I_{\max} = [(P_{\mathrm{rad}} + P_{\mathrm{conv}} - P_{\mathrm{sol}})/R_{\mathrm{T}}]^{1/2} \qquad (8)$$

where

R_{T} is the electrical resistance of conductor at a temperature T (Ω/m)

and P_{sol}, P_{rad} and P_{conv} are calculated from equations (3), (4), and (5).

3.9 *Determination of the maximum permissible aluminium temperature*

The maximum permissible aluminium temperature is determined either from the economical optimization of losses or from the maximum admissible loss of tensile strength in aluminium.

In all cases, appropriate clearances under maximum temperature have to be checked and maintained.

3.10 *Calculated values of current carrying capacity*

Equation (8) enables the current carrying capacity (CCC) of any conductor in any condition to be calculated.

As a reference, the tables in annex A gives the CCC of the recommended conductor sizes[2] under the following conditions. It is important to note that any change to these conditions (specially with wind speed and ambient temperature) will result in different CCC which will have to be recalculated according to above equation (8):

- speed of cross wind (90° to the line), $v = 1$ m/s
- intensity of solar radiation, $S_i = 900$ W/m^2
- solar absorption coefficient, $\gamma = 0{,}5$
- emissivity with respect to black body, $K_e = 0{,}6$
- aluminium temperature $T_2 = 353$ K and 373 K (equal to 80 °C and 100 °C)
- ambient temperature, $T_1 = 293$ K (= 20 °C)
- frequency = 50 Hz (values for 60 Hz are very close, usually within 2 %)

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[2] In this document conductor sizes are those recommended in IEC 1089.

4 Alternating current resistance, inductive and capacitive reactances

4.1 *General*

The electrical resistance of a conductor is a function of the conductor material, length, cross-sectional area and the effect of the conductor lay. In more accurate calculations, it also depends on current and frequency.

The nominal values of DC resistance are defined in IEC 1089 at 20 °C temperature for a range of resistance exceeding 0,02 Ω/km.

In order to evaluate the electrical resistance at other temperatures, a correction factor has to be applied to the resistance at 20 °C.

The alternating current (AC) resistance at a given temperature T is calculated from the DC resistance, corrected to the temperature T and considering the skin effect increment on the conductor that reflects the increased apparent resistance caused by the inequality of current density.

The other important effects due to the alternating current are the inductive and capacitive reactances. They can be divided into two terms: the first one due to flux within a radius of 0,30 m and the second which represents the reactance between 0,30 m radius and the equivalent return conductor. Only the first term of both reactances is listed in tables of annex B.

The methods of calculation adopted in this clause are based on the *Aluminum Electrical Conductor Handbook* of The Aluminum Association and on the *Transmission Line Reference Book for 345 kV and above* of the Electric Power Research Institute (EPRI).

4.2 *Alternating current (AC) resistance*

The AC resistance is calculated from the DC resistance at the same temperature. The DC resistance of a conductor increases linearly with the temperature, according to the following equation:

$$R_{T2} = R_{T1}\,[1 + \alpha\,(T_2 - T_1)] \qquad (9)$$

where

R_{T1} is the DC resistance at temperature T_1

R_{T2} is the DC resistance at temperature T_2

α is the temperature coefficient of electrical resistance at temperature T_1

In this chapter, R_{T1} corresponds to the DC resistance at 20 °C given in IEC 1089. The temperature coefficients of resistance at 20 °C are the following:

- for type A1 aluminium: $\alpha = 0{,}00403\ \text{K}^{-1}$
- for types A2 and A3 aluminium: $\alpha = 0{,}00360\ \text{K}^{-1}$

Based on these values at 20 °C, the DC resistances have been calculated for temperatures of 50 °C, 80 °C and 100 °C.

The AC resistance of the conductor is higher than the DC resistance mainly because of the "skin effect". The cause of this phenomenon can be explained by the fact that the inner portion of the conductor has a higher inductance than the outer portion because the inner portion experiences more flux linkages. Since the voltage drop along any length of the conductor must be necessarily the same over the whole cross-section, there will be a current concentration in the outer portion of the conductor, increasing the effective resistance.

Various methods are available for computing the ratio between AC and DC resistances. The values given in annex B are based on one of the accepted methods [1][3] in the industry for AC resistance.

For conductors having steel wires in the core (Ax/Sxy conductors), the magnetic flux in the core varies with the current, thus the AC/DC ratio also varies with it, especially when the number of aluminium layers is odd, because there is an unbalance of magnetomotive force due to opposite spiralling directions of adjacent layers.

Although this magnetic effect may be significant in some single layer Ax/Sxy conductors and moderate in 3-layer conductors, the values of AC resistances for these types of conductors have been calculated without this influence. Further information and a more complete comparison and evaluation of magnetic flux and unbalance of magnetomotive force may be found in chapter 3 of the Aluminum Electrical Conductor Handbook.

There are other factors with minor influence on the conductor electrical AC resistance, e.g. hysteresis and eddy current losses not only in the conductors but also in adjacent metallic parts but they are usually estimated by actual tests and their effects have not been taken into account in this clause.

4.3 *Inductive reactance*

The inductive reactance of conductors is calculated considering the flux linkages caused by the current flowing through the conductors. In order to make computations easier, the inductive reactance is divided into two parts:

a) the one resulting from the magnetic flux within a 0,3 m[4] radius;

b) the one resulting from the magnetic flux from 0,3 m to the equivalent return conductor.

This separation of reactances was first proposed by Lewis [1] and the 0,3 m radius has been used by all designers and conductor manufacturers and is herein adopted in order to allow a comparison between the characteristics of the new conductor series and old ones.

The advantages of this procedure are that part a) above is a geometric factor (function of conductor dimensions) while part b) depends only on the separation between conductors and phases of the transmission line. As stated earlier in this clause, only the first term a) is herein listed and part b) can be obtained from the usual technical literature.

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[3] Figures in square brackets refer to bibliography in annex C.

[4] Exact number is 0,3048.

The first step to determine the inductive reactance for 0,3 m radius is to calculate the Geometric Mean Radius (*GMR*) of the conductor. The related expressions are the following:

$$GMR = 0{,}5\ D\ K_g \qquad (10)$$

where

GMR is the geometric mean radius of conductor (m)

D is the overall diameter of conductor (m)

K_g is the layer factor (ratio of radii [1])

The "K_g" layer factor depends only on the type of conductor and geometry of layers (number of layers and wires). The calculated values of "K_g" for the various stranding types defined in this report are given in table 1.

Table 1 – Values of K_g for inductive reactance calculations

Aluminium		Steel		Layer factor K_g
No. of wires	No. of layers	No. of wires	No. of layers	
6	1	1	–	*)
18	2	1	–	0,7765
7	1	–	–	0,7256
22	2	7	1	0,7949
26	2	7	1	0,8116
19	2	–	–	0,7577
37	3	–	–	0,7678
61	4	–	–	0,7722
45	3	7	1	0,7939
54	3	7	1	0,8099
72	4	7	1	0,7889
84	4	7	1	0,8005
91	5	–	–	0,7743
54	3	19	2	0,8099
72	4	19	2	0,7889
84	4	19	2	0,8005

* Values vary with the conductor size due to the presence of the steel core. For individual conductors, K_g can be calculated from the inductive reactance. The average value of K_g for conductor sizes with 6/1 stranding is 0,5090.

The inductive reactance for 0,3 m radius is then given by equation (11):

$$X_i = 4 \times 10^{-4}\ \pi\ f \ln(0{,}3/GMR) = 0{,}1736\ (f/60)\ \lg\ (0{,}3/GMR) \qquad (11)$$

where

X_i is the inductive reactance for 0,3 m radius (Ω/km)

f is the frequency (Hz)

GMR is the geometric mean radius (m)