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TECHNICAL REPORT

Overhead electrical conductors – Calculation methods for stranded bare conductors

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OVERHEAD ELECTRICAL CONDUCTORS – CALCULATION METHODS FOR STRANDED BARE CONDUCTORS

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IEC TR 61597 has been prepared by IEC technical committee 7: Overhead electrical conductors. It is a Technical Report.

This second edition cancels and replaces the first edition published in 1995. This edition constitutes a technical revision.

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

a) Addition of Clause 2 and Clause 3 since the "Normative references" and "Terms and definitions" clauses are mandatory elements of the text according to the new IEC template.

b) In Clause 6, addition of new kinds of aluminium alloy and aluminium clad steel and their values of temperature coefficients of resistance.

c) In Clause 6, addition of guidelines for the calculation of AC resistance taken into account hysteresis and eddy current losses.

d) In Clause 7, addition of the values of coefficient of linear expansion of aluminium alloy conductor aluminium-clad steel reinforced series.

e) Deletion of Clause 8 “Calculation of maximum conductor length on drums” in the last version.

f) Annex A, replaced by “A practical example of CCC calculation”.

g) Annex B, replaced by “Indicative conditions for CCC calculation”.

The text of this Technical Report is based on the following documents:

Draft	Report on voting
7/704/DTR	7/707/RVDTR

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

The language used for the development of this Technical Report is English.

This document was drafted in accordance with ISO/IEC Directives, Part 2, and developed in accordance with ISO/IEC Directives, Part 1 and ISO/IEC Directives, IEC Supplement, available at www.iec.ch/members_experts/refdocs. The main document types developed by IEC are described in greater detail at www.iec.ch/standardsdev/publications.

The committee has decided that the contents of this document will remain unchanged until the stability date indicated on the IEC website under webstore.iec.ch in the data related to the specific document. At this date, the document will be

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OVERHEAD ELECTRICAL CONDUCTORS – CALCULATION METHODS FOR STRANDED BARE CONDUCTORS

1 Scope

This document, which is a Technical Report, provides information with regard to conductors specified in IEC 61089 and other aluminium and aluminium steel conductors. 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

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 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements 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 TR 60943:1998, *Guidance concerning the permissible temperature rise for parts of electrical equipment, in particular for terminals*
IEC TR 60943:1998/AMD1:2008

IEC 61089:1991, *Round wire concentric lay overhead electrical stranded conductors*
IEC 61089:1991/AMD1:1997

IEC 60104:1987, *Aluminium-magnesium-silicon alloy wire for overhead line conductors*

IEC 60889:1987, *Hard-drawn aluminium wire for overhead line conductors*

IEC 61232:1993, *Aluminium-clad steel wires for electrical purposes*

IEC 61395:1998, *Overhead electrical conductors – Creep test procedures for stranded conductors*

IEC 62004:2007, *Thermal-resistant aluminium alloy wire for overhead line conductor*

3 Terms and definitions

No terms and definitions are listed in this document.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

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- IEC Electropedia: available at http://www.electropedia.org/
  ISO Online browsing platform: available at http://www.iso.org/obp

4 Symbols, units and abbreviated terms

4.1 Symbols and units

A	cross-sectional area of the conductor (mm^2)
A_a	cross-sectional area of aluminium wires (mm^2)
A_s	cross-sectional area of steel wires (mm^2)
D	conductor diameter (m)
E	modulus of elasticity of complete conductor (MPa)
E_a	modulus of elasticity of aluminium wires(MPa)
E_s	modulus of elasticity of steel wires(MPa)
f	frequency (Hz)
F	tensile force in the complete conductor (kN)
F_a	tensile force in the aluminium wires
F_s	tensile force in steel wires
I	conductor current (A)
K_1	relative rigidity of steel to aluminium wires
K_c	creep coefficient
K_e	emissivity coefficient in respect to black body
K_g	layer factor
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)
R_e	Reynolds number
R_T	electrical resistance of conductor at a temperature T (Ω/m)
s	Stefan-Boltzmann constant ($5{,}67\times10^{-8}$ $W\cdot m^{-2}\cdot K^{-4}$)
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
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}

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β_a coefficient of linear expansion for aluminium in K^{-1}

β_s coefficient of linear expansion for steel in K^{-1}

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 of conductor

ε_s elastic strain of steel wires

ε_T thermal strain of conductor

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 ($W \cdot m^{-1} \cdot K^{-1}$)

μ coefficient for time (t) dependence in creep calculations

σ stress (MPa)

Ψ coefficient for stress (σ) dependence in creep calculations

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4.2 Abbreviated terms

CCC current carrying capacity (A)

GMR geometric mean radius of the conductor (m)

5 Current carrying capacity

5.1 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.

5.2 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):

$$P_j + P_{\text{sol}} = P_{\text{rad}} + P_{\text{conv}} \tag{1}$$

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 6.1, 6.2 and 6.3), corona heat gain, or evaporative heat loss are not taken into account in equation (1).

5.3 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 available methods and they all lead to current carrying capacities within approximately 10 % for classical conductor in operational conditions (for example, conductor temperature below 100 °C).

NOTE Various methods were compared to IEC 60943, IEEE, practices in Germany, Japan, France, etc.

IEC TR 60943 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 CIGRE has published a detailed method for calculating CCC in CIGRE TB 601 [4][1].

5.4 Joule effect

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

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

where

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

I is the conductor current (A), AC or DC

5.5 Solar heat gain

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

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

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)

5.6 Radiated heat loss

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

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

where

s is the Stefan-Boltzmann constant (5,67x10^{-8} W·m^{-2}·K^{-4})

D is the conductor diameter (m)

K_e is the emissivity coefficient in respect to black body

T_1 ambient temperature (K)

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

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T_2 final equilibrium temperature (K)

5.7 Convection heat loss

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

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

where

λ is the thermal conductivity of the air film in contact with the conductor. If assumed constant, it is equal to: 0,0258 5 W × m^{-1} × K^{-1}. If assumed variable, such equations can be found in [4].

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

$$Nu = 0.65\,Re^{0.2} + 0.23\,Re^{0.61} \tag{6}$$

Another expression of the Nusselt Number could be used and found in [4].

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

$$Re = 1{,}644 \times 10^9 v \cdot D \cdot [T_1 + 0.5(T_2 - T_1)]^{-1.78} \tag{7}$$

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)

5.8 Method to calculate current carrying capacity (CCC)

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

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

where

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

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

5.9 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.

If needed, the equation of core temperature versus surface temperature can be found in [4].

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5.10 Calculated values of current carrying capacity

Equation (8) enables the current carrying capacity (CCC) of any conductor at any condition to be calculated. Table B.1 gives indicative conditions in some countries and regions for CCC calculation.

6 Alternating current resistance, Inductive and capacitive reactances

6.1 General

The electrical resistance of a conductor is a function of the conductor material, length, cross-sectional area and 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 61089 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.

The methods of calculation adopted in this clause refer to [1] and [5].

6.2 Alternating current (AC) resistance

The DC resistance of a conductor increases linearly with the temperature, according to the following equation:

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

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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 clause, R_{T1} corresponds to the DC resistance at 20 °C given in IEC 61089 and IEC 62004. The temperature coefficients of resistance at 20 °C, which are given in IEC 60889, IEC 60104 and IEC 61232, are the following:

– for type A1 aluminium: α= 0,004 03 K^{-1}
– for type A2 aluminium: α= 0,003 60 K^{-1}
– for type A3 aluminium: α= 0,003 60 K^{-1}
– for type AT1 aluminium: α= 0,004 00 K^{-1}
– for type AT2 aluminium: α= 0,003 60 K^{-1}

– for type AT3 aluminium: α= 0,004 00 K^{-1}
– for type AT4 aluminium: α= 0,003 83 K^{-1}
– for type 20SA: α= 0,003 60 K^{-1}
– for type 27SA: α= 0,003 60 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 is calculated from the DC resistance at the same temperature. Calculation methods are in [1],[2],[3],[4]. Clause A.2 gives an example based on [1].

The AC resistance of the conductor is higher than the DC resistance at the same temperature. 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 ([1], [2], [3], [4]).

For conductors having steel wires in the core (Ax/Sxy or Ax/xySA 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 spiraling 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 [1].

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, and they can be estimated by actual tests. The method in [6] takes into account the above factors.

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

NOTE Exact number is 0,304 8.

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

$$GMR = 0.5\ D \cdot K_g \tag{10}$$

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
No. of wires	No. of layers	No. of wires	No. of layers	K_g
6	1	1	-	[a]
18	2	1	-	0,776 5
7	1	-	-	0,725 6
22	2	7	1	0,794 9
26	2	7	1	0,811 6
19	2	-	-	0,757 7
37	3	-	-	0,767 8
61	4	-	-	0,772 2
45	3	7	1	0,793 9
54	3	7	1	0,809 9
72	4	7	1	0,788 9
84	4	7	1	0,800 5
91	5	-	-	0,774 3
54	3	19	2	0,809 9
72	4	19	2	0,788 9
84	4	19	2	0,800 5

[a] 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.

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

$$X_i = 4 \times 10^{-4}\pi \cdot f \cdot ln(0.3/GMR) = 0.1736\ (f/60)\ \cdot lg\ \ (0.3/GMR) \tag{11}$$

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)

For conductors with steel core (Ax/Sxy or Ax/xySA designations), the magnetic flux in the core depends on the current and this influence, as far as the inductive reactance is concerned, can be considered negligible for conductors with three aluminium layers and more or with even number of layers. For single-layer Ax/Sxy type, the effect is not negligible and X_i is usually determined after tests on complete conductor samples.

As there are no available results from tests carried out on conductor samples of the new IEC series, X_i for single-layer conductors has been estimated in comparison with experimental figures obtained for usual Ax/Sxy designations (old ACSR) at 25 ℃,published by the Aluminium Association. These values are accurate within 3 %.

6.4 Capacitive reactance

The capacitive reactance can also be divided into two parts:

a) the capacitive reactance for 0,3 m radius;

b) the capacitive reactance from 0,3 m to the equivalent return conductor.

Considering the same reason given in 6.3, only part a) above is herein listed and part b) can be obtained from readily available technical literature.

As far as capacitive reactance is concerned, it is neither current nor steel wire dependent. Hence the calculation is quite simple, depending only on the frequency and the conductor dimensions, as shown in equation (12):

$$X_C = (9/\pi f) \cdot ln(2 \times 0.3/D) = 0.1099\ (60/f)\ \cdot lg\ \ (2 \times 0.3/D) \qquad (12)$$

where

X_c is the capacitive reactance for 0,3 m radius (MΩ·km)

f is the frequency (Hz)

D is the conductor diameter (m)

7 Elongation of stranded conductors

7.1 General

Elongation of conductors can be caused by various sources such as:

– elastic elongation
– thermal elongation
– plastic elongation
– creep
– elongation due to the slack in the wires during stranding
– radial compression and local indentation of conductor layers at wire contacts

NOTE In this document, elongation is considered in a general way: it can either be positive or negative.

When a conductor is subjected to tensile forces, the distribution of stresses in its wires is intimately related to the elongations listed above.

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In this clause, these elongations are discussed separately and, whenever applicable, generalized models are proposed for each type of elongation.

It is noted that more detailed test information on creep and conductor elongation can be obtained from IEC 61395.

7.2 Thermal elongation

Changes in temperature will affect the length of a conductor. The thermal strain or unit elongation (ε_T) of homogeneous aluminium conductors have the following format:

$$\varepsilon_T = \beta_a \cdot \Delta T \qquad (13)$$

where

β_a is coefficient of linear expansion for aluminium in K^{-1}

ΔT is the temperature T increment

For all conductors designated A1, A2, A3, A1/A2 and A1/A3,the value of β_a = 23×10^{-6} K^{-1} is used.

The thermal elongation of inhomogeneous conductors (designation Ax/Sxy or Ax/xySA) is more complex to establish because of the intimate relationship between elongations and stresses of constituent wires.

Conductors used in overhead transmission lines are continuously subjected to mechanical tension and, in most cases, both aluminium and steel wires or aluminium clad steel wires share the total tension in proportion to their relative rigidity.

When both aluminium and steel wires or aluminium clad steel wires are subjected to tensile stresses, thermal strain and tensile strain are related. In this case the following relations apply:

$$\Delta F_s / A_s E_s = \beta_s \Delta T \qquad \text{(applicable to steel portion)} \qquad (14)$$

$$\Delta F_a / A_a E_a = \beta_a \Delta T \qquad \text{(applicable to aluminium portion)} \qquad (15)$$

$$\Delta F / AE = \beta \Delta T \qquad \text{(applicable to complete conductor)} \qquad (16)$$

where

ΔF, ΔF_a, ΔF_s	are respectively increments in conductor, aluminium, and steel tensions
β	is the coefficient of linear expansion of conductor in K^{-1} (β_a for aluminium, β_s for steel or aluminium clad steel)
ΔT	is the temperature T increment

Since $\Delta F = \Delta F_a + \Delta F_s$ equations (14), (15), and (16) can be reduced to:

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$$\beta = (E_a A_a \beta_a + E_s A_s \beta_s)/EA$$

or

$$\beta = (E_a A_a \beta_a + E_s A_s \beta_s)/(E_a A_a + E_s A_s) \quad (17)$$

If the relative rigidity of the steel section to the aluminium section is assumed to be K_1 (that is: $K_1 = E_s A_s / E_a A_a$), equation (17) can thus be simplified to:

$$\beta = (\beta_a + K_1 \beta_s)/(1 + K_1) \quad (18)$$

The values of β given in Table 2 and Table 3 for various conductor designations are based on β_a = 23×10^{-6} K^{-1} and β_s = 11,5×10^{-6} K^{-1}(for steel) or 13,0×10^{-6} K^{-1}(for aluminium clad steel, 20SA) and calculated according to equation (18) for E_a= 55 000 MPa and E_s = 190 000 MPa (for steel) or 159 000 MPa (for aluminium clad steel, 20SA).

NOTE This figure is applicable to 7-wire and 19-wire cores. For larger cores, different values may have to be used. For single wire steel core, E_s = 207 000 MPa (for steel) or 162 000 MPa (for aluminium clad steel).

The corresponding values of aluminium conductor aluminium-clad steel reinforced or aluminium alloy conductor aluminium-clad steel reinforced can also be calculated according to above equations (see Table 3).

In cases where tensile forces in aluminium wires are nil, the steel core carries all the conductor tension. In such cases, the thermal elongation of the conductor is identical to the elongation of the steel core alone, that is $\beta = \beta_s$.

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Table 2 – Coefficient of linear expansion β of inhomogeneous conductors designated Ax/Sxy

Ax	Sxy	A_s/A_a	κ_1	β $10^{-6}K^{-1}$
6	1	0,17	0,58	18,8
7	7	0,20	0,69	18,3
12	7	0,58	2,00	15,3
18	1	0,06	0,19	21,1
22	7	0,10	0,34	20,1
24	7	0,13	0,45	19,4
26	7	0.16	0,56	18,9
30	7	0,23	0,79	17,9
42	7	0,05	0,17	21,3
45	7	0,07	0,24	20,8
48	7	0,09	0,31	20,3
54	7	0,13	0,45	19,4
54	19	0,13	0,44	19,5
72	7	0,04	0,15	21,5
72	19	0,04	0,15	21,5
84	7	0,08	0,29	20,4
84	19	0,08	0,28	20,5

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Table 3 – Coefficient *of* linear expansion *β* of inhomogeneous conductors designated Ax/20SA

Ax	20SA	A_s/A_a	β $10^{-6}K^{-1}$
6	1	0,17	19,7
7	7	0,20	19,3
12	7	0,58	16,7
18	1	0,06	21,6
22	7	0,10	20,8
24	7	0,13	20,3
26	7	0,16	19,8
30	7	0,23	19,0
42	7	0,05	21,7
45	7	0,07	21,3
48	7	0,09	21,0
54	7	0,13	20,3
54	19	0,13	20,3
72	7	0,04	21,9
72	19	0,04	21,9
84	7	0,08	21,1
84	19	0,08	21,1

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7.3 Stress-strain properties

Stress-strain curves of conductors depend on the elasto-plastic behaviour of the component wires, the geometric settlement and the metallurgical creep of wires. The first two parameters are not time dependent on the opposite of the third one.

As a consequence of time dependency of the conductor strain, stress-strain curves are always associated with a time reference.

In some cases, two stress-strain curves are used to characterize behaviour of conductors. The first one is the initial curve which includes the one-hour creep and the second one, the final curve, which includes the 10-year creep at 20 °C (or even longer durations). Such curves are used in the experimental plastic elongation (EPE) model for sag-tension calculation. This model is described in the CIGRE TB 324 [7].

In other cases, only a final curve is given and initial conditions are derived through a temperature compensation. Furthermore, a separate creep curve is sometimes provided to predict creep after any period of time.

The stress-strain behaviour of inhomogeneous conductors (Ax/Sxy) depend on the properties of the constituent wires, their number and layers.

In a conductor subjected to tensile loads, the total conductor tension, F, is equal to the sum of tensions in the aluminium and steel portions (respectively F_a and F_s). Furthermore, the total conductor elongation is equal to that of each component, i.e.:

$$F = F_a + F_s \tag{19}$$

$$\varepsilon = \varepsilon_a = \varepsilon_s \tag{20}$$

$$F/AE = F_a/A_aE_a = F_s/A_sE_s \tag{21}$$

Resolving equations (19) to (21), where it is assumed (in equation (21)) that all components behave elastically, leads to the following results:

$$F_a = FE_aA_a/EA \tag{22}$$

$$F_s = FE_sA_s/EA \tag{23}$$

$$E = (E_aA_a + E_sA_s)/A \tag{24}$$

If A_a/A and A_s/A are respectively defined as α_a and α_s (aluminium and steel are as expressed as percentage of the total conductor area), then equation (24) can be rewritten:

$$E = E_a\alpha_a + E_s\alpha_s \tag{25}$$

Equation (25) can be used to establish the final elastic modulus of elasticity of the inhomogeneous conductor after being subjected to tension because during unloading the behaviour of the conductor becomes elastic.

Since aluminium wires are subjected to creep and settlement strain (ε_c), equation (21) can be rewritten in order to include the effect of this additional strain ε_c.

$$F/AE = F_a/A_aE_a + \varepsilon_c = F_s/A_sE_s \tag{26}$$

Resolving equations (19) and (26) leads to the following results:

$$F_a = FE_aA_a(1 - \varepsilon_cE_sA_s/F)/EA \tag{27}$$

$$F_s = FE_sA_s(1 + \varepsilon_cE_aA_a/F)/EA \tag{28}$$

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$$E = (E_a \alpha_a + E_s \alpha_s)/(1 + \varepsilon_c E_a A_a / F) \quad (29)$$

When equations (27), (28) and (29) are compared with equations (22), (23) and (24), the following results can be derived:

– creep of aluminium wires reduces the tensile load carried by these wires and transfers this load to steel wires. The amount of reduction in the tension of aluminium wires can be obtained by subtracting F_a in equation (27) from F_a in equation (22) which corresponds to:

$$\Delta F_a = (E_a A_a E_s A_s)\varepsilon_c / EA \quad (30)$$

– the tension in aluminium wires decreases with creep. Under extreme conditions aluminium wires will not carry any tensile load, i.e. when

$$\varepsilon_c = F / E_s A_s \quad (31)$$

– In this case, aluminium wires become completely slack and all the conductor tension is transferred to the steel core. The same condition can result from using conductors at very high temperatures beyond the operation temperature and depending on the duration (see Figure 2).

Recent studies have indicated that in multiple-layer conductors, the aluminium wires can carry some compressive load (stresses not exceeding 5 MPa to 10 MPa) before birdcaging which can force the steel core to carry more tension than the total conductor tension. For practical reasons, compressive stresses can be neglected unless the suspended conductor is expected to be subjected to very high temperatures.

7.4 Assessment of final elastic modulus

The final modulus of elasticity of conductors can be derived from equation (25) ($E = E_a \alpha_a + E_s \alpha_s$) where E_a and E_s are respectively the aluminium and steel moduli.

If the aluminium and steel wires of a conductor were straight solid wires, their corresponding moduli of elasticity of E_a = 68 000MPa and E_s = 207 000 MPa could have been used directly in equation (25).

However, since wires are helically wound, a unit elongation along the axis of the conductor leads to less strain in the axis of the wire and thus reduces the effective modulus of elasticity.

Furthermore, the radial compression between layers at contact points of wires tends also to generate strain along the axis of the conductor.

For the above reasons, the modulus of elasticity of the aluminium portion tends to decrease with increasing number of layers and wires. The same applies to steel wire layers, but to a lesser degree, due to the surface hardness at contact points.

The ideal way to generate the stress-strain characteristics of the aluminium portion of a conductor is to perform stress-strain tests as suggested in IEC 61089.

In the absence of such data, values found in the technical literature can be used in order to obtain approximate stress-strain calculations of conductors. These values are based on one of the following methods:

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a) average the values obtained from tests of similar stranding and generalize the results. Values given in Table 4 are based on published curves of the Aluminium Association [1] and should represent a good approximation in the absence of direct test.

b) use equation (25) and assume E_a = 55 000 MPa and E_s = 190 000 MPa constant. The results of this method are given in Table 5 and Table 6 and agree to within 5 % of those obtained in method a).

c) start from the modulus of single steel and aluminium wires and reduce them by the following factors: 0,80 to 0,90 for A1 wires, 0,85 to 0,95 for A2 and A3 wires, and 0,90 to 0,95 for steel wires.

It is however noted that variations in the final modulus of elasticity in the order of 5 % usually lead to final sag variations less than 1 %.

NOTE Except for single, steel wire core where E_s = 207 000 MPa.

Table 4 – Typical stress-strain data of stranded conductors based on published test results

Conductor data				Strain of conductor in %					
				Stress levels MPa					
Type	Ax	Sx	Final modulus MPa×10^3	25	50	75	100	125	150
Ax[a]	7	0	63,3	0,05	0,11	0,17	0,26	0,39	0,58
	19	0	61,2	0,05	0,11	0,18	0,27	0,41	0,60
	37	0	58,9	0,05	0,11	0,18	0,27	0,41	0,60
	61	0	58,3	0,05	0,12	0,20	0,30	0,44	0,64
Ax/Sxy	6	1	79,0	0,04	0,08	0,11	0,15	0,20	0,25
	18	1	68,0	0,05	0,10	0,15	0,21	0,27	0,36
	22	7	71,0	0,05	0,09	0,15	0,20	0,25	0,33
	26	7	74,2	0,05	0,09	0,14	0,18	0,23	0,28
	45	7	64,5	0,06	0,11	0,16	0,22	0,29	0,38
	54	7	67,1	0,05	0,10	0,15	0,20	0,26	0,33
	54	19	69,7	0,05	0,09	0,14	0,19	0,25	0,31
	72	7	61,1	0,07	0,12	0,18	0,24	0,31	0,41
	72	19	61,0	0,07	0,12	0,18	0,24	0,32	0,42
	84	7	66,6	0,05	0,09	0,15	0,21	0,28	0,36
	84	19	66,5	0,05	0,09	0,14	0,20	0,27	0,35

[a] Values derived for A1, but can also be used for A2 and A3 in the absence of relevant test data.

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Table 5 – Final modulus of elasticity calculated with E_a= 55 000 MPa and E_s= 190 000 MPa

Ax	Sxy	Aluminium ratio α_a	Steel ratio α_s	Elasticity modulus in MPa×10³
6	1	0,857	0,143	76,7
18	1	0,947	0,053	63,1
22	7	0,910	0,090	67,1
26	7	0,860	0,140	73,9
45	7	0,935	0,065	63,7
54	7	0,885	0,115	70,5
54	19	0,888	0,112	70,2
72	7	0,959	0,041	60,6
72	19	0,959	0,041	60,5
84	7	0,923	0,077	65,4
84	19	0,925	0,075	65,2

NOTE Except for single-wire steel core where E_s = 207000 MPa.

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Table 6 – Final modulus of elasticity calculated with E_a= 55 000 MPa and E_s= 159 000 MPa (20SA)

Ax	20SA	Aluminium ratio α_a	Aluminium clad steel ratio α_s	Elasticity modulus in MPa×10³
6	1	0,857	0,143	70,3
18	1	0,947	0,053	60,6
22	7	0,910	0,090	64,6
26	7	0,860	0,140	70,0
45	7	0,935	0,065	61,9
54	7	0,885	0,115	67,3
54	19	0,888	0,112	67,0
72	7	0,959	0,041	59,4
72	19	0,959	0,041	59,3
84	7	0,923	0,077	64,2
84	19	0,925	0,075	63,1

NOTE Except for single-wire aluminium clad steel core where E_s = 162000 MPa.

8 Conductor creep

8.1 General

A conductor suspended between two supports will in time get an increase in sag which must be considered by the transmission line engineer in order to satisfy the required ground and crossing clearances. This additional sag is caused by a characteristic of the material called creep, normally defined as the long-term change in shape depending on applied forces.

Many investigations have been made throughout the world to calculate or measure the creep in conductors in order to predict the final elongation and thus the final sag.

A general finding is that the total elongation for conductors can be divided into two different parts: One being mainly a geometric settlement when wires are tightened together initiating stresses at wire cross-over points. The other is regarded as a pure metallurgical creep within the wires.

More detailed information on conductor creep can be obtained from IEC 61395. It is noted that IEC 61395 test method is valid for test at room temperature (20 °C), for test at higher temperature secondary creep starts later and linear regression should neglect initial values liked to primary creep.

8.2 Creep of single wires

When creep testing a conductor, a certain load is applied and the elongation is recorded versus the time. If the elongation is plotted on a double logarithmic diagram the readings will likely follow a straight line as in Figure 1.

This is also the case when testing only an aluminium wire.

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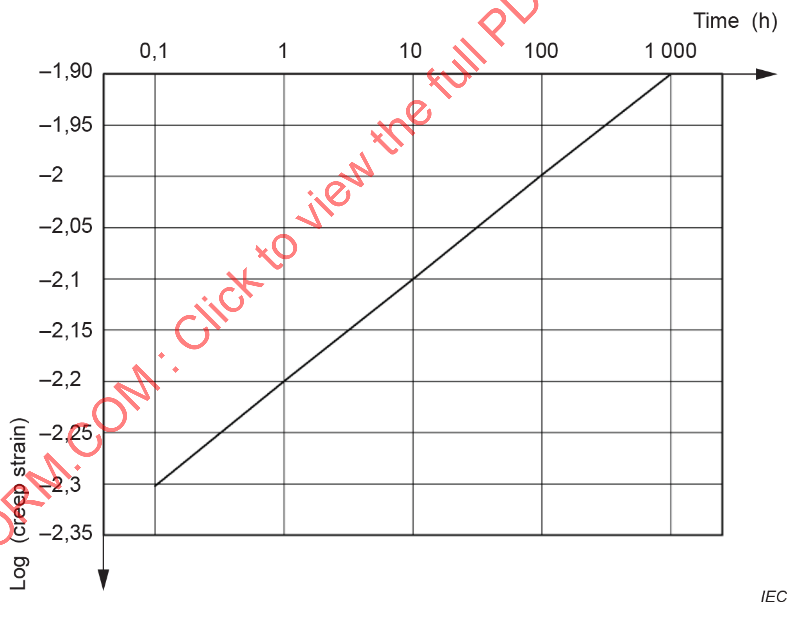

Figure 1 – Typical creep curve

The equation for the straight line is:

$$lg\,\varepsilon_c = lg\,a + b \times lg\,t \tag{32}$$

or

$$\varepsilon_c = a \times t^b \tag{33}$$

The constants *a* and *b* are only valid for given load history and temperatures.

8.3 Total conductor creep

The total creep elongation for different loads and temperature has been shown to follow equation (34):

$$\varepsilon_c = K_c \times e^{\Phi T} \times \sigma^{\Psi} \times t^{\mu} \tag{34}$$

Where

K_c is the creep coefficient depending mainly on number of wires in the conductor

Φ is the coefficient for the temperature (T) dependence

Ψ is the coefficient for the stress (σ) dependence

μ is the coefficient for the time (t) dependence

In order to determine these coefficients, tests must be made according to a very precise procedure. The reason for this is that a large portion of the creep will take place in the very beginning of the test. The method for loading the conductor and starting the reading of the elongation must therefore be accurate.

The coefficients K_c, Φ, Ψ and μ are shown to depend upon the number of component wires and their materials. This together with the fact that creep tests take a long time to perform complicate the establishing of the creep equation coefficients.

8.4 Prediction of conductor creep

Different techniques have been used to predict the life-time creep for a conductor:

a) using a creep predictor formula as explained in 8.3 together with an anticipated life-time history including different conductor conditions such as normal and overload mechanical and temperature. Coefficients in the predictor creep formula must be known.

b) using creep values from conductor creep tests made at actual mechanical and temperature conditions under long time (normally more than two months) and extrapolate the creep curve up to 10, 30 or 50 years. Normally the final sag calculation is made by using the creep at 10 years. The reason for this is that the additional creep from 10 to 50 years is relatively small and that a reasonable amount of the creep may have been elapsed from the time of stringing up to the time of clamping in the conductor.

c) using creep values from accelerated conductor creep tests made at a higher mechanical tension. The creep value at a certain time will then correspond to what is known to be found under real conditions after 30 years.

For all these methods a final creep value is obtained. In order to simplify the conductor sag calculation, the elongation due to creep can be simulated by a temperature difference using the coefficient of linear expansion given in this document.

NOTE A conductor that was subject to a large instantaneous plastic deformation will not accumulate creep deformations at the same rate.

8.5 Creep values

The following creep values and correspondingly calculated temperature are for guidance only. The values have been taken as rounded mean values from many creep tests reported. It maybe pointed out that these values refer to ordinary conductors and ordinary stringing tensions. In some cases especially designed conductors and/or prestress stringing techniques significantly reduce the creep. Also abnormal conductor conditions such as, for example, very high temperatures or high everyday tensions could be expected to increase the creep more than that mentioned in Table 7.

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Table 7 – Indicative creep values of stranded conductors(25 % RTS, 20 ℃)

Type of conductor	Estimated creep after 10 years µm/m	Equivalent temperature difference °C
A1	750 to 850	35
A2, A3	450 to 500	22
A1/A2, A1/A3	580 to 650	30
A1/Sxy	490 to 550	25
A1/20SA	550 to 600	25

NOTE The calculation of temperature difference is based on the intermediate creep values of the estimated range in the table.

9 Loss of strength

The passage of electric current through a conductor causes a rise in temperature which can have an annealing effect on aluminium and a combined annealing/over-ageing effect on aluminium alloy, thus causing a loss of strength. The amount of strength that is lost depends on the temperature and the duration, and the effect is cumulative: 10 hours each year for 10 years has a similar effect to heating the conductor continuously for 100 hours at the same temperature. A cumulative duration of no less than 400 hours could be considered.

The loss of strength will vary with the method of manufacture and the values quoted in this clause are for guidance only. For aluminium alloy the information provided covers only wires which have received a heat treatment after drawing.

The percentage reduction in tensile strength of aluminium A1 at different temperatures and durations is shown in Figure 2, while Figure 3 shows the same for aluminium alloy(finally heat-treated). These figures are based on data assembled from various sources and test results. Note these values are not applicable to alloys which have not received heat treatment after drawing or before stranding.

It is normal practice to limit operating temperatures (such as 80 °C) and emergency load temperatures (such as 125 °C), depending on the conductor types and local conditions.

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