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Edition 3.0 2023-05

INTERNATIONAL STANDARD

Electric cables – Calculation of the current rating –
Part 1-1: Current rating equations (100 % load factor) and calculation of losses –
General

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IEC 60287-1-1:2023-05(en)

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Electric cables – Calculation of the current rating – Part 1-1: Current rating equations (100 % load factor) and calculation of losses – General

INTERNATIONAL ELECTROTECHNICAL COMMISSION

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ELECTRIC CABLES – CALCULATION OF THE CURRENT RATING –

Part 1-1: Current rating equations (100 % load factor) and calculation of losses – General

FOREWORD

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IEC 60287-1-1 has been prepared by IEC technical committee 20: Electric cables. It is an International Standard.

This third edition cancels and replaces the second edition published in 2006 and Amendment 1:2014. This edition constitutes a technical revision.

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

a) thorough redefinition of symbols used across the IEC 60287 and IEC 60853 series to realign and unify definitions, eliminate inconsistencies and to improve cross-use of the different parts of both IEC 60287 and IEC 60853 series;
b) introduction of corrective factors on relevant calculated physical characteristics to take into account the effect of multicore lay-lengths; a dedicated annex to highlight correction factors for different number of cores has been introduced (Annex A).

The text of this International Standard is based on the following documents:

Draft	Report on voting
20/2096/FDIS	20/2103/RVD

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 International Standard 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/publications.

A list of all parts in the IEC 60287 series, published under the general title *Electric cables – Calculation of the current rating*, can be found on the IEC website.

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

- reconfirmed,
- withdrawn,
- replaced by a revised edition, or
- amended.

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INTRODUCTION

This part of IEC 60287 contains formulae for the quantities R_C, W_d, λ_1 and λ_2.

It contains methods for calculating the permissible current rating of cables from details of the permissible temperature rise, conductor resistance, losses and thermal resistivities.

Formulae for the calculation of losses are also given.

The formulae in this document contain quantities which vary with cable design and materials used. The values given in the tables are either internationally agreed, for example, electrical resistivities and resistance temperature coefficients, or are those which are generally accepted in practice, for example, thermal resistivities and permittivities of materials. In this latter category, some of the values given are not characteristic of the quality of new cables but are considered to apply to cables after a long period of use. In order that uniform and comparable results can be obtained, the current ratings should be calculated with the values given in this document. However, where it is known with certainty that other values are more appropriate to the materials and design, then these may be used, and the corresponding current rating declared in addition, provided that the different values are quoted.

Quantities related to the operating conditions of cables are liable to vary considerably from one country to another. For instance, with respect to the ambient temperature and soil thermal resistivity, the values are governed in various countries by different considerations. Superficial comparisons between the values used in the various countries can lead to erroneous conclusions if they are not based on common criteria: for example, there can be different expectations for the life of the cables, and in some countries design is based on maximum values of soil thermal resistivity, whereas in others average values are used. Particularly, in the case of soil thermal resistivity, it is well known that this quantity is very sensitive to soil moisture content and can vary significantly with time, depending on the soil type, the topographical and meteorological conditions, and the cable loading.

The following procedure for choosing the values for the various parameters should, therefore, be adopted.

Numerical values should preferably be based on results of suitable measurements. Often such results are already included in national specifications as recommended values, so that the calculation can be based on these values generally used in the country in question; a survey of such values is given in IEC 60287-3-1.

A suggested list of the information required to select the appropriate type of cable is given in IEC 60287-3-1.

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ELECTRIC CABLES – CALCULATION OF THE CURRENT RATING –

Part 1-1: Current rating equations (100 % load factor) and calculation of losses – General

1 Scope

This part of IEC 60287 is applicable to the conditions of steady-state operation of cables at all alternating voltages, and direct voltages up to 5 kV, buried directly in the ground, in ducts, troughs or in steel pipes, both with and without partial drying-out of the soil, as well as cables in air. The term "steady state" is intended to mean a continuous constant current (100 % load factor) just sufficient to produce asymptotically the maximum conductor temperature, the surrounding ambient conditions being assumed constant.

This document provides formulae for current ratings and losses.

The formulae given are essentially literal and designedly leave open the selection of certain important parameters. These can be divided into three groups:

– parameters related to construction of a cable (for example, thermal resistivity of insulating material) for which representative values have been selected based on published work;
– parameters related to the surrounding conditions, which can vary widely, the selection of which depends on the country in which the cables are used or will be used;
– parameters which result from an agreement between manufacturer and user and which involve a margin for security of service (for example, maximum conductor temperature).

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 60228, *Conductors of insulated cables*

IEC 60287-1-3, *Electric cables – Calculation of the current rating – Part 1-3: Current rating equations (100 % load factor) and calculation of losses – Current sharing between parallel single-core cables and calculation of circulating current losses*

IEC 60287-2-1:2023, *Electric cables – Calculation of the current rating – Part 2-1: Thermal resistance – Calculation of the thermal resistance*

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3 Terms, definitions and symbols

3.1 Terms and definitions

No terms and definitions are listed in this document.

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

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

3.2 Symbols

The symbols used in this document and the quantities which they represent are given in the following list.

A_A	cross-sectional area of the armour	mm^2
B_1, B_2	coefficients (see 5.4.3)	Ω/m
C	capacitance per core	F/m
C_F	coefficient defined in 5.3.6	
C_{fL}	coefficient to take into account the position of the neutral axis of the helically wound core in Annex A	
C_{gs}	coefficient used in 5.3.7.1	
C_{LL}	length correction factor for considering laying up of cores	
C_{M1}	coefficient defined in 5.3.6	
C_N	coefficient defined in 5.3.6	
C_P	coefficient defined in 5.3.4	Ω/m
C_p	coefficient used in 5.3.7.2	
C_Q	coefficient defined in 5.3.4	Ω/m
C_q	coefficient used in 5.3.7.2	
D_e^*	external diameter of cable	m
D_i	diameter over insulation	mm
D_p^*	diameter over the individual core of a multicore cable	m
D_s	external diameter of metal sheath	mm
D_{oc}	diameter of the imaginary coaxial cylinder which just touches the crests of a corrugated sheath	mm
D_{it}	diameter of the imaginary cylinder which just touches the inside surface of the troughs of a corrugated sheath	mm
E_e	intensity of solar radiation	W/m^2
H	magnetizing force (see 5.4.3)	A/m
H_s	inductance of sheath	H/m
H_1, H_2, H_3	components of inductance due to the steel wires (see 5.4.3)	H/m
I	current in one conductor (RMS value)	A
I_S	current in sheath (RMS value)	A
L_L^*	axial cable length over which the cores make one full helical turn	m

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R_C	alternating current resistance of conductor at its maximum operating temperature per unit length of the cable	Ω/m
R_A	AC resistance of armour at its maximum operating temperature per unit length of the cable	Ω/m
R_{Ao}	AC resistance of armour at 20 °C per unit length of the cable	Ω/m
R_e	equivalent AC resistance of sheath and armour in parallel	Ω/m
R_s	AC resistance of cable sheath or screen at their maximum operating temperature per unit length of the cable	Ω/m
R_{so}	AC resistance of cable sheath or screen at 20 °C per unit length of the cable	Ω/m
R'	DC resistance of conductor at maximum operating temperature per unit length of the cable	Ω/m
R_o	DC resistance of conductor at 20 °C per unit length of the cable	Ω/m
T_1	thermal resistance per core between conductor and sheath per unit length of the cable	K · m/W
T_2	thermal resistance between sheath and armour per unit length of the cable	K · m/W
T_3	thermal resistance of external serving per unit length of the cable	K · m/W
T_4	thermal resistance of surrounding medium (ratio of cable surface temperature rise above ambient to the losses per unit length)	K · m/W
$T^{\#}_4$	thermal resistance in free air, adjusted for solar radiation	K · m/W
T_4'	thermal resistance between cable and duct (or pipe)	K · m/W
T_4''	thermal resistance of the duct (or pipe)	K · m/W
T_4'''	thermal resistance of the medium surrounding the duct (or pipe)	K · m/W
U_o	voltage between conductor and screen or sheath	V
W_A	losses in armour per unit length of the cable	W/m
W_c	losses in conductor per unit length of the cable	W/m
W_d	dielectric losses per unit length of the cable per phase	W/m
W_s	losses dissipated in sheath per unit length of the cable	W/m
$W_{(s+A)}$	total losses in sheath and armour per unit length of the cable	W/m
X	reactance of sheath (two-core cables and three-core cables in trefoil) per unit length of the cable	Ω/m
X_1	reactance of sheath (cables in flat formation)	Ω/m
X_m	mutual reactance between the sheath of one cable and the conductors of the other two when cables are in flat information	Ω/m
a	shortest minor length in a cross-bonded electrical section having unequal minor lengths	m
c	distance between the axes of conductors and the axis of the cable for three-core cables	mm
d	mean diameter of sheath or screen	mm
d'	mean diameter of sheath and reinforcement	mm

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d_2	mean diameter of reinforcement	mm
d_A	mean diameter of armour	mm
d_c	external diameter of conductor	mm
d'_c	external diameter of equivalent round solid conductor having the same central duct as a hollow conductor	mm
d_d	internal diameter of pipe	mm
d_f	diameter of a steel wire	mm
d_i	internal diameter of hollow conductor	mm
d_M	major diameter of screen or sheath of an oval conductor	mm
d_m	minor diameter of screen or sheath of an oval conductor	mm
d_x	diameter of an equivalent circular conductor having the same cross-sectional area and degree of compactness as the shaped one	mm
f	system frequency	Hz
k_f	factor used in the calculation of hysteresis losses in armour or reinforcement (see 5.4.3.4)	
k_p	factor used in calculating x_p (proximity effect)	
k_s	factor used in calculating x_s (skin effect)	
l^*	length of a cable section (general symbol, see 5.3.5)	m
ln	natural logarithm (logarithm to base e, see IEC 60027-3)	
m	parameter used in calculation of eddy-current loss factor	10^{-7} m/Ω
n	number of conductors in a cable	
n_1	number of steel wires in a cable (see 5.4.3)	
p	length of lay of a steel wire along a cable (see 5.4.3)	
r_1	circumscribing radius of two- or three-sector shaped conductors	mm
s	axial separation of conductors	mm
s_1	axial separation of two adjacent cables in a horizontal group of three, not touching	mm
s_2	axial spacing between adjacent cables in trefoil formation; for cables in flat formation s_2 is the geometric mean of the three spacings	mm
t_0	insulation thickness between conductors	mm
t_3	thickness of the serving	mm
t_s	thickness of the sheath	mm
v	ratio of the thermal resistivities of dry and moist soils ($v = \rho_d/\rho_w$)	
x_p	argument of a Bessel function used to calculate proximity effect	
x_s	argument of a Bessel function used to calculate skin effect	
y_p	proximity effect factor (see 5.1)	
y_s	skin effect factor (see 5.1)	

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α_{20}	temperature coefficient of electrical resistivity at 20 °C, per kelvin	I/K
β_1	coefficient used in 5.3.7.1	
β_2	angle between axis of armour wires and axis of cable (see 5.4.3)	
γ	angular time delay (see 5.4.3)	
Δ_1, Δ_2	coefficients used in 5.3.7.1	
δ_A	equivalent thickness of armour or reinforcement	mm
$\tan\delta$	loss factor of insulation	
ε	relative permittivity of insulation	
ε_0	permittivity of vacuum	F/m
θ	maximum operating temperature of conductor	°C
θ_a	ambient temperature	°C
θ_{ar}	maximum operating temperature of armour	°C
θ_{sc}	maximum operating temperature of cable screen or sheath	°C
θ_x	critical temperature of soil; this is the temperature of the boundary between dry and moist zones	°C
$\Delta\theta$	permissible temperature rise of conductor above ambient temperature	K
$\Delta\theta_x$	critical temperature rise of soil; this is the temperature rise of the boundary between dry and moist zones above the ambient temperature of the soil	K
λ_0	coefficient used in 5.3.7.1	
λ_1, λ_2	ratio of the total losses in metallic sheaths and armour respectively to the total conductor losses (or losses in one sheath or armour to the losses in one conductor)	
λ'_1	ratio of the losses in one sheath caused by circulating currents in the sheath to the losses in one conductor	
λ''_1	ratio of the losses in one sheath caused by eddy currents to the losses in one conductor	
λ'_{1m}	loss factor for the middle cable of three cables in flat formation without transposition, with sheaths bonded at both ends	
λ'_{11}	loss factor for the outer cable with the greater losses of three cables in flat formation without transposition, with sheaths bonded at both ends	
λ'_{12}	loss factor for the outer cable with the least losses of three cables in flat formation without transposition, with sheaths bonded at both ends	
μ	relative magnetic permeability of armour material	
μ_e	longitudinal relative permeability	
μ_t	transverse relative permeability	
ρ_{20}	conductor resistivity at 20 °C	Ω · m
ρ_d	thermal resistivity of dry soil	K · m/W
ρ_w	thermal resistivity of moist soil	K · m/W

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ρ_s	sheath resistivity at 20 °C	Ω · m
σ	absorption coefficient of solar radiation for the cable surface	
ω	angular frequency of system ($2\pi f$)	

4 Permissible current rating of cables

4.1 General

When the permissible current rating is being calculated under conditions of partial drying out of the soil, it is also necessary to calculate a rating for conditions where drying out of the soil does not occur. The lower of the two ratings shall be used.

4.2 Buried cables where drying out of the soil does not occur or cables in air

4.2.1 AC cables

The permissible current rating of an AC cable can be derived from the expression for the temperature rise above ambient temperature:

$$\Delta\theta = (I^2 R_C + \frac{1}{2} W_d) T_1 + n[I^2 R_C (1+\lambda_1) + W_d] T_2 + n[I^2 R_C (1+\lambda_1+\lambda_2) + W_d](T_3 + T_4) \qquad (1)$$

where

I is the current flowing in one conductor (A);

$\Delta\theta$ is the conductor temperature rise above the ambient temperature (K);

NOTE The ambient temperature is the temperature of the surrounding medium under normal conditions, at a situation in which cables are installed, or will be installed, including the effect of any local source of heat, but not the increase of temperature in the immediate neighbourhood of the cables due to heat arising therefrom.

R_C is the alternating current resistance per unit length of the cable at maximum operating temperature (Ω/m);

W_d is the dielectric loss per unit length of the cable for the insulation surrounding the conductor (W/m);

T_1 is the thermal resistance per unit length of the cable between one conductor and the sheath (K · m/W);

T_2 is the thermal resistance per unit length of the cable of the bedding between sheath and armour (K · m/W);

T_3 is the thermal resistance per unit length of the cable of the external serving of the cable (K · m/W);

T_4 is the thermal resistance per unit length between the cable surface and the surrounding medium, as derived from IEC 60287-2-1 (K · m/W);

n is the number of load-carrying conductors in the cable (conductors of equal size and carrying the same load);

λ_1 is the ratio of losses in the metal sheath to total losses in all conductors in that cable;

λ_2 is the ratio of losses in the armouring to total losses in all conductors in that cable.

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The permissible current rating is obtained from Formula (1) as follows:

$$I = \left[\frac{\Delta\theta - W_d \left[0,5\ T_1 + n\ (T_2 + T_3 + T_4)\right]}{R_C T_1 + nR_C\ (1+\lambda_1)\ T_2 + nR_C\ (1+\lambda_1+\lambda_2)\ (T_3 + T_4)} \right]^{0,5} \quad (2)$$

Where the cable is exposed to direct solar radiation, the formulae given in IEC 60287-2-1:2023, 4.2.1.2 shall be used.

The current rating for a four-core low-voltage cable may be taken to be equal to the current rating of a three-core cable for the same voltage and conductor size having the same construction, provided that the cable is used in a three-phase system where the fourth conductor is either a neutral conductor or a protective conductor. When it is a neutral conductor, the current rating applies to a balanced load.

4.2.2 DC cables up to 5 kV

The permissible current rating of a DC cable is obtained from the following simplification of the AC Formula (2):

$$I = \left[\frac{\Delta\theta}{R' T_1 + nR' T_2 + nR'(T_3 + T_4)} \right]^{0,5}$$

where

R' is the direct current resistance per unit length of the cable at maximum operating temperature (Ω/m).

Where the cable is exposed to direct solar radiation, the formulae given in IEC 60287-2-1:2023, 4.2.1.2 shall be used.

4.3 Buried cables where partial drying-out of the soil occurs

4.3.1 AC cables

The following method shall be applied to a single isolated cable or circuit only, laid at conventional depths. The method is based on a simple two-zone approximate physical model of the soil where the zone adjacent to the cable is dried out whilst the other zone retains the site's thermal resistivity, the zone boundary being on isotherm[1]. This method is considered to be appropriate for those applications in which soil behaviour is considered in simple terms only.

NOTE 1 Installations of more than one circuit as well as the necessary spacing between circuits are under consideration.

Changes in external thermal resistance, consequent to the formation of a dry zone around a single isolated cable or circuit, shall be obtained from the following Formula (3), compared with Formula (2):

$$I = \left[\frac{\Delta\theta - W_d \left[0,5\ T_1 + n\ (T_2 + T_3 + vT_4) + (v-1)\Delta\theta_x\right]}{R_C [T_1 + n(1+\lambda_1)\ T_2 + n(1+\lambda_1+\lambda_2)\ (T_3 + vT_4)]} \right]^{0,5} \quad (3)$$

[1] "Current ratings of cables buried in partially dried-out soil, Part 1": *Electra* No. 104, p. 11, January 1966 (in particular section 3 and Appendix 1).

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where

v is the ratio of the thermal resistivities of the dry and moist soil zones $(v = \rho_d / \rho_w)$;

R_C is the AC resistance of the conductor at its maximum operating temperature per unit length of the cable (Ω/m);

ρ_d is the thermal resistivity of the dry soil (K · m/W);

ρ_w is the thermal resistivity of the moist soil (K · m/W);

θ_x is the critical temperature of the soil and temperature of the boundary between dry and moist zones (°C);

θ_a is the ambient temperature (°C);

$\Delta\theta_x$ is the critical temperature rise of the soil. This is the temperature rise of the boundary between the dry and moist zones above the ambient temperature of the soil $(\theta_x - \theta_a)$ (K);

T_4 is calculated using the thermal resistivity of the moist soil (ρ_w) using IEC 60287-2-1:2023, 4.2.3.3. Mutual heating by modification of the temperature rise as in IEC 60287-2-1:2023, 4.2.3.2 cannot be applied.

θ_x and ρ_d shall be determined from a knowledge of the soil conditions.

NOTE 2 The choice of suitable soil parameters is under consideration. In the meantime, values can be agreed between the manufacturer and purchaser.

4.3.2 DC cables up to 5 kV

The permissible current rating of a DC cable is obtained from the following simplification of the AC Formula (3):

$$I = \left[\frac{\Delta\theta + (v-1)\,\Delta\theta_x}{R'\left[T_1 + nT_2 + n\,(T_3 + vT_4)\right]} \right]^{0,5}$$

where

R' is the direct current resistance per unit length of the cable at maximum operating temperature (Ω/m).

When considering cable installations in pipes or ducts, the thermal resistance of the surrounding medium T_4 is composed by three additive contributions of thermal resistances, i. e. that of the medium inside the pipe, the pipe itself and the ambient medium around the pipe T_4', T_4'' and T_4''', see IEC 60287-2-1. In that case only the contribution T_4''' is affected by drying out of the soil and in the above two formulae the term vT_4 shall be replaced by the term $T_4' + T_4'' + vT_4'''$.

4.4 Buried cables where drying-out of the soil shall be avoided

4.4.1 AC cables

Where it is desired that moisture migration be avoided by limiting the temperature rise of the cable surface to not more than $\Delta\theta_x$, the corresponding rating shall be obtained from:

$$I = \left[\frac{\Delta\theta_x - nW_d T_4}{nR_C T_4 \left(1 + \lambda_1 + \lambda_2\right)} \right]^{0,5} \tag{4}$$

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However, depending on the value of $\Delta\theta_x$ this can result in a conductor temperature which exceeds the maximum permissible value. The current rating used shall be the lower of the two values obtained, either from the above Equation (4) or from Equation (1).

The conductor resistance R_C shall be calculated for the appropriate conductor temperature, which can be less than the maximum permitted value. An estimate of the operating temperature shall be made and, if necessary, subsequently amended.

NOTE For four-core low-voltage cables, see the final paragraph in 4.2.1.

4.4.2 DC cables up to 5 kV

The permissible current rating of a DC cable shall be obtained from the following simplification of the AC Formula (4):

$$I = \left[\frac{\Delta\theta_x}{nR' T_4} \right]^{0,5}$$

The conductor resistance R' shall be modified as in 4.3.2.

4.5 Cables directly exposed to solar radiation

4.5.1 General

Taking into account the effect of solar radiation on a cable, the permissible current rating is given by Formulae (5) and (6):

4.5.2 AC cables

$$I = \left[\frac{\Delta\theta - W_d \left[0,5\, T_1 + n\,(T_2 + T_3 + T_4^{\#}) \right] - \sigma\, D_e^{*}\, E_e\, T_4^{\#}}{R_C T_1 + nR_C\,(1+\lambda_1)\, T_2 + nR_C\,(1+\lambda_1+\lambda_2)\,(T_3 + T_4^{\#})} \right]^{0,5} \tag{5}$$

DC cables up to 5 kV

$$I = \left[\frac{\Delta\theta - \sigma\, D_e^{*}\, E_e\, T_4^{\#}}{R'\, T_1 + nR'\, T_2 + nR'\,(T_3 + T_4^{\#})} \right]^{0,5} \tag{6}$$

where

σ is the absorption coefficient of solar radiation for the cable surface (see Table 4);

E_e is the intensity of solar radiation which should be taken as 1 000 W/m^2 for most latitudes; it is recommended that the local value be obtained where possible;

$T_4^{\#}$ is the external thermal resistance of the cable in free air, adjusted to take account of solar radiation (see IEC 60287-2-1) (K · m/W);

D_e^{*} is the external diameter of the cable (m) for corrugated sheaths
$D_e^{*} = (D_{oc} + 2t_3) \cdot 10^{-3}$ (m);

t_3 is the thickness of the serving (mm).

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5 Calculation of losses

5.1 AC resistance of conductor

5.1.1 General

The AC resistance per unit length of the cable at its maximum operating temperature is given by the following Formula (7), except in the case of pipe-type cables (see 5.1.6):

$$R_C = R'(1 + y_s + y_p) \qquad (7)$$

where

R_C is the alternating current resistance of the conductor at maximum operating temperature per unit length of the cable (Ω/m);

R' is the DC resistance of the conductor at maximum operating temperature per unit length of the cable (Ω/m);

y_s is the skin effect factor;

y_p is the proximity effect factor.

5.1.2 DC resistance of conductor

The DC resistance per unit length of the cable at its maximum operating temperature θ is given by:

$$R' = R_o[1 + \alpha_{20}(\theta - 20\text{K})]$$

where

R_o is the DC resistance of the conductor at 20 °C per unit length of the cable (Ω/m);

The value of R_o shall be derived directly from IEC 60228. Where the conductor size is outside the range covered by IEC 60228, the value of R_o can be chosen by agreement between the manufacturer and purchaser. The conductor resistance should then be calculated using the values of resistivity given in Table 1 and considering the length of the conductor in the finished cable, see also Annex A.

α_{20} is the constant mass temperature coefficient at 20 °C per kelvin (see Table 1 for standard values);

θ is the maximum operating temperature in degrees Celsius (this will be determined by the type of insulation to be used); see appropriate IEC specification or national standard.

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5.1.3 Skin effect factor y_s

The skin effect factor y_s is given by the following equations:

For $0 < x_s \leq 2{,}8$

$$y_s = \frac{x_s^4}{192 + 0{,}8\, x_s^4}$$

For $2{,}8 < x_s \leq 3{,}8$

$$y_s = -0{,}136 - 0{,}0177 x_s + 0{,}0563 x_s^2$$

For $x_s > 3{,}8$

$$y_s = 0{,}354 x_s - 0{,}733$$

where

$x_s^2 = \frac{8\pi f}{R'} 10^{-7} k_s$;

f is the supply frequency in Hz.

Values for k_s are given in Table 2.

In the absence of alternative formulae, it is recommended that the formulae in 5.1.3 be used also for sector and oval-shaped conductors.

5.1.4 Proximity effect factor y_p for two-core cables and for two single-core cables

The proximity effect factor is given by:

$$y_p = \frac{x_p^4}{192 + 0{,}8\, x_p^4} \left(\frac{d_c}{s}\right)^2 \times 2{,}9$$

where

$x_p^2 = \frac{8\pi f}{R'} 10^{-7} k_p$;

d_c is the diameter of the conductor (mm);

s is the distance between conductor axes (mm).

Values for k_p are given in Table 2.

The formulae in 5.1.4 are accurate providing x_p does not exceed 2,8, and therefore applies to the majority of practical cases.

5.1.5 Proximity effect factor y_p for three-core cables and for three single-core cables

5.1.5.1 Circular conductor cables

The proximity effect factor is given by:

$$y_p = \frac{x_p^4}{192 + 0{,}8\, x_p^4} \left(\frac{d_c}{s}\right)^2 \left[0{,}312 \left(\frac{d_c}{s}\right)^2 + \frac{1{,}18}{\frac{x_p^4}{192 + 0{,}8\, x_p^4} + 0{,}27}\right]$$

where

$x_p^2 = \frac{8\pi f}{R'} 10^{-7} k_p$;

d_c is the diameter of the conductor (mm);

s is the distance between conductor axes (mm).

For cables in flat formation, s is the spacing between adjacent phases. Where the spacing between adjacent phases is not equal, the distance will be taken as $s = \sqrt{s_1 \times s_2}$.

Values for k_p are given in Table 2.

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The formulae in 5.1.5.1 are accurate provided x_p does not exceed 2,8, and therefore applies to the majority of practical cases.

5.1.5.2 Shaped conductor cables

In the case of multicore cables with shaped conductors, the value of y_p shall be two-thirds of the value calculated according to 5.1.5.1,

with:

$d_c = d_x =$ diameter of an equivalent circular conductor of the same cross-sectional area, and degree of compaction (mm);

$s = (d_x + t_0)$ (mm),

where

t_0 is the thickness of insulation between conductors (mm).

Values for k_p are given in Table 2.

This calculation is accurate provided x_p does not exceed 2,8, and therefore applies to the majority of practical cases.

5.1.6 Skin and proximity effects in pipe-type cables

For pipe-type cables, the skin and proximity effects calculated according to 5.1.3, 5.1.4 and 5.1.5 shall be increased by a factor of 1,5. For these cables,

$$R_C = R'\left[1 + 1{,}5\left(y_s + y_p\right)\right] \quad (\Omega/\text{m})$$

5.2 Dielectric losses (applicable to AC cables only)

The dielectric loss is voltage dependent and thus only becomes important at voltage levels related to the insulation material being used.

The dielectric loss should be taken into account for values of U_0 equal to or higher than the following:

38 kV	for cables with solid-type impregnated paper insulation;
63,5 kV	for oil-filled and gas-pressure cables;
18 kV	for butyl rubber insulated cables;
63,5 kV	for EPR insulated cables;
6 kV	for PVC insulated cables;
127 kV	for PE (HD and LD) insulated cables;
127 kV	for XLPE (unfilled) insulated cables;
63,5 kV	for XLPE (filled) insulated cables.

It is not necessary to calculate the dielectric loss for unscreened multicore or DC cables.

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The dielectric loss per unit length of cable in each phase is given by:

$$W_d = \omega C U_0^2 \tan\delta \quad \text{(W/m)}$$

where

ω = $2\pi f$;

C is the capacitance per unit length of a cable (F/m);

U_0 is the voltage to earth (V).

Values of tan δ, the loss factor of the insulation at power frequency and operating temperature, are given in Table 3.

The capacitance for cylindrical screens around circular conductors is given by:

$$C = \frac{2\pi\varepsilon_0\varepsilon}{\ln\left(\frac{D_i}{d_c}\right)} C_{LL} \quad \text{(F/m)}$$

where

ε_0 is the permittivity of the vacuum $\approx 8{,}854 \cdot 10^{-12}$ F/m;

ε is the relative permittivity of the insulation;

D_i is the external diameter of the insulation (excluding screen) (mm);

d_c is the diameter of the conductor, including screen, if any (mm).

C_{LL} is the length correction factor for considering laying up cores. The calculation is given in Annex A.

The same formula can be used for oval conductors if the geometric mean of the appropriate major and minor diameters is substituted for D_i and d_c.

Values of ε are given in Table 3.

5.3 Loss factor for sheath and screen (applicable to power frequency AC cables only)

5.3.1 General

The power loss in the sheath or screen (λ_1) consists of losses caused by circulating currents (λ_1') and eddy currents (λ_1''),

thus:

$$\lambda_1 = \lambda_1' + \lambda_1''$$

The formulae given in this Subclause 5.3 express the loss in terms of the total power loss in the conductor(s) and for each particular case it is indicated which type of loss shall be considered. The formulae for single-core cables apply to single circuits only and the effects of earth return paths are neglected. Methods are given for both smooth-sided and corrugated sheaths.

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For single-core cables with sheaths bonded at both ends of an electrical section, only the loss due to circulating currents in the sheaths shall be considered (see 5.3.2, 5.3.3 and 5.3.4). An electrical section is defined as a portion of the route between points at which the sheaths or screens of all cables are solidly bonded.

To consider the effect of different spacing of certain spans along the route, see 5.3.5

For cables with Milliken conductors, the loss factor should be increased to take account of the loss due to eddy currents in the sheaths (see 5.3.6).

For a cross-bonded installation, it is considered unrealistic to assume that minor sections are electrically identical and that the loss due to circulating currents in the sheaths is negligible. Recommendations are made in 5.3.7 for augmenting the losses in the sheaths to take account of this electrical unbalance.

The electrical resistivities and temperature coefficients of lead and aluminium, for use in calculating the resistance of the sheath R_s are given in Table 1.

The formulae given in this Subclause 5.3 use the resistance of the sheath or screen at its maximum operating temperature. The maximum operating temperature of the sheath or screen is given by:

$$\theta_{sc} = \theta - \left(I^2 R_C + 0{,}5 W_d\right) T_1 \quad (°C)$$

where

θ_{sc} is the maximum operating temperature of the cable screen or sheath (°C).

Because the temperature of the sheath or screen is a function of the current, I, an iterative method is used for the calculation.

The resistance of the sheath or screen at its maximum operating temperature is given by:

$$R_s = R_{so}\left[1 + \alpha_{20}\left(\theta_{sc} - 20\text{K}\right)\right] \quad (\Omega/\text{m})$$

where

R_{so} is the resistance of the cable sheath or screen at 20 °C per unit length of the cable (Ω/m).

5.3.2 Two single-core cables, and three single-core cables (in trefoil formation), sheaths bonded at both ends of an electrical section

For two single-core cables, and three single-core cables (in trefoil formation) with sheaths bonded at both ends, the loss factor is given by:

$$\lambda_1' = \frac{R_s}{R_C} \frac{1}{1 + \left(\frac{R_s}{X}\right)^2}$$

where

R_s is the resistance of the sheath or screen per unit length of cable at its maximum operating temperature (Ω/m);

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X is the reactance per unit length of sheath or screen per unit length of cable, $2\ \omega\ 10^{-7}\ \ln\left(\frac{2s}{d}\right)$ (Ω/m);

ω is $2\ \pi \times$ frequency (1/s);

s is the distance between conductor axes in the electrical section being considered (mm);

d is the mean diameter of the sheath (mm);

– for oval-shaped cores, d is given by $\sqrt{d_M \cdot d_m}$ where d_M and d_m are the major and minor mean diameters respectively of the sheath or screen;

– for corrugated sheaths, d is given by ½ (D_{oc} + D_{it}).

λ_1'' = 0, i.e. eddy-current loss is ignored, except for cables having Milliken conductors when λ_1'' is calculated by the method given in 5.3.6.

5.3.3 Three single-core cables in flat formation, with regular transposition, sheaths bonded at both ends of an electrical section

For three single-core cables in flat formation, with the middle cable equidistant from the outer cables, regular transposition of the cables and the sheaths bonded at every third transposition, the loss factor is given by:

$$\lambda_1' = \frac{R_S}{R_C} \frac{1}{1+\left(\frac{R_S}{X_1}\right)^2}$$

where

X_1 is the reactance per unit length of sheath, $2\omega 10^{-7}\ ln\left\{2\sqrt[3]{2}\left(\frac{s}{d}\right)\right\}$ (Ω/m);

λ_1'' = 0, i.e. eddy-current loss is ignored, except for cables having Milliken conductors when λ_1'' is calculated by the method given in 5.3.6.

5.3.4 Three single-core cables in flat formation, without transposition, sheaths bonded at both ends of an electrical section

For three single-core cables in flat formation, with the middle cable equidistant from the outer cables, without transposition and with the sheaths bonded at both ends of an electrical section, the loss factor for the cable which has the greatest loss (i.e. the outer cable carrying the lagging phase) is given by:

$$\lambda_{11}' = \frac{R_S}{R_C}\left[\frac{0{,}75\,C_P^2}{R_S^2+C_P^2} + \frac{0{,}25\,C_Q^2}{R_S^2+C_Q^2} + \frac{2\,R_S\,C_P\,C_Q\,X_m}{\sqrt{3}(R_S^2+C_P^2)\,(R_S^2+C_Q^2)}\right] \quad (8)$$

For the other outer cable, the loss factor is given by:

$$\lambda_{12}' = \frac{R_S}{R_C}\left[\frac{0{,}75\,C_P^2}{R_S^2+C_P^2} + \frac{0{,}25\,C_Q^2}{R_S^2+C_Q^2} - \frac{2\,R_S\,C_P\,C_Q\,X_m}{\sqrt{3}\,(R_S^2+C_P^2)\,(R_S^2+C_Q^2)}\right] \quad (9)$$

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For the middle cable, the loss factor is given by:

$$\lambda'_{1m} = \frac{R_s}{R_C} \frac{C_Q^2}{R_s^2 + C_Q^2} \tag{10}$$

In these Formulae (8), (9) and (10):

$$C_P = X + X_m$$

$$C_Q = X - \frac{X_m}{3}$$

where

X is the reactance of the sheath or screen per unit length of cable for two adjacent single-core cables, $2\,\omega\,10^{-7}\ \ln\left(\frac{2s}{d}\right)$ (Ω/m);

X_m is the mutual reactance per unit length of cable between the sheath of an outer cable and the conductors of the other two, when the cables are in flat formation, $2\,\omega\,10^{-7}\ \ln(2)$ (Ω/m);

λ''_1 = 0, i.e. eddy-current loss is ignored, except for cables having Milliken conductors when λ''_1 is calculated by the method given in 5.3.6.

Ratings for cables in air should be based on the loss for the outer cable carrying the lagging phase.

5.3.5 Variation of spacing of single-core cables between sheath bonding points

For single-core cable circuits with sheaths solidly bonded at both ends and possibly at intermediate points, the circulating currents and the consequent loss increase as the spacing increases, and it is advisable to use as close a spacing as possible. The optimum spacing is achieved by considering both losses and mutual heating between cables.

It is not always possible to install cables with one value of spacing all along a route. The following recommendations relate to the calculation of sheath circulating current losses when it is not possible to install cables with a constant value of spacing over the length of one electrical section. A section is defined as a portion of the route between points at which sheaths of all cables are solidly bonded. The recommendations below give values for loss factors which apply to the whole of a section, but it should be noted that the appropriate values of conductor resistance and external thermal resistance shall be calculated on the basis of the closest cable spacing at any place along the section.

a) Where spacing along a section is not constant but the various values are known, the value for X in 5.3.2, 5.3.3 and 5.3.4 shall be derived from:

$$X = \frac{l_a^* X_a + l_b^* X_b + \ldots + l_n^* X_n}{l_a^* + l_b^* + \ldots + l_n^*}$$

where

$l_a^*, l_b^* \ldots l_n^*$ are lengths with different spacings along an electrical section;

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$X_a, X_b \dots X_n$ are the reactances per unit length of cable, the relevant formulae being given in 5.3.2, 5.3.3 and 5.3.4 where appropriate values of spacings $s_a, s_b \dots s_n$ are used.

The proposed formula is an approximation. If more detailed results are required, the user shall refer to IEC 60287-1-3. For mixed formations, that comprise flat and trefoil sections, the user shall refer to IEC 60287-1-3.

b) Where in any section the spacing between cables and its variation along the route are not known and cannot be anticipated, the losses in that section, calculated from the design spacing, shall be arbitrarily increased by 25 %, this value having been found to be appropriate for lead-sheathed HV cables. A different increase can be used by agreement if it is considered that 25 % is not appropriate to a particular installation.

c) Where the section includes a spread-out end, it is possible that the allowance in b) will not be sufficient and it is recommended that an estimate of the probable spacing be made and the loss calculated by the procedure given in a) above.

NOTE This increase does not apply to installations with single-point bonding or cross-bonding (see 5.3.7).

5.3.6 Effect of Milliken conductors

Where the conductors are subjected to a reduced proximity effect, as with Milliken conductors, the sheath loss factor λ_1'' of 5.3.2, 5.3.3 and 5.3.4 cannot be ignored, but shall be obtained by multiplying the value of λ_1'', obtained from 5.3.7 for the same cable configuration, by the factor C_F given by the formula:

$$C_F = \frac{4\, C_{M1}^2 C_N^2 + (C_{M1} + C_N)^2}{4\,(C_{M1}^2 + 1)\,(C_N^2 + 1)}$$

where

$C_{M1} = C_N = \frac{R_s}{X}$ for cables in trefoil formation

and

$C_{M1} = \frac{R_s}{X + X_m}$ and $C_N = \frac{R_s}{X - \frac{X_m}{3}}$ for cables in flat formation with equidistant spacing.

Where the spacing along a section is not constant the value of X shall be calculated as in 5.3.5 a).

5.3.7 Single-core cables, with sheaths bonded at a single point or cross-bonded

5.3.7.1 Eddy-current losses

For single-core cables with sheaths bonded at a single point or cross-bonded the eddy-current loss factor is given by:

$$\lambda_1'' = \frac{R_s}{R_C}\left[C_{gs}\, \lambda_0\, (1 + \Delta_1 + \Delta_2) + \frac{(\beta_1\, t_s)^4}{12 \times 10^{12}} \right]$$

where

$$C_{gs} = 1 + \left(\frac{t_s}{D_s}\right)^{1{,}74} (\beta_1\, D_s\, 10^{-3} - 1{,}6);$$

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$\beta_1 = \sqrt{\dfrac{4\pi\omega}{10^7\,\rho_s}}$;

ρ_s is the electrical resistivity of the sheath material at operating temperature (see Table 1) (Ω m);

D_s is the external diameter of the cable sheath (mm);

For corrugated sheaths, the mean outside diameter $\dfrac{D_{oc}+D_{it}}{2}+t_s$ shall be used.

t_s is the thickness of the sheath (mm);

ω = $2\pi f$;

For lead-sheathed cables, C_{gs} can be taken as unity and $\dfrac{(\beta_1 t_s)^4}{12\times 10^{12}}$ can be neglected.

For aluminium sheathed cables, it can be necessary for both terms to be evaluated when the sheath diameter is greater than approximately 70 mm or the sheath is thicker than usual.

For cables with a wire screen and an equalizing tape, or foil screen over the wires, the eddy-current losses are considered negligible.

Formulae for λ_0, Δ_1 and Δ_2 are given below:

(in which: $m = \dfrac{\omega}{R_s}10^{-7}$, for $m \le 0{,}1$, Δ_1 and Δ_2 can be neglected)

1) Three single-core cables in trefoil formation:

$$\lambda_0 = 3\left(\frac{m^2}{1+m^2}\right)\left(\frac{d}{2s}\right)^2$$

$$\Delta_1 = (1{,}14m^{2{,}45} + 0{,}33)\left(\frac{d}{2s}\right)^{(0{,}92\,m+1{,}66)}$$

$$\Delta_2 = 0$$

2) Three single-core cables, flat formation:

a) centre cable:

$$\lambda_0 = 6\left(\frac{m^2}{1+m^2}\right)\left(\frac{d}{2s}\right)^2$$

$$\Delta_1 = 0{,}86m^{3{,}08}\left(\frac{d}{2s}\right)^{(1{,}4\,m+0{,}7)}$$

$$\Delta_2 = 0$$

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b) outer cable leading phase:

$$\lambda_0 = 1{,}5\left(\frac{m^2}{1+m^2}\right)\left(\frac{d}{2s}\right)^2$$

$$\Delta_1 = 4{,}7m^{0{,}7}\left(\frac{d}{2s}\right)^{(0{,}16m+2)}$$

$$\Delta_2 = 21m^{3{,}3}\left(\frac{d}{2s}\right)^{(1{,}47m+5{,}06)}$$

c) outer cable lagging phase:

$$\lambda_0 = 1{,}5\left(\frac{m^2}{1+m^2}\right)\left(\frac{d}{2s}\right)^2$$

$$\Delta_1 = -\frac{0{,}74\,(m+2)\,m^{0{,}5}}{2+(m-0{,}3)^2}\left(\frac{d}{2s}\right)^{(m+1)}$$

$$\Delta_2 = 0{,}92m^{3{,}7}\left(\frac{d}{2s}\right)^{(m+2)}$$

5.3.7.2 Circulating current losses

The circulating current loss is zero for installations where the sheaths are single-point bonded, and for installations where the sheaths are cross-bonded and each major section is divided into three electrically identical minor sections.

Where a cross-bonded installation contains sections whose unbalance is not negligible, a residual voltage is produced which results in a circulating current loss in that section which shall be taken into account.

For installations where the actual lengths of the minor sections are known, the loss factor λ_1' can be calculated by multiplying the circulating current loss factor for the cable configuration concerned, calculated as if it were bonded and earthed at both ends of each major section without cross-bonding by:

$$\frac{C_\text{p}^2 + C_\text{q}^2 + 1 - C_\text{p} - C_\text{p}C_\text{q} - C_\text{q}}{\left(C_\text{p} + C_\text{q} + 1\right)^2} \quad (11)$$

Where in any major section, the two longer minor sections are C_p and C_q times the length of the shortest minor section (i.e. the minor section lengths are a, $C_\text{p}a$ and $C_\text{q}a$, where the shortest section is a).

This Formula (11) deals only with differences in the length of minor sections.

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Any variations in spacing shall also be taken into account.

Where lengths of the minor sections are not known, C_p should be set to 1 and C_q to 1,2, this gives a value of 0,004.

5.3.8 Two-core unarmoured cables with common sheath

For a two-core unarmoured cable where the cores are contained in a common metallic sheath, λ_1' is negligible and the loss factor is given by one of the following Formulae (12) and (13):

– for round or oval conductors:

$$\lambda_1'' = \frac{16\omega^2\, 10^{-14}}{R_C\, R_s}\left(\frac{c}{d}\right)^2\left[1+\left(\frac{c}{d}\right)^2\right] \tag{12}$$

– for sector-shaped conductors:

$$\lambda_1'' = \frac{10{,}8\omega^2\, 10^{-16}}{R_C\, R_s}\left(\frac{1{,}48 r_1 + t_0}{d}\right)^2\left[12{,}2+\left(\frac{1{,}48 r_1 + t_0}{d}\right)^2\right] \tag{13}$$

where

ω = $2\pi f$;

f is the frequency (Hz);

c is the distance between the axis of one conductor and the axis of the cable (mm);

r_1 is the radius of the circle circumscribing the two sector-shaped conductors (mm);

d is the mean diameter of the sheath (mm);

– for oval-shaped cores, d is given by $\sqrt{d_M \cdot d_m}$ where d_M and d_m are the major and minor mean diameters respectively;

– for corrugated sheaths, d is given by ½ (D_{oc} + D_{it}).

5.3.9 Three-core unarmoured cables with common sheath

For a three-core unarmoured cable where the cores are contained in a common metallic sheath, λ_1' is negligible and the loss factor is, therefore, given by one of the following Formulae (14), (15) and (16):

– for round or oval conductors, and where the sheath resistance R_s is less than or equal to 100 µΩ/m:

$$\lambda_1'' = \frac{3 R_s}{R_C}\left[\left(\frac{2c}{d}\right)^2 \frac{1}{1+\left(\frac{R_s}{\omega}10^7\right)^2} + \left(\frac{2c}{d}\right)^4 \frac{1}{1+4\left(\frac{R_s}{\omega}10^7\right)^2}\right] \tag{14}$$

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– for round or oval conductors, and where the sheath resistance R_s is greater than 100 μΩ/m:

$$\lambda_1'' = \frac{3{,}2\,\omega^2}{R_C\,R_s}\left(\frac{2c}{d}\right)^2 10^{-14} \tag{15}$$

– for sector-shaped conductors, and R_s any value:

$$\lambda_1'' = 0{,}94\,\frac{R_s}{R_C}\left(\frac{2r_1+t_0}{d}\right)^2 \frac{1}{1+\left(\frac{R_s}{\omega}10^7\right)^2} \tag{16}$$

where

c is the distance between the axes of conductors and the axis of the cable for three-core cables (mm);

r_1 is the radius of the circle circumscribing the three shaped conductors (mm);

t_0 is the thickness of insulation between conductors (mm);

d is the mean diameter of the sheath (mm);

- for oval-shaped cores, d is given by $\sqrt{d_M \cdot d_m}$ where d_M and d_m are the major and minor mean diameters respectively of the sheath or screen;
- for corrugated sheaths, d is given by ½ $(D_{oc} + D_{it})$.

5.3.10 Two-core and three-core cables with steel tape armour

The addition of steel tape armour increases the eddy-current loss in the sheath. The values for λ_1'' given in 5.3.8 and 5.3.9 should be multiplied by the following factor if the cable has steel-tape armour:

$$\left[1+\left(\frac{d}{d_A}\right)^2 \frac{1}{1+\frac{d_A}{\mu\delta_A}}\right]^2$$

where

d_A is the mean diameter of the armour (mm);

μ is the relative permeability of the steel tape (usually taken as 300);

δ_A is the equivalent thickness of the armour = $\frac{A_A}{\pi\,d_A}$ (mm);

where A_A is the cross-sectional area of the armour (mm²).

This correction is only known to be applicable to tapes 0,3 mm to 1,0 mm thick.

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5.3.11 Cables with each core in a separate metallic sheath (SL type) and armoured

For a three-core cable of which each core has a separate metallic sheath λ_1'' is zero and the loss factor for the sheaths is given by:

$$\lambda_1' = \frac{R_S}{R_C} \frac{1{,}5}{1+\left(\frac{R_S}{X}\right)^2}$$

where

$X = 2\omega 10^{-7} \ln\left(\frac{2s}{d}\right) C_{LL}$ (Ω/m);

s is the distance between conductor axes (mm).

C_{LL} is the length correction factor for considering laying up cores. The calculation is given in Annex A.

The loss factor for unarmoured cables with each core in a separate metallic sheath is obtained from 5.3.2.

5.3.12 Losses in screen and sheaths of pipe-type cables

If each conductor of a pipe-type cable has a screen only over the insulation, for example a lead sheath or copper tape, the ratio of the screen loss to the conductor loss may be calculated by the formula given in 5.3.2 for the sheath of a single-core cable, provided that the formula is corrected for the additional loss caused by the presence of the steel pipe and considering the unit length of the cable when calculating the reactance X.

This modifies the formula to:

$$\lambda_1' = \frac{R_S}{R_C} \frac{1{,}5}{1+\left(\frac{R_S}{X}\right)^2}$$

If each core has a diaphragm sheath and non-magnetic reinforcement, the same formula is used, but the resistance R_S is replaced by the parallel combination of the resistance of the sheath and reinforcement. The diameter d is replaced by the value d':

$$d' = \sqrt{\frac{d^2 + d_2^2}{2}}$$

where

d' is the mean diameter of the sheath and reinforcement (mm);

d is the mean diameter of the screen or sheath (mm);

d_2 is the mean diameter of the reinforcement (mm).

In the case of oval-shaped cores d and d_2 are given by $\sqrt{d_M \cdot d_m}$ where d_M and d_m are the major and minor mean diameters respectively of the sheath or screen.

NOTE See also 5.4.3.

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5.4 Loss factor for armour, reinforcement and steel pipes (applicable to power frequency AC cables only)

5.4.1 General

The formulae given in this Subclause 5.4 express the power loss occurring in metallic armour, reinforcement or steel pipes of a cable in terms of an increment λ_2 of the power loss in all conductors.

Appropriate values of electrical resistivity and resistance temperature coefficients for the materials used for armour and reinforcement are given in Table 1.

The formulae given in this Subclause 5.4 use the resistance of the armour at its maximum operating temperature. The maximum operating temperature of the armour is given by:

$$\theta_{\mathrm{ar}} = \theta - \left\{ \left(I^2 R_{\mathrm{C}} + 0{,}5\ W_{\mathrm{d}} \right) T_1 + \left[I^2 R_{\mathrm{C}} \left(1 + \lambda_1 \right) + W_{\mathrm{d}} \right] n T_2 \right\} \quad (°\mathrm{C})$$

where

θ_{ar} is the maximum operating temperature of the armour (°C).

Because the temperature of the armour is a function of the current, I, an iterative method is used for the calculation.

The resistance of the armour per unit length of the cable at its maximum operating temperature is given by:

$$R_{\mathrm{A}} = R_{\mathrm{A0}} \left[1 + \alpha_{20} \left(\theta_{\mathrm{ar}} - 20\mathrm{K} \right) \right] \quad (\Omega/\mathrm{m})$$

where

R_{A0} is the resistance of the armour per unit length of the cable at 20 °C (Ω/m).

Where the equivalent resistance of sheath and armour in parallel is used, it is sufficiently accurate to assume that both components are at the operating temperature of the armour and to use an average value for the temperature coefficient of the materials.

5.4.2 Non-magnetic armour or reinforcement

The general procedure is to combine the calculation of the loss in the reinforcement with that of the sheath. The formulae are given in 5.3 and the parallel combination of sheath and reinforcement resistance is used in place of the single sheath resistance R_{s}. The root mean square value of the sheath and reinforcement diameter replaces the mean sheath diameter d (see 5.3.12). This procedure applies to both single, twin and multicore cables.

The value of the reinforcement resistance is dependent on the lay of the tapes as follows:

a) If the tapes have a very long lay (longitudinal tapes), the resistance is based on a cylinder having the same mass of material per unit length of cable and also the same internal diameter as the tapes.

b) If the tapes are wound at approximately 54° to the cable axis, the resistance is twice the value calculated according to item a) above.

c) If the tapes are wound with a very short lay (circumferential tapes), the resistance is regarded as infinite, i.e. the loss can be neglected.

d) If there are two or more layers of tapes in contact with each other, having a very short lay, the resistance is twice the value calculated according to item a) above.

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These considerations apply also to the cores of pipe-type cables dealt with in 5.3.12.

5.4.3 Magnetic armour or reinforcement

5.4.3.1 Single-core lead-sheathed cables – Steel wire armour, bonded to sheath at both ends

The following method does not take into account the possible influence of the surrounding media, which can be appreciable in particular for cables laid under water. The method is intended for installations where spacing between cables is large (i.e. 10 m or more). It gives values for the sheath and armour losses that are usually higher than the actual ones, so that ratings are on the safe side. It should be noted that the hottest part of the cable route can be the on-shore section where both the losses and mutual heating can be high.

Where the influence of the surrounding media can be ignored, for example in air, the method may be used for any spacing between cables.

Calculation of the power loss in the lead sheath and armour of single-core cables with steel-wire armour with the sheath and armour bonded together at both ends is as follows:

a) The equivalent resistance of sheath and armour in parallel is given by:

$$R_e = \frac{R_s R_A}{R_s + R_A} \quad (\Omega/\mathrm{m})$$

where

R_s is the resistance of the sheath per unit length of cable at its maximum operating temperature (Ω/m);

R_A is the AC resistance of the armour per unit length of cable at its maximum operating temperature (Ω/m).

The AC resistance of the armour wire varies from about 1,2 times the DC resistance of 2 mm diameter wires up to 1,4 times the DC resistance for 5 mm wires. The resistance does not critically affect the final result.

b) The inductance of the elements of the circuit is calculated per phase, as follows:

$$H_s = 2 \times 10^{-7} \ln\left(\frac{2 s_2}{d}\right)$$

where H_s is the inductance due to the sheath per unit length of the cable (H/m)

$$H_1 = \pi \mu_e \left(\frac{n_1 \, d_f^2}{p \, d_A}\right) 10^{-7} \sin\beta \cos\gamma$$

$$H_2 = \pi \mu_e \left(\frac{n_1 \, d_f^2}{p \, d_A}\right) 10^{-7} \sin\beta \sin\gamma$$

$$H_3 = 0{,}4\left(\mu_t (\cos\beta)^2 - 1\right)\left(\frac{d_f}{d_A}\right) 10^{-6}$$

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H_3 is taken as zero for spaced wires.

where

H_1, H_2 and H_3 are the components of the inductance due to the steel wires (H/m);

s_2 is the axial spacing between adjacent cables in trefoil formation; for cables in flat formation s_2 is the geometric mean of the three spacings (mm);

d_A is the mean diameter of the armour (mm);

d_f is the diameter of a steel wire (mm);

p is the length of lay of a steel wire along the cable (mm);

n_1 is the number of steel wires;

β is the angle between the axis of the armour wire and the axis of the cable;

γ is the angular time delay of the longitudinal magnetic flux in the steel wires behind the magnetizing force;

μ_e is the longitudinal relative permeability of steel wires;

μ_t is the transverse relative permeability of steel wires;

For values of γ, μ_e and μ_t, see item d).

Let $B_1 = \omega\,(H_s + H_1 + H_3)$ (Ω/m)

$B_2 = \omega\,H_2$ (Ω/m).

c) The total loss in the sheath and armour $W_{(s+A)}$ per unit length of the cable is given by:

$$W_{(s+A)} = I^2 R_e \frac{B_2^2 + B_1^2 + R_e\,B_2}{(R_e + B_2)^2 + B_1^2} \quad \text{(W/m)}$$

The loss in the sheath and armour may be assumed to be approximately equal, so that:

$$\lambda_1' = \lambda_2 = \frac{W_{(s+A)}}{2\,W_c}$$

where

$W_c = I^2 R_C$ is the loss in the conductor per unit length of the cable (W/m).

d) Choice of magnetic properties γ, μ_e and μ_t.

These quantities vary with the particular sample of steel and unless reference can be made to measurements on the steel wire to be used, some average values should be assumed.

No appreciable error is involved if, for wires of diameters from 4 mm to 6 mm and tensile breaking strengths around 400 N/mm^2, the following values are assumed:

μ_e = 400;

μ_t = 10, when wires are in contact;

μ_t = 1, where wires are separated;

γ = 45°.

If a more precise calculation is required and the wire properties are known, then it is initially necessary to know an approximate value for the magnetizing force H in order to find the appropriate magnetic properties.

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$$H = \frac{1000\left|\overline{I} + \overline{I}_s\right|}{\pi\, d_A} \quad \text{(ampere turns per metre)}$$

where $\overline{I}$ and $\overline{I}_s$ are the vectorial values of the conductor current and sheath current. For the initial choice of magnetic properties, it is usually satisfactory to assume that $\left|\overline{I} + \overline{I}_s\right|$ = 0,6 I, and to repeat the calculations if it is subsequently established that the calculated value is significantly different.

5.4.3.2 Two-core cables – Steel wire armour

$$\lambda_2 = \frac{0{,}62\, \omega^2\, 10^{-14}}{R_C R_A} + \frac{3{,}82\, A_A \omega\, 10^{-5}}{R_C}\left[\frac{1{,}48\, r_1 + t_0}{d_A^2 + 95{,}7\, A_A}\right]^2$$

where

R_A is the AC resistance of the armour at maximum armour temperature per unit length of the cable (Ω/m);

d_A is the mean diameter of the armour (mm);

A_A is the cross-sectional area of the armour (mm^2);

r_1 is the circumscribing radius over conductors (mm);

t_0 is the insulation thickness between conductors (mm).

No correction has been made for non-uniform current distribution in the conductors because it is considered negligible for conductor sizes up to 400 mm^2.

5.4.3.3 Three-core cables – Steel wire armour

5.4.3.3.1 Round conductor cable

$$\lambda_2 = 1{,}23\, \frac{R_A}{R_C}\left(\frac{2c}{d_A}\right)^2 \frac{1}{\left(\frac{2{,}77\, R_A\, 10^6}{\omega}\right)^2 + 1}$$

where

R_A is the AC resistance of the armour at maximum armour temperature (Ω/m);

d_A is the mean diameter of the armour (mm);

c is the distance between the axis of a conductor and the cable centre, (for sector-shaped conductors $= 0{,}55 r_1 + 0{,}29 t_0$) (mm);

r_1 is the circumscribing radius over conductors (mm);

t_0 is the insulation thickness between conductors (mm).

No correction has been made for non-uniform current distribution in the conductors because it is considered negligible for conductor sizes up to 400 mm^2. This equation is under consideration because it can overestimate the armour loss factor for some cable designs.

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5.4.3.3.2 Sector conductor cables

$$\lambda_2 = 0{,}358 \frac{R_A}{R_C} \left(\frac{2r_1}{d_A}\right)^2 \frac{1}{\left(\frac{2{,}77\, R_A 10^6}{\omega}\right)^2 + 1}$$

where

r_1 is the radius of the circle circumscribing the three shaped conductors (mm);

ω = $2\pi f$;

f is the frequency of supply (Hz).

5.4.3.4 Three-core cables – Steel tape armour or reinforcement

The following Formulae (17), (18), (19) and (20) apply to tapes 0,3 mm to 1 mm thick.

The hysteresis loss is given for a frequency of 50 Hz by:

$$\lambda_2' = \frac{s^2\, k_f^2\, 10^{-7}}{R_C\, d_A\, \delta_A} \tag{17}$$

where

s is the distance between conductor axes (mm);

δ_A is the equivalent thickness of the armour (mm), i.e. $\frac{A_A}{\pi\, d_A}$;

and

A_A is the armour cross-sectional area (mm^2);

d_A is the mean diameter of the armour (mm).

The factor k_f is given by:

$$k_f = \frac{1}{1 + \frac{d_A}{\mu \delta_A}} \tag{18}$$

where

μ is the relative permeability of the steel tape, usually taken as 300.

For frequencies f other than 50 Hz, multiply the value of k_f given by the above Formula (18) by the factor $\frac{f}{50}$.

The eddy-current loss is given for a frequency of 50 Hz by:

$$\lambda_2'' = \frac{2{,}25\, s^2\, k_f^2\, \delta_A\, 10^{-8}}{R_C\, d_A} \tag{19}$$

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