IEC 60287-2-1

Edition 2.0 2015-04
REDLINE VERSION

INTERNATIONAL STANDARD

colour inside

Electric cables – Calculation of the current rating –
Part 2-1: Thermal resistance – Calculation of thermal resistance

IEC 60287-2-1:2015-04 RLV(en)

IEC Central Office
3, rue de Varembé
CH-1211 Geneva 20
Switzerland

Tel.: +41 22 919 02 11
Fax: +41 22 919 03 00
info@iec.ch
www.iec.ch

About the IEC
The International Electrotechnical Commission (IEC) is the leading global organization that prepares and publishes International Standards for all electrical, electronic and related technologies.

About IEC publications
The technical content of IEC publications is kept under constant review by the IEC. Please make sure that you have the latest edition, a corrigenda or an amendment might have been published.

IEC Catalogue - webstore.iec.ch/catalogue
The stand-alone application for consulting the entire bibliographical information on IEC International Standards, Technical Specifications, Technical Reports and other documents. Available for PC, Mac OS, Android Tablets and iPad.

IEC publications search - www.iec.ch/searchpub
The advanced search enables to find IEC publications by a variety of criteria (reference number, text, technical committee,…). It also gives information on projects, replaced and withdrawn publications.

IEC Just Published - webstore.iec.ch/justpublished
Stay up to date on all new IEC publications. Just Published details all new publications released. Available online and also once a month by email.

Electropedia - www.electropedia.org
The world's leading online dictionary of electronic and electrical terms containing more than 30 000 terms and definitions in English and French, with equivalent terms in 15 additional languages. Also known as the International Electrotechnical Vocabulary (IEV) online.

IEC Glossary - std.iec.ch/glossary
More than 60 000 electrotechnical terminology entries in English and French extracted from the Terms and Definitions clause of IEC publications issued since 2002. Some entries have been collected from earlier publications of IEC TC 37, 77, 86 and CISPR.

IEC Customer Service Centre - webstore.iec.ch/csc
If you wish to give us your feedback on this publication or need further assistance, please contact the Customer Service Centre: csc@iec.ch.

IEC 60287-2-1

Edition 2.0 2015-04
REDLINE VERSION

INTERNATIONAL STANDARD

colour inside

Electric cables – Calculation of the current rating –
Part 2-1: Thermal resistance – Calculation of thermal resistance

INTERNATIONAL
ELECTROTECHNICAL
COMMISSION

ICS 29.060.20

ISBN 978-2-8322-2618-6

CONTENTS

INTERNATIONAL ELECTROTECHNICAL COMMISSION

____

ELECTRIC CABLES –
CALCULATION OF THE CURRENT RATING –

Part 2-1: Thermal resistance –
Calculation of thermal resistance

FOREWORD

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

2) The formal decisions or agreements of IEC on technical matters express, as nearly as possible, an international consensus of opinion on the relevant subjects since each technical committee has representation from all interested IEC National Committees.

3) IEC Publications have the form of recommendations for international use and are accepted by IEC National Committees in that sense. While all reasonable efforts are made to ensure that the technical content of IEC Publications is accurate, IEC cannot be held responsible for the way in which they are used or for any misinterpretation by any end user.

4) In order to promote international uniformity, IEC National Committees undertake to apply IEC Publications transparently to the maximum extent possible in their national and regional publications. Any divergence between any IEC Publication and the corresponding national or regional publication shall be clearly indicated in the latter.

5) IEC itself does not provide any attestation of conformity. Independent certification bodies provide conformity assessment services and, in some areas, access to IEC marks of conformity. IEC is not responsible for any services carried out by independent certification bodies.

6) All users should ensure that they have the latest edition of this publication.

7) No liability shall attach to IEC or its directors, employees, servants or agents including individual experts and members of its technical committees and IEC National Committees for any personal injury, property damage or other damage of any nature whatsoever, whether direct or indirect, or for costs (including legal fees) and expenses arising out of the publication, use of, or reliance upon, this IEC Publication or any other IEC Publications.

8) Attention is drawn to the Normative references cited in this publication. Use of the referenced publications is indispensable for the correct application of this publication.

9) Attention is drawn to the possibility that some of the elements of this IEC Publication may be the subject of patent rights. IEC shall not be held responsible for identifying any or all such patent rights.

This redline version of the official IEC Standard allows the user to identify the changes made to the previous edition. A vertical bar appears in the margin wherever a change has been made. Additions are in green text, deletions are in strikethrough red text.

International Standard IEC 60287-2-1 has been prepared by IEC technical committee 20: Electric cables.

This second edition of IEC 60287-2-1 cancels and replaces the first edition, published in 1994, Amendment 1:2001, Amendment 2:2006 and Corrigendum 1:2008. The document 20/1448/CDV, circulated to the National Committees as Amendment 3, led to the publication of this new edition. This edition constitutes a technical revision.

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

a) inclusion of a reference to the use of finite element methods where analytical methods are not available for the calculation of external thermal resistance;
b) explanation about SL and SA type cables;
c) calculation method for T3 for unarmoured three-core cables with extruded insulation and individual copper tape screens on each core;
d) change of condition for X in 5.4;
e) inclusion of constants or installation conditions for water filled ducts in Table 4.

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

FDIS	Report on voting
20/1561/FDIS	20/1588/RVD

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

This publication has been drafted in accordance with the ISO/IEC Directives, Part 2.

A list of all parts 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 publication will remain unchanged until the stability date indicated on the IEC website under "http://webstore.iec.ch" in the data related to the specific publication. At this date, the publication will be

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

IMPORTANT – The "colour inside" logo on the cover page of this publication indicates that it contains colours which are considered to be useful for the correct understanding of its contents. Users should therefore print this publication using a colour printer.

INTRODUCTION

IEC 60287 has been divided into three parts ~~and sections~~ so that revisions of, and additions to the document can be carried out more conveniently.

Each part is subdivided into ~~sections~~ subparts which are published as separate standards.

Part 1: Formulae of ratings and power losses

Part 2: Formulae for thermal resistance

Part 3: ~~Sections on~~ Operating conditions

This part of IEC 60287-2 contains methods for calculating the internal thermal resistance of cables and the external thermal resistance for cables laid in free air, ducts and buried.

The formulae in this standard 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 may be obtained, the current ratings should be calculated with the values given in this standard. 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 may lead to erroneous conclusions if they are not based on common criteria: for example, there may 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 may 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 may 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.

ELECTRIC CABLES – CALCULATION OF THE CURRENT RATING –

Part 2-1: Thermal resistance – Calculation of thermal resistance

~~1 General~~

1 Scope

This part of IEC 60287 is solely 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, in 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 part of IEC 60287 provides formulae for thermal resistance.

The formulae given are essentially literal and designedly leave open the selection of certain important parameters. These may 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 may vary widely, the selection of which depends on the country in which the cables are used or are to 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).

Equations given in this part of IEC 60287 for calculating the external thermal resistance of a cable buried directly in the ground or in a buried duct are for a limited number of installation conditions. Where analytical methods are not available for calculation of external thermal resistance finite element methods may be used. Guidance on the use of finite element methods for calculating cable current ratings is given in IEC TR 62095.

2 Normative references

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

IEC 60287-1-1:2006, *Electric cables – Calculation of the current rating – Part 1-1: Current rating equations (100 % load factor) and calculation of losses – General*
IEC 60287-1-1:2006/AMD1:2014

IEC 60853-2, *Calculation of the cyclic and emergency current rating of cables – Part 2: Cyclic rating of cables greater than 18/30 (36) kV and emergency ratings for cables of all voltages*

3 Symbols

The symbols used in this part of IEC 60287 and the quantities which they represent are given in the following list:

D'_a	external diameter of armour	mm
D_d	internal diameter of duct	mm
D_e	external diameter of cable, or equivalent diameter of a group of cores in pipe-type cable	mm
D^*_e	external diameter of cable (used in 4.2.1)	m
D_o	external diameter of duct	mm
D_s	external diameter of metal sheath	mm
D_{oc}	the diameter of the imaginary coaxial cylinder which just touches the crests of a corrugated sheath	mm
D_{ot}	the diameter of the imaginary coaxial cylinder which would just touch the outside surface of the troughs of a corrugated sheath = $D_{it} + 2t_s$	mm
D_{ic}	the diameter of the imaginary cylinder which would just touch the inside surface of the crests of a corrugated sheath = $D_{oc} - 2t_s$	mm
D_{it}	the diameter of the imaginary cylinder which just touches the inside surface of the troughs of a corrugated sheath	mm
E	constant used in 4.2.1.1	
F_1	coefficient for belted cables defined in 4.1.2.2.3	
F_2	coefficient for belted cables defined in 4.1.2.2.6	
G	geometric factor for belted cables	
$\overline{G}$	geometric factor for SL and SA type cables	
H	intensity of solar radiation (see 4.2.1.2)	W/m^2
K	screening factor for the thermal resistance of screened cables	
K_A	coefficient used in 4.2.1	
L	depth of laying, to cable axis or centre of trefoil	mm
L_G	distance from the soil surface to the centre of a duct bank	mm
N	number of loaded cables in a duct bank (see 4.2.7.4)	
T_1	thermal resistance per core between conductor and sheath	K·m/W
T_2	thermal resistance between sheath and armour	K·m/W
T_3	thermal resistance of external serving	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	external 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	constant used in 4.2.7.2	
V	constant used in 4.2.7.2	
W_d	dielectric losses per unit length per phase	W/m
W_k	losses dissipated by cable k	W/m

W_{TOT}	total power dissipated in the trough per unit length	W/m
Y	coefficient used in 4.2.7.2	
Z	coefficient used in 4.2.1.1	
d_a	external diameter of belt insulation	mm
d_c	external diameter of conductor	mm
d_{cm}	minor diameter of an oval conductor	mm
d_{cM}	major diameter of an oval 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
g	coefficient used in 4.2.1.1	
h	heat dissipation coefficient	$W/m^2K^{5/4}$
ln	natural logarithm (logarithm to base e)	
n	number of conductors in a cable	
p	the part of the perimeter of the cable trough which is effective for heat dissipation (see 4.2.6.2)	m
r_1	circumscribing radius of two or three-sector shaped conductors	mm
s_1	axial separation of two adjacent cables in a horizontal group of three, not touching	mm
t	insulation thickness between conductors	mm
t_1	insulation thickness between conductors and sheath	mm
t_2	thickness of the bedding	mm
t_3	thickness of the serving	mm
t_i	thickness of core insulation, including screening tapes plus half the thickness of any non-metallic tapes over the laid up cores	mm
t_s	thickness of the sheath	mm
u	$\frac{2L}{D_e}$ in 4.2.	
u	$\frac{L_G}{r_b}$ in 4.2.7.4	
x, y	sides of duct bank ($y>x$) (see 4.2.7.4)	mm
θ_m	mean temperature of medium between a cable and duct or pipe	°C
$\Delta\theta$	permissible temperature rise of conductor above ambient temperature	K
$\Delta\theta_d$	factor to account for dielectric loss for calculating T_4 for cables in free air	K
$\Delta\theta_{ds}$	factor to account for both dielectric loss and direct solar radiation for calculating T_4^* for cables in free air using Figure 10	K
$\Delta\theta_{duct}$	difference between the mean temperature of air in a duct and ambient temperature	K
$\Delta\theta_s$	difference between the surface temperature of a cable in air and ambient temperature	K
$\Delta\theta_{tr}$	temperature rise of the air in a cable trough	K

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'_{1m}	loss factor for the middle cable	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		
λ'_{12}	loss factor for the outer cable with the least losses		
ρ_i	thermal resistivity of the insulation		K·m/W
ρ_f	thermal resistivity of the filler material		K·m/W
ρ_e	thermal resistivity of earth surrounding a duct bank		K·m/W
ρ_c	thermal resistivity of concrete used for a duct bank		K·m/W
ρ_m	thermal resistivity of metallic screens on multicore cables		K·m/W
ρ_T	thermal resistivity of material		K·m/W
σ	absorption coefficient of solar radiation for the cable surface		

4 Calculation of thermal resistances

4.1 Thermal resistance of the constituent parts of a cable, T_1, T_2 and T_3

4.1.1 General

Clause 4 gives the formulae for calculating the thermal resistances per unit length of the different parts of the cable T_1, T_2 and T_3 (see 1.4 of ~~part 1~~ IEC 60287-1-1:2006 and IEC 60287-1-1:2006/AMD1:2014). The thermal resistivities of materials used for insulation and for protective coverings are given in Table 1.

Where screening layers are present, for thermal calculations metallic tapes are considered to be part of the conductor or sheath while semi-conducting layers (including metallized carbon paper tapes) are considered as part of the insulation. The appropriate component dimensions ~~must~~ shall be modified accordingly.

4.1.2 Thermal resistance between one conductor and sheath T_1

4.1.2.1 Single-core cables

The thermal resistance between one conductor and the sheath T_1 is given by:

$$T_1 = \frac{\rho_T}{2\pi} \ln\left[1 + \frac{2t_1}{d_c}\right]$$

where

ρ_T is the thermal resistivity of insulation (K·m/W);

d_c is the diameter of conductor (mm);

t_1 is the thickness of insulation between conductor and sheath mm).

NOTE For corrugated sheaths, t_1 is based on the mean internal diameter of the sheath which is given by:

$$\left(\frac{D_{it} + D_{oc}}{2}\right) - t_s$$

4.1.2.2 Belted cables

4.1.2.2.1 General

The thermal resistance T_1 between one conductor and sheath is given by:

$$T_1 = \frac{\rho_T}{2\pi} G$$

where

G is the geometric factor

NOTE For corrugated sheaths, t_1 is based on the mean internal diameter of the sheath which is given by:

$$\left(\frac{D_{it} + D_{oc}}{2}\right) - t_s$$

4.1.2.2.2 Two-core belted cables with circular conductors

The geometric factor G is given in Figure 2.

4.1.2.2.3 Two-core belted cables with sector-shaped conductors

The geometric factor G is given by:

$$G = 2\, F_1 \ln\left[\frac{d_a}{2\, r_1}\right]$$

where

$$F_1 = 1 + \frac{2{,}2\, t}{2\pi\, (d_x + t) - t}$$

d_a is the external diameter of the belt insulation (mm);

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

d_x is the diameter of a circular conductor having the same cross-sectional area and degree of compaction as the shaped one (mm);

t is the insulation thickness between conductors (mm).

4.1.2.2.4 Three-core belted cables with circular conductors

For three-core belted cables with circular conductors

$$T_1 = \frac{\rho_i}{2\pi} G + 0{,}031(\rho_f - \rho_i) e^{0{,}67 \frac{t_1}{d_c}}$$

where

ρ_i is the thermal resistivity of the insulation (K·m/W);

ρ_f is the thermal resistivity of the filler material (K·m/W).

The geometric factor G is given in Figure 3.

NOTE For paper-insulated cables $\rho_f = \rho_i$ and, hence, the second term on the right hand side of the above equation can be ignored.

For cables with extruded insulation, the thermal resistivity of the filler material is likely to be between 6 K·m/W and 13 K·m/W, depending on the filler material and its compaction. A value of 10 K·m/W is suggested for fibrous polypropylene fillers.

The above equation is applicable to cables with extruded insulation where each core has an individual screen of spaced wires and to cables with a common metallic screen over all three cores. For unarmoured cables of this design t_1 is taken to be the thickness of the material between the conductors and outer covering (serving).

4.1.2.2.5 Three-core belted cables with oval conductors

The cable shall be treated as an equivalent circular conductor cable with an equivalent diameter $d_c = \sqrt{d_{cM} \times d_{cm}}$ (mm)

where

d_{cM} is the major diameter of the oval conductor (mm);

d_{cm} is the minor diameter of the oval conductor (mm).

4.1.2.2.6 Three-core belted cables with sector-shaped conductors

The geometric factor G for these cables depends on the shape of the sectors, which varies from one manufacturer to another. A suitable formula is:

$$G = 3F_2 \ln\left[\frac{d_a}{2r_1}\right]$$

where

$$F_2 = 1 + \frac{3t}{2\pi(d_x + t) - t}$$

d_a is the external diameter of the belt insulation (mm);

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

d_x is the diameter of a circular conductor having the same cross-sectional area and degree of compaction as the shaped one (mm);

t is the insulation thickness between conductors (mm).

4.1.2.3 Three-core cables, metal tape screened type

4.1.2.3.1 Screened cables with circular conductors

~~Cables~~ Paper insulated of this type may be first considered as belted cables for which $\frac{t_1}{t}$ is 0,5. Then, in order to take account of the thermal conductivity of the metallic screens, the result shall be multiplied by a factor K, called the screening factor, which is given in Figure 4 for different values of $\frac{t_1}{d_c}$ and different cable specifications.

Thus:

$$T_1 = K\frac{\rho_T}{2\pi}G$$

Three-core cables with extruded insulation and individual copper tape screens on each core should be treated as SL type cables (see 4.1.2.5 and 4.1.3.2).

See 4.1.2.2.4 for three-core cables with extruded insulation and an individual screen of spaced copper wires on each core or a common metallic screen over all three cores.

4.1.2.3.2 Screened cables with oval-shaped conductors

The cable shall be treated as an equivalent circular conductor cable with an equivalent diameter $d_c = \sqrt{d_{cM} \cdot d_{cm}}$.

4.1.2.3.3 Screened cables with sector-shaped conductors

T_1 is calculated for these cables in the same way as for belted cables with sector-shaped conductors, but d_a is taken as the diameter of a circle which circumscribes the core assembly. The result is multiplied by a screening factor given in Figure 5.

4.1.2.4 Oil-filled cables

4.1.2.4.1 Three-core cables with circular conductors and metallized paper core screens and circular oil ducts between the cores

The thermal resistance between one conductor and the sheath T_1 is given by:

$$T_1 = 0{,}385\,\rho_T \left(\frac{2\,t_i}{d_c + 2\,t_i} \right)$$

where

d_c is the conductor diameter (mm);

t_i is the thickness of core insulation including carbon black and metallized paper tapes plus half of any non-metallic tapes over the three laid up cores (mm);

ρ_T is the thermal resistivity of insulation (K·m/W).

This formula assumes that the space occupied by the metal ducts and the oil inside them has a thermal conductance very high compared with the insulation, it therefore applies irrespective of the metal used to form the duct or its thickness.

4.1.2.4.2 Three-core cables with circular conductors and metal tape core screens and circular oil ducts between the cores

The thermal resistance T_1 between one conductor and the sheath is given by:

$$T_1 = 0{,}35\,\rho_T \left(0{,}923 - \frac{d_c}{d_c + 2\,t_i} \right)$$

where

t_i is the thickness of core insulation including the metal screening tapes and half on any non-metallic tapes over the three laid up cores (mm).

NOTE This formula is independent of the metals used for the screens and for the oil ducts.

4.1.2.4.3 Three-core cables with circular conductors, metal tape core screens, without fillers and oil ducts, having a copper woven fabric tape binding the cores together and a corrugated aluminium sheath

The thermal resistance T_1 between one conductor and the sheath is given by:

$$T_1 = \frac{475}{D_c^{1{,}74}} \left[\frac{t_g}{D_c} \right]^{0{,}62} + \frac{\rho_T}{2\pi} \ln\left(\frac{d_c - 2\,\delta_1}{d_c} \right)$$

where

$$t_g = 0{,}5\left(\left[\frac{D_{it} + D_{ic}}{2} \right] - 2{,}16\,D_c \right)$$

D_c is the diameter of a core over its metallic screen tapes (mm);

t_g is the average nominal clearance between the core metallic screen tapes and the average inside diameter of the sheath (mm);

δ_1 is the thickness of metallic tape core screen (mm).

NOTE The formula is independent of the metal used for the screen tapes.

4.1.2.5 SL and SA type cables

An SL or SA type cable is a three-core cable where each core has an individual lead or aluminium sheath. The sheath is considered to be sufficiently substantial so as to provide an isotherm at the outer surface of the insulation.

The thermal resistance T_1 is calculated in the same way as for single-core cables.

4.1.3 Thermal resistance between sheath and armour T_2

4.1.3.1 Single-core, two-core and three-core cables having a common metallic sheath

The thermal resistance between sheath and armour, T_2, is given by:

$$T_2 = \frac{1}{2\pi} \rho_T \ln\left[1 + \frac{2t_2}{D_s}\right]$$

where

t_2 is the thickness of the bedding (mm);

D_s is the external diameter of the sheath (mm).

NOTE For unarmoured cables with extruded insulation where each core has an individual screen of spaced wires and for unarmoured cables with a common metallic screen over all three cores T_2 = 0.

4.1.3.2 SL and SA type cables

The thermal resistance of fillers and bedding under the armour is given by:

$$T_2 = \frac{\rho_T}{6\pi}\overline{G}$$

where

$\overline{G}$ is the geometric factor given in Figure 6.

4.1.4 Thermal resistance of outer covering (serving) T_3

4.1.4.1 General case

The external servings are generally in the form of concentric layers and the thermal resistance T_3 is given by:

$$T_3 = \frac{1}{2\pi} \rho_T \ln\left(1 + \frac{2t_3}{D'_a}\right)$$

where

t_3 is the thickness of serving (mm);

D'_a is the external diameter of the armour (mm).

NOTE For unarmoured cables D'_a is taken as the external diameter of the component immediately beneath it, i.e. sheath, screen or bedding.

For corrugated sheaths:

$$T_3 = \frac{1}{2\pi}\rho_T \ln\left[\frac{D_{oc}+2t_3}{\left(\frac{D_{oc}+D_{it}}{2}\right)+t_s}\right]$$

4.1.4.2 Unarmoured three-core cables with extruded insulation and individual copper tape screens on each core

The thermal resistance of the fillers, binder and external serving is given by:

$$T_3 = \frac{\rho_T}{2\pi}\ln\left(1+\frac{2t_3}{D'_a}\right)+\frac{\rho_f}{6\pi}\overline{G}$$

where

ρ_f is the thermal resistivity of filler (K·m/W);

$\overline{G}$ is the geometric factor given in Figure 6 based on the thickness of material between the copper tape screen and the outer covering (serving);

D'_a is taken as the diameter over the binder tape.

4.1.5 Pipe-type cables

For these three-core cables, we have:

a) The thermal resistance T_1 of the insulation of each core between the conductor and the screen. This is calculated by the method set out in 4.1.2 for single-core cables.

b) The thermal resistance T_2 is made up of two parts:

1) The thermal resistance of any serving over the screen or sheath of each core. The value to be substituted for part of T_2 in the rating equation of 1.4 of ~~part 1~~ IEC 60287-1-1:2006 and IEC 60287-1-1:2006/AMD1:2014 is the value per cable, i.e. the value for a three-core cable is one-third the value of a single core.

   The value per core is calculated by the method given in 4.1.3 for the bedding of single-core cables. For oval cores, the geometric mean of the major and minor diameter $\sqrt{d_M \cdot d_m}$ shall be used in place of the diameter for a circular core assembly.

2) The thermal resistance of the gas or oil between the surface of the cores and the pipe. This resistance is calculated in the same way as that part of T_4 which is between a cable and the internal surface of a duct, as given in 4.2.7.2.

   The value calculated will be per cable and should be added to the quantity calculated in 4.1.5 b) above, before substituting for T_2 in the rating equation of 1.4 of ~~part 1~~ IEC 60287-1-1:2006 and IEC 60287-1-1:2006/AMD1:2014.

c) The thermal resistance T_3 of any external covering on the pipe is dealt with as in 4.1.4. The thermal resistance of the metallic pipe itself is negligible.

4.2 External thermal resistance T_4

4.2.1 Cables laid in free air

4.2.1.1 Cables protected from direct solar radiation

The thermal resistance T_4 of the surroundings of a cable in air and protected from solar radiation is given by the formula:

$$T_4 = \frac{1}{\pi D_e^* h (\Delta\theta_s)^{1/4}}$$

where

$$h = \frac{Z}{(D_e^*)^g} + E$$

D_e^* is the external diameter of cable (m)

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

NOTE Throughout 4.2.1 D_e^* is expressed in metres.

h is the heat dissipation coefficient obtained either from the above formula using the appropriate values of constants Z, E and g given in Table 2, or from the curves in Figures 7, 8 and 9, which are reproduced for convenience (W/m² *(K)*$^{5/4}$);

served cables and cables having a non-metallic surface should be considered to have a black surface. Unserved cables, either plain lead or armoured should be given a value of h equal to 88 % of the value for a black surface;

$\Delta\theta_s$ is the excess of cable surface temperature above ambient temperature (see hereinafter for method of calculation) *(K)*.

For cables in unfilled troughs, see 4.2.6.

Calculation of $(\Delta\theta_s)^{1/4}$:

A simple iterative method of calculating $(\Delta\theta_s)^{1/4}$ is given below. The alternative graphical method is described in 5.7.

Calculate

$$K_A = \frac{\pi D_e^* h}{(1+\lambda_1+\lambda_2)} \left[\frac{T_1}{n} + T_2\ (1+\lambda_1) + T_3\ (1+\lambda_1+\lambda_2) \right]$$

then

$$(\Delta\theta_s)_{n+1}^{1/4} = \left[\frac{\Delta\theta + \Delta\theta_d}{1 + K_A\ (\Delta\theta_s)_n^{1/4}} \right]^{0,25}$$

Set the initial value of $(\Delta\theta_s)^{1/4} = 2$ and reiterate until $(\Delta\theta_s)_{n+1}^{1/4} - (\Delta\theta_s)_n^{1/4} \leq 0{,}001$

where

$$\Delta\theta_d = W_d \left[\left(\frac{1}{1+\lambda_1+\lambda_2} - \frac{1}{2} \right) T_1 - \frac{n\,\lambda_2\, T_2}{1+\lambda_1+\lambda_2} \right]$$

This is a factor, having the dimensions of temperature difference, accounts for the dielectric losses. If the dielectric losses are neglected, $\Delta\theta_d = 0$.

$\Delta\theta$ is the permissible conductor temperature rise above ambient temperature.

4.2.1.2 Cables directly exposed to solar radiation – External thermal resistance T_4^*

Where cables are directly exposed to solar radiation, T_4^* is calculated by the method given in 4.2.1.1 except that in the iterative method $(\Delta\theta_s)^{1/4}$ is calculated using the following formula:

$$(\Delta\theta_s)_{n+1}^{1/4} = \left[\frac{\Delta\theta + \Delta\theta_d + \Delta\theta_{ds}}{1 + K_A \ (\Delta\theta_s)_n^{1/4}} \right]^{0,25}$$

where

$$\Delta\theta_{ds} = \frac{\sigma D_e^* H}{(1+\lambda_1+\lambda_2)} \left[\frac{T_1}{n} + T_2 \ (1+\lambda_1) + T_3 \ (1+\lambda_1+\lambda_2) \right]$$

This is a factor which, having the dimensions of temperature difference, accounts for direct solar radiation.

where

σ is the absorption coefficient of solar radiation for the cable surface (see Table 3);

H is the intensity of solar radiation which should be taken as 10^3 W/m² for most latitudes; it is recommended that the local value should be obtained where possible;

D_e^* is the external diameter of cable (m)

for corrugated sheaths $D_e^* = (D_{oc} + 2\,t_3) \cdot 10^{-3}$ (m).

The alternative graphical method is included in Figure 10.

4.2.2 Single isolated buried cable

$$T_4 = \frac{1}{2\pi} \rho_T \ln\left(u + \sqrt{u^2 - 1}\right)$$

where

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

$u = \dfrac{2L}{D_e}$;

L is the distance from the surface of the ground to the cable axis (mm);

D_e is the external diameter of the cable (mm)
for corrugated sheaths $D_e = D_{oc} + 2\,t_3$.

When the value of u exceeds 10, a good approximation (closer than 1 part in 1 000) is:

$$T_4 = \frac{1}{2\pi} \rho_T \ln(2u)$$

For cable circuits installed at laying depths of more than 10 m, an alternative approach for calculating the current rating is to determine the continuous current rating for a designated time period (usually 40 years) by applying the formulae given in IEC 60853-2, taking into account as far as is practical seasonal variations in load and ground conditions, if any. Finite element modelling may provide a more versatile model for such a lifetime assessment. This subject is under consideration.

4.2.3 Groups of buried cables (not touching)

4.2.3.1 General

Such cases may be solved by using superposition, assuming that each cable acts as a line source and does not distort the heat field due to the other cables.

These cables are of two main types: the first, and most general type, is a group of unequally loaded cables of different construction, and for this problem a general indication of the method only can be given. The second type, which is a more particular one, is a group of equally loaded identical cables, and for this problem a fairly simple solution can be derived.

4.2.3.2 Unequally loaded cables

The method suggested for groups of unequally loaded dissimilar cables is to calculate the temperature rise at the surface of the cable under consideration caused by the other cables of the group, and to subtract this rise from the value of $\Delta\theta$ used in the equation for the rated current in 1.4 of ~~part 1~~ IEC 60287-1-1:2006 and IEC 60287-1-1:2006/AMD1:2014. An estimate of the power dissipated per unit length of each cable ~~must~~ shall be made beforehand, and this can be subsequently amended as a result of the calculation where this becomes necessary.

Thus, the temperature rise $\Delta\theta_p$ above ambient at the surface of the p^{th} cable, whose rating is being determined, caused by the power dissipated by the other (q – 1) cables in the group, is given by:

$$\Delta\theta_p = \Delta\theta_{1p} + \Delta\theta_{2p} + \ldots \Delta\theta_{kp} + \ldots \Delta\theta_{qp}$$

(the term $\Delta\theta_{pp}$ is excluded from the summation)

where

$\Delta\theta_{kp}$ is the temperature rise at the surface of the cable produced by the power W_k watt per unit length dissipated in cable k:

$$\Delta\theta_{kp} = \frac{1}{2\pi}\rho_T W_k \ln\left(\frac{d'_{pk}}{d_{pk}}\right)$$

The distances d_{pk} and d'_{pk} are measured from the centre of the p^{th} cable to the centre of cable k, and to the centre of the reflection of cable k in the ground-air surface respectively (see Figure 1).

The value of $\Delta\theta$ in the equation for the rated current in 1.4 of ~~part 1~~ IEC 60287-1-1:2006 and IEC 60287-1-1:2006/AMD1:2014 is then reduced by the amount $\Delta\theta_p$ and the rating of the p^{th} cable is determined using a value T_4 corresponding to an isolated cable at position p.

This calculation is performed for all cables in the group and is repeated where necessary to avoid the possibility of overheating any cable.

4.2.3.3 Equally loaded identical cables

4.2.3.3.1 General

The second type of grouping is where the rating of a number of equally loaded identical cables is determined by the rating of the hottest cable. It is usually possible to decide from the configuration of the installation which cable will be the hottest, and to calculate the rating for this one. In cases of difficulty, a further calculation for another cable may be necessary. The method is to calculate a modified value of T_4 which takes into account the mutual heating of the group and to leave unaltered the value of $\Delta\theta$ used in the rating equation of 1.4 of ~~part 1~~ IEC 60287-1-1:2006 and IEC 60287-1-1:2006/AMD1:2014.

The modified value of the external thermal resistance T_4 of the p^{th} cable is given by:

$$T_4 = \frac{1}{2\pi}\rho_T \ln\left\{\left(u+\sqrt{u^2-1}\right)\left[\left(\frac{d'_{p1}}{d_{p1}}\right)\left(\frac{d'_{p2}}{d_{p2}}\right)\ldots\left(\frac{d'_{pk}}{d_{pk}}\right)\ldots\left(\frac{d'_{pq}}{d_{pq}}\right)\right]\right\}$$

There are $(q-1)$ terms, with the term $\frac{d'_{pp}}{d_{pp}}$ excluded.

The distances d_{pk}, etc., are the same as those shown in Figure 1, for the first method.

The simpler version $2\,u$ may be used instead of $u+\sqrt{u^2-1}$ if suitable (see 4.2.2).

For simple configurations of cables, this formula may be simplified considerably. The following examples were obtained by the use of superposition.

4.2.3.3.2 Two cables having equal losses, laid in a horizontal plane, spaced apart

$$T_4 = \frac{1}{2\pi}\rho_T\left\{\ln\left(u+\sqrt{u^2-1}\right)+\frac{1}{2}\ln\left[1+\left(\frac{2L}{s_1}\right)^2\right]\right\}$$

where

$u = \frac{2L}{D_e}$;

L is the distance from the surface of the ground to the cables axis (mm);

D_e is the external diameter of one cable (mm);

s_1 is the axial separation between two adjacent cables (mm).

When the value of u exceeds 10, the term $\left(u+\sqrt{u^2-1}\right)$ may be replaced by $(2\,u)$.

4.2.3.3.3 Three cables having approximately equal losses, laid in a horizontal plane; equally spaced apart

$$T_4 = \frac{1}{2\pi}\rho_T\left\{\ln\left(u+\sqrt{u^2-1}\right)+\ln\left[1+\left(\frac{2L}{s_1}\right)^2\right]\right\}$$

The value T_4 is that of the centre cable of the group and is used directly in the equation of 1.4.1 of ~~part 1~~ IEC 60287-1-1:2006.

4.2.3.3.4 Three cables having unequal sheath losses, laid in a horizontal plane; equally spaced apart

When the losses in the sheaths of single-core cables laid in a horizontal plane are appreciable, and the sheaths are laid without transposition and/or the sheaths are bonded at all joints, their inequality affects the external thermal resistances of the hottest cable. In such cases the value of T_4 to be used in the numerator of the rating equation in 1.4.1 of ~~part 1~~ IEC 60287-1-1:2006 is as given in 4.2.3.3.3, but a modified value of T_4 ~~must~~ shall be used in the denominator, and is given by:

$$T_4 = \frac{1}{2\pi}\rho_T\left\{\ln\left(u+\sqrt{u^2-1}\right)+\left[\frac{1+0{,}5(\lambda'_{11}+\lambda'_{12})}{1+\lambda'_{lm}}\right]\ln\left[1+\left(\frac{2L}{s_1}\right)^2\right]\right\}$$

This assumes that the centre cable is the hottest cable. The value of λ_1 to be used in the rating equation of 1.4.1 of ~~part 1~~ IEC 60287-1-1:2006 is that for the centre cable,

where

$u = \frac{2L}{D_e}$;

L is the distance from the surface of the ground to the cables axis (mm);

D_e is the external diameter of one cable (mm);

s_1 is the axial separation between two adjacent cables (mm);

λ'_{11} is the sheath loss factor for an outer cable of the group;

λ'_{12} is the sheath loss factor for the other outer cable of the group;

λ'_{lm} is the sheath loss factor for the middle cable of the group.

When the value of u exceeds 10, the term $(u+\sqrt{u^2-1})$ may be replaced by $(2u)$.

4.2.4 Groups of buried cables (touching) equally loaded

4.2.4.1 Two single-core cables, flat formation

4.2.4.1.1 Metallic sheathed cables

Metallic sheathed cables are taken to be cables where it can be assumed that there is a metallic layer that provides an isotherm at, or immediately under, the outer sheath of the cable.

$$T_4 = \frac{\rho_T}{\pi}\left(\ln(2u) - 0{,}451\right) \quad \text{for } u \geq 5$$

4.2.4.1.2 Non-metallic sheathed cables

Non-metallic sheathed cables are taken to be cables where any metallic layer at, or immediately under, the outer sheath of the cable is not sufficient to provide an isotherm.

$$T_4 = \frac{\rho_T}{\pi}\left(\ln(2u) - 0{,}295\right) \quad \text{for } u \geq 5$$

This formula is used for non-metallic sheathed cables having a copper wire screen and for the external thermal resistance of non-metallic touching ducts (see 4.2.7.4).

4.2.4.2 Three single-core cables, flat formation

4.2.4.2.1 Metallic sheathed cables

Metallic sheathed cables are taken to be cables where it can be assumed that there is a metallic layer that provides an isotherm at, or immediately under, the outer sheath of the cable. The value of λ_1 used in the rating equation of 1.4.1.1 of IEC 60287-1-1:2006 is the average of the λ_1 values for the three cables.

$$T_4 = \rho_T \left(0{,}475 \ \ln\left(2u\right) - 0{,}346\right) \quad \text{for } u \geq 5$$

4.2.4.2.2 Non-metallic sheathed cables

Non-metallic sheathed cables are taken to be cables where any metallic layer at, or immediately under, the outer sheath of the cable is not sufficient to provide an isotherm.

$$T_4 = \rho_T \left(0{,}475 \ \ln\left(2u\right) - 0{,}142\right) \quad \text{for } u \geq 5$$

This formula is used for non-metallic sheathed cables having a copper wire screen and for the external thermal resistance of non-metallic touching ducts (see 4.2.7.4).

4.2.4.3 Three single-core cables, trefoil formation

4.2.4.3.1 General

For this configuration, L is measured to the centre of the trefoil group and D_e is the diameter of one cable. T_4 is the external thermal resistance of any one of the cables and the configuration may be with the apex either at the top or at the bottom of the group.

For corrugated sheaths, $D_e = D_{oc} + 2\ t_3$.

4.2.4.3.2 Metallic sheathed cables

$$T_4 = \frac{1{,}5}{\pi} \rho_T \left[\ln\left(2u\right) - 0{,}630\right]$$

In this case, the thermal resistance of the serving over the sheath or armour, T_3, as calculated by the method given in 4.1.4 shall be multiplied by a factor of 1,6.

4.2.4.3.3 Part-metallic covered cables (where helically laid armour or screen wires cover from 20 % to 50 % of the cable circumference)

This formula is based on long lay (15 times the diameter under the wire screen) 0,7 mm diameter, individual copper wires having a total cross-sectional area of between 15 mm^2 and 35 mm^2.

$$T_4 = \frac{1{,}5}{\pi} \rho_T \left[\ln\left(2u\right) - 0{,}630\right]$$

In this case, the thermal resistance of the insulation T_1, as calculated by the method given in 4.1.2.1 and the thermal resistance of the serving T_3, as calculated by the method given in 4.1.3 shall be multiplied by the following factors:

T_1: by 1,07 for cables up to 35 kV

by 1,16 for cables from 35 kV to ~~110~~ 150 kV

T_3: by 1,6.

4.2.4.3.4 Non-metallic sheathed cables

$$T_4 = \frac{1}{2\pi} \rho_T \left[\ln\left(2u\right) + 2\ln\left(u\right)\right]$$

~~NOTE This subject is under consideration.~~

This formula is used for non-metallic sheathed cables having a screen of spaced copper wires and for the external thermal resistance of touching ducts (see 4.2.7.4).

4.2.5 Buried pipes

The external thermal resistance of buried pipes used for pipe-type cables is calculated as for ordinary cables, using the formula in 4.2.2. In this case, the depth of laying L is measured to the centre of the pipe and D_e is the external diameter of the pipe, including anti-corrosion covering.

4.2.6 Cables in buried troughs

4.2.6.1 Buried troughs filled with sand

Where cables are installed in sand-filled troughs, either completely buried or with the cover flush with the ground surface, there is danger that the sand will dry out and remain dry for long periods. The cable external thermal resistance may then be very high and the cable may reach undesirably high temperatures. It is advisable to calculate the cable rating using a value of 2,5 K·m/W for the thermal resistivity of the sand filling unless a specially selected filling has been used for which the dry resistivity is known.

4.2.6.2 Unfilled troughs of any type, with the top flush with the soil surface and exposed to free air

An empirical formula is used which gives the temperature rise of the air in the trough above the air ambient as:

$$\Delta\theta_{tr} = \frac{W_{TOT}}{3p}$$

where

W_{TOT} is the total power dissipated in the trough per metre length (W/m);

p is that part of the trough perimeter which is effective for heat dissipation (m).

~~NOTE The validity of this formula is at present under investigation.~~

Any portion of the perimeter, which is exposed to sunlight, is therefore not included in the value of p. The rating of a particular cable in the trough is then calculated as for a cable in free air (see 4.2.1), but the ambient temperature shall be increased by $\Delta\theta_{tr}$.

4.2.7 Cables in ducts or pipes

4.2.7.1 General

The external thermal resistance of a cable in a duct consists of three parts.

a) The thermal resistance of the air space between the cable surface and duct internal surface T_4' .

b) The thermal resistance of the duct itself, T_4''. The thermal resistance of a metal pipe is negligible.

c) The external thermal resistance of the duct T_4'''.

The value of T_4 to be substituted in the equation for the permissible current rating in 1.4 of ~~part 1~~ IEC 60287-1-1:2006 and IEC 60287-1-1:2006/AMD1:2014 will be the sum of the individual parts, i.e.:

$$T_4 = T_4' + T_4'' + T_4'''$$

~~NOTE~~ Cables in ducts which have been completely filled with a pumpable material having a thermal resistivity not exceeding that of the surrounding soil, either in the dry state or when sealed to preserve the moisture content of the filling material, may be treated as directly buried cables.

4.2.7.2 Thermal resistance between cable and duct (or pipe) T_4'

For the cable diameters in the range 25 mm to 100 mm the following formula shall be used for ducted cable. It shall also be used for the thermal resistance of the space between cores and pipe surface of a pipe-type cable (see 4.1.5 b)), when the equivalent diameter of the three cores in the pipe is within the range 75 mm to 125 mm. The equivalent diameter is defined below:

$$T_4' = \frac{U}{1 + 0{,}1\,(V + Y\theta_m)\,D_e}$$

where

U, V, Y are constants, depending on the installations the values of which are given in Table 4;

D_e is the external diameter of the cable (mm);

when the formula is used for pipe-type cables (see 4.1.5 b)), D_e becomes the equivalent diameter of the group of cores as follows:

- two cores: D_e = 1,65 × core outside diameter (mm);
- three cores: D_e = 2,15 × core outside diameter (mm);
- four cores: D_e = 2,50 × core outside diameter (mm);

θ_m is the mean temperature of the medium filling the space between cable and duct. An assumed value has to be used initially and the calculation repeated with a modified value if necessary (°C).

4.2.7.3 Thermal resistance of the duct (or pipe) itself T_4''

The thermal resistance (T_4'') across the wall of a duct shall be calculated from:

$$T_4'' = \frac{1}{2\pi}\,\rho_T\,\ln\left(\frac{D_o}{D_d}\right)$$

where

D_o is the outside diameter of the duct (mm);

D_d is the inside diameter of the duct (mm);

ρ_T is the thermal resistivity of duct material (K·m/W).

The value of ρ_T can be taken as zero for metal ducts, for other materials, see Table 1.

4.2.7.4 External thermal resistance of the duct (or pipe) T_4'''

This shall be determined for single-way duct(s) not embedded in concrete in the same way as for cable, using the appropriate formulae given in 4.2.1, 4.2.2, 4.2.3 or 4.2.4, and the external radius of the duct or pipe including any protective covering thereon, replacing the external radius of the cable. When the ducts are embedded in concrete, the calculation of the thermal resistance outside the ducts is first of all made assuming a uniform medium outside the ducts having a thermal resistivity equal to the concrete. A correction is then added algebraically to take account of the difference, if any, between the thermal resistivities of concrete and soil for that part of the thermal circuit exterior to the duct bank.

The correction to the thermal resistance is given by:

$$\frac{N}{2\pi}(\rho_e - \rho_c)\ln(u + \sqrt{u^2 - 1})$$

where

N is the number of loaded cables in the duct bank;

ρ_e is the thermal resistivity of earth around bank (K·m/W);

ρ_c is the thermal resistivity of concrete (K·m/W);

$u = \dfrac{L_G}{r_b}$

L_G is the depth of laying to centre of duct bank (mm);

r_b is the equivalent radius of concrete bank (mm) given by:

$$\ln r_b = \frac{1}{2}\frac{x}{y}\left(\frac{4}{\pi} - \frac{x}{y}\right)\ln\left(1 + \frac{y^2}{x^2}\right) + \ln\frac{x}{2}$$

The quantities x and y are the shorter and longer sides, respectively, of the duct bank section irrespective of its position, in millimetres.

This formula is only valid for ratios of $\frac{y}{x}$ less than 3.

5 Digital calculation of quantities given graphically

5.1 General

Clause 5 gives formulae and methods suitable for digital calculation for those quantities given in Figures 2 to 6 and the procedure for calculating $\Delta\theta_s$ by means of Figure 10. The method used is approximation by algebraic expressions, followed by quadratic or linear interpolation where necessary. The maximum percentage error prior to interpolation is given for each case.

5.2 Geometric factor G for two-core belted cables with circular conductors

See Figure 2.

Denote $X = t_1/d_c$

$Y = (2t_1/t) - 1$

then $G = MG_s$

where

$$M = \text{formule Mie} = \ln\left[\frac{1 - \alpha\beta + \left[(1-\alpha^2)(1-\beta^2)\right]^{0,5}}{\alpha - \beta}\right]$$

$$\alpha = \frac{1}{\left[1 + \dfrac{X}{1 + X/(1+Y)}\right]^2}$$

$$\frac{\beta}{\alpha} = \frac{\dfrac{X}{1+Y} - \dfrac{1}{2}}{\dfrac{X}{1+Y} + \dfrac{3}{2}}$$

$G_s = G_s\ (X, Y)$, i.e. is a function of both X and Y.

Calculate the three quantities $G_s\ (X, 0)$, $G_s\ (X, 0{,}5)$ and $G_s\ (X, 1)$

where:

$G_s\ (X, 0) = 1{,}060\ 19 - 0{,}067\ 177\ 8\ X + 0{,}017\ 952\ 1\ X^2$

$G_s\ (X, 0{,}5) = 1{,}067\ 98 - 0{,}065\ 164\ 8\ X + 0{,}015\ 812\ 5\ X^2$

$G_s\ (X, 1) = 1{,}067\ 00 - 0{,}055\ 715\ 6\ X + 0{,}012\ 321\ 2\ X^2$

$G_s\ (X, Y)$ may be obtained by quadratic interpolation using the following formula:

$$G_s\ (X, Y) = G_s\ (X, 0) + Y\ [-3\ G_s\ (X, 0) + 4\ G_s\ (X, 0{,}5) - G_s\ (X, 1)] + Y^2\ [\ 2\ G_s\ (X, 0) - 4\ G_s\ (X, 0{,}5) + 2\ G_s\ (X, 1)]$$

The maximum percentage error in the calculation of $G_s\ (X, 0)$, $G_s\ (X, 0{,}5)$ and $G_s\ (X, 1)$ is less than 0,5 % compared with corresponding graphical values.

5.3 Geometric factor G for three-core belted cables with circular conductors

See Figure 3.

Denote $X = t_1/d_c$

$Y = (2t_1/t) - 1$

and $G = MG_s$

where

$$M = \text{formule Mie} = \ln\left[\frac{1-\alpha\beta + \left[(1-\alpha^2)(1-\beta^2)\right]^{0,5}}{\alpha-\beta}\right]$$

$$\alpha = \frac{1}{\left[1 + \dfrac{2\,X}{1+\dfrac{2}{\sqrt{3}}\left(1+\dfrac{2\,X}{1+Y}\right)}\right]^3}$$

$$\frac{\beta}{\alpha} = \frac{\dfrac{2}{\sqrt{3}}\left(1+\dfrac{2\,X}{1+Y}\right)-3}{\dfrac{2}{\sqrt{3}}\left(1+\dfrac{2\,X}{1+Y}\right)+3}$$

$G_s = G_s\ (X, Y)$, i.e., is a function of both X and Y.

Calculate the three quantities $G_s\ (X, 0)$, $G_s\ (X, 0{,}5)$ and $G_s\ (X, 1)$

where

$G_s\ (X, 0) = 1{,}094\ 14 - 0{,}094\ 404\ 5\ X + 0{,}023\ 446\ 4\ X^2$

$G_s\ (X, 0{,}5) = 1{,}096\ 05 - 0{,}080\ 185\ 7\ X + 0{,}017\ 691\ 7\ X^2$

$G_s(X, 1) = 1{,}098\ 31 - 0{,}072\ 063\ 1\ X + 0{,}014\ 590\ 9\ X^2$

and obtain $G_s(X, Y)$ by quadratic interpolation between the three calculated values.

This may be done by substituting $G_s(X, 0)$, $G_s(X, 0{,}5)$ and $G_s(X, 1)$ in the following formula:

$$G_s(X, Y) = G_s(X, 0) + Y\,[-3\,G_s(X, 0) + 4\,G_s(X, 0{,}5) - G_s(X, 1)] + Y^2\,[\,2\,G_s(X, 0) - 4\,G_s(X, 0{,}5) + 2\,G_s(X, 1)]$$

The maximum percentage error in the calculation of $G_s(X, 0)$, $G_s(X, 0{,}5)$ and $G_s(X, 1)$ is less than 0,5 % compared with corresponding graphical values.

5.4 Thermal resistance of three-core screened cables with circular conductors compared to that of a corresponding unscreened cable

See Figure 4.

Denote $X = (\delta_1\,\rho_T)/(d_c\,\rho_m)$

$Y = t_1/d_c$

The screening factor K is a function of both X and Y. Calculate the three quantities $K(X, 0{,}2)$, $K(X, 0{,}6)$ and $K(X, 1)$ from the following formulae according to whether $0 < X \le 6$ or $6 < X \le 25$.

$0 < X \le 6$

$$K(X, 0{,}2) = 0{,}998\ 095 - 0{,}123\ 369\ X + 0{,}020\ 262\ 0\ X^2 - 0{,}001\ 416\ 67\ X^3$$

$$K(X, 0{,}6) = 0{,}999\ 452 - 0{,}089\ 658\ 9\ X + 0{,}012\ 023\ 9\ X^2 - 0{,}000\ 722\ 228\ X^3$$

$$K(X, 1) = 0{,}997\ 976 - 0{,}052\ 857\ 1\ X + 0{,}003\ 452\ 38\ X^2$$

~~0~~ 6 $< X \le 25$

$$K(X, 0{,}2) = 0{,}824\ 160 - 0{,}028\ 872\ 1\ X + 0{,}000\ 928\ 511\ X^2 - 0{,}000\ 013\ 712\ 1\ X^3$$

$$K(X, 0{,}6) = 0{,}853\ 348 - 0{,}024\ 687\ 4\ X + 0{,}000\ 966\ 967\ X^2 - 0{,}000\ 015\ 996\ 7\ X^3$$

$$K(X, 1) = 0{,}883\ 287 - 0{,}015\ 378\ 2\ X + 0{,}000\ 260\ 292\ X^2$$

$K(X, Y)$ is then obtained by quadratic interpolation between the three calculated values. This may be done by substitution in the following formula:

$$K(X, Y) = K(X, 0{,}2) + Z\,[-3\,K(X, 0{,}2) + 4\,K(X, 0{,}6) - K(X, 1)] + Z^2\,[\,2\,K(X, 0{,}2) - 4\,K(X, 0{,}6) + 2\,K(X, 1)]$$

where $Z = 1{,}25\ Y - 0{,}25$

The maximum percentage error in the calculation of the sector correction factor is less than 0,5 % compared with graphical values.

5.5 Thermal resistance of three-core screened cables with sector-shaped conductors compared to that of a corresponding unscreened cable

See Figure 5.

Denote $X = (\delta_1\,\rho_T)/(d_x\,\rho_m)$

$Y = t_1/d_x$

The screening factor K is a function of both X and Y. Calculate the three quantities $K(X, 0{,}2)$, $K(X, 0{,}6)$ and $K(X, 1)$ from the following formulae according to whether $0 < X \leq 3$, $3 < X \leq 6$, or $6 < X \leq 25$.

$0 < X \leq 3$ $\quad K(X, 0{,}2) = 1{,}001\ 69 - 0{,}094\ 5\ X + 0{,}007\ 523\ 81\ X^2$

$K(X, 0{,}6) = 1{,}001\ 71 - 0{,}076\ 928\ 6\ X + 0{,}005\ 357\ 14\ X^2$

$K(X, 1) = K(X, 0{,}6)$

$3 < X \leq 6$ $\quad K(X, 0{,}2)$ and $K(X, 0{,}6)$ are given by the same formula as for $0 < X \leq 3$

$K(X, 1) = 1{,}001\ 17 - 0{,}075\ 214\ 3\ X + 0{,}005\ 333\ 34\ X^2$

$6 < X \leq 25$ $\quad K(X, 0{,}2) = 0{,}811\ 646 - 0{,}023\ 841\ 3\ X + 0{,}000\ 994\ 933\ X^2 - 0{,}000\ 015\ 515\ 2\ X^3$

$K(X, 0{,}6) = 0{,}833\ 598 - 0{,}022\ 315\ 5\ X + 0{,}000\ 978\ 956\ X^2 - 0{,}000\ 015\ 831\ 1\ X^3$

$K(X, 1) = 0{,}842\ 875 - 0{,}022\ 725\ 5\ X + 0{,}001\ 058\ 25\ X^2 - 0{,}000\ 017\ 742\ 7\ X^3$

For $0 < X \leq 3$ and $0{,}2 < Y \leq 0{,}6$, $K(X, Y)$ is obtained by linear interpolation between $K(X, 0{,}2)$ and $K(X, 0{,}6)$ as follows:

$$K(X, Y) = K(X, 0{,}2) + 2{,}5\,(Y - 0{,}2)\,[K(X, 0{,}6) - K(X, 0{,}2)]$$

For $3 < X < 25$, $K(X, Y)$ is obtained by quadratic interpolation between the three calculated values. The relevant formula is:

$$K(X, Y) = K(X, 0{,}2) + Z\,[-3\,K(X, 0{,}2) + 4\,K(X, 0{,}6) - K(X, 1)] + Z^2\,[\,2\,K(X, 0{,}2) - 4\,K(X, 0{,}6) + 2\,K(X, 1)]$$

where $Z = 1{,}25\ Y - 0{,}25$

The maximum percentage error in the calculation of the sector correction factor is less than 1 % compared with graphical values.

5.6 Curve for $\overline{G}$ for obtaining the thermal resistance of the filling material between the sheaths and armour of SL and SA type cables

See Figure 6.

Denote X = thickness of material between sheaths and armour expressed as a fraction of the outer diameter of the sheath.

The lower curve is given by:

$0 < X \leq 0{,}03$ $\quad \overline{G} = 2\pi\,(0{,}000\ 202\ 380 + 2{,}032\ 14\ X - 21{,}666\ 7\ X^2)$

$0{,}03 < X \leq 0{,}15$ $\quad \overline{G} = 2\pi\,(0{,}012\ 652\ 9 + 1{,}101\ X - 4{,}561\ 04\ X^2 + 11{,}509\ 3\ X^3)$

The maximum percentage error in the calculation of $\overline{G}$ is less than 1 %.

The upper curve is given below:

$0 < X \leq 0{,}03$ $\quad \overline{G} = 2\pi\,(0{,}000\ 226\ 19 + 2{,}114\ 29\ X - 20{,}476\ 2\ X^2)$

$0{,}03 < X \leq 0{,}15$ $\quad \overline{G} = 2\pi\,(0{,}014\ 210\ 8 + 1{,}175\ 33\ X - 4{,}497\ 37\ X^2 + 10{,}635\ 2\ X^3)$

The maximum percentage error in the calculation of $\overline{G}$ is less than 1 %.

5.7 Calculation of $\Delta\theta_s$ by means of a diagram

See Figure 10.

The procedure is as follows:

a) calculate the value of K_A using the formula:

$$K_A = \frac{\pi D_e^* h}{1+\lambda_1+\lambda_2}\left[\frac{T_1}{n} + T_2\,(1+\lambda_1) + T_3\,(1+\lambda_1+\lambda_2)\right]$$

b) locate the line on Figure 10 with the value of a) above as ordinate, and then locate the point on this line for the appropriate value of:

$$\Delta\theta + \Delta\theta_d + \Delta\theta_{ds} = \text{constant}$$

c) read off the abscissa of this point to obtain:

$$(\Delta\theta_s)^{1/4}$$

1) cables protected from solar radiation

$$\Delta\theta_d = W_d\left[\left(\frac{1}{1+\lambda_1+\lambda_2} - \frac{1}{2}\right)T_1 - \frac{n\lambda_2\,T_2}{1+\lambda_1+\lambda_2}\right]$$

if the dielectric losses are neglected, $\Delta\theta_d = 0$
$\Delta\theta_{ds} = 0$

2) cables subjected to solar radiation

$$\Delta\theta_d = W_d\left[\left(\frac{1}{1+\lambda_1+\lambda_2} - \frac{1}{2}\right)T_1 - \frac{n\lambda_2\,T_2}{1+\lambda_1+\lambda_2}\right]$$

if the dielectric losses are neglected, $\Delta\theta_d = 0$

$$\Delta\theta_{ds} = \sigma D_e^* H\left[\frac{T_1 + n\,(1+\lambda_1)\,T_2 + n\,(1+\lambda_1+\lambda_2)\,T_3}{n\,(1+\lambda_1+\lambda_2)}\right]$$

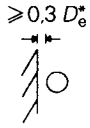
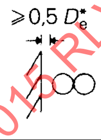
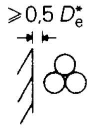
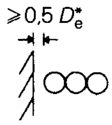
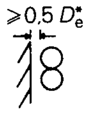
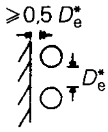
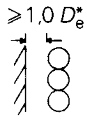
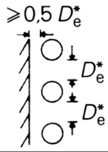
Table 1 – Thermal resistivities of materials

Material	Thermal resistivity (ρ_T) K·m/W
Insulating materials[a]	
Paper insulation in solid type cables	6,0
Paper insulation in oil-filled cables	5,0
Paper insulation in cables with external gas pressure	5,5
Paper insulation in cables with internal gas pressure:	
a) pre-impregnated	5,5
b) mass-impregnated	6,0
PE	3,5
XLPE	3,5
PPL	5,5
Polyvinyl chloride:	
up to and including 3 kV cables	5,0
greater than 3 kV cables	6,0
EPR:	
up to and including 3 kV cables	3,5
greater than 3 kV cables	5,0
Butyl rubber	5,0
Rubber	5,0
Protective coverings	
Compounded jute and fibrous materials	6,0
Rubber sandwich protection	6,0
Polychloroprene	5,5
PVC:	
up to and including 35 kV cables	5,0
greater than 35 kV cables	6,0
PVC/bitumen on corrugated aluminium sheaths	6,0
PE	3,5
Materials for duct installations	
Concrete	1,0
Fibre	4,8
Asbestos	2,0
Earthenware	1,2
PVC	6,0
PE	3,5

[a] For the purposes of current rating calculations, the semiconducting screening materials are assumed to have the same thermal properties as the adjacent dielectric materials.

Where plastic or elastomeric materials are used for protective coverings, the thermal resistivities shall be taken to be the same as those for the insulating grades of the materials given in this table.

Table 2 – Values for constants *Z*, *E* and *g* for black surfaces of cables in free air

No.	Installation	*Z*	*E*	*d*	Mode
~~2 a)~~ **Installation on non-continuous brackets, ladder supports or cleats, D_e^* not greater than 0,15 m**					
1	Single cable[a]	0,21	3,94	0,60	
2	Two cables touching, horizontal	0,29	2,35	0,50	
3	Three cables in trefoil	0,96	1,25	0,20	
4	Three cables touching, horizontal	0,62	1,95	0,25	
5	Two cables touching, vertical	1,42	0,86	0,25	
6	Two cables spaced, D_e^* vertical	0,75	2,80	0,30	
7	Three cables touching, vertical	1,61	0,42	0,20	
8	Three cables spaced, D_e^* vertical	1,31	2,00	0,20	
~~2 b)~~ **Installation clipped direct to a vertical wall (D_e^* not greater than 0,08 m)**					
9	Single cable	1,69	0,63	0,25	
10	Three cables in trefoil	0,94	0,79	0,20	

[a] Values for a “single cable” also apply to each cable of a group when they are spaced horizontally with a clearance between cables of at least 0,75 times the cable overall diameter.

Table 3 – Absorption coefficient of solar radiation for cable surfaces

Material	σ
Bitumen/jute serving	0,8
Polychloroprene	0,8
PVC	0,6
PE	0,4
Lead	0,6

Table 4 – Values of constants *U*, *V* and *Y*

Installation condition	*U*	*V*	*Y*
In metallic conduit	5,2	1,4	0,011
In fibre duct in air	5,2	0,83	0,006
In fibre duct in concrete	5,2	0,91	0,010
In asbestos cement:			
duct in air	5,2	1,2	0,006
duct in concrete	5,2	1,1	0,011
Gas pressure cable in pipe	0,95	0,46	0,002 1
Oil pressure pipe-type cable	0,26	0,0	0,002 6
Plastic ducts	~~Under consideration~~		
	1,87	0,312	0,003 7
Earthenware ducts	1,87	0,28	0,003 6
Water filled ducts	0,1	0,03	0,001

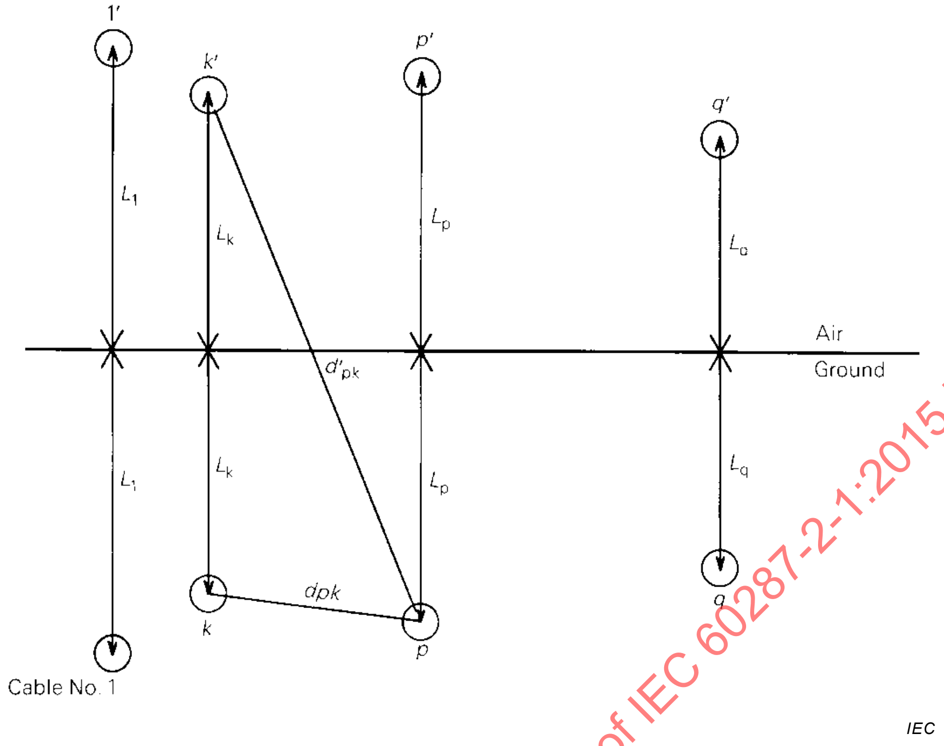


Figure 1 – Diagram showing a group of *q* cables and their reflection in the ground-air surface

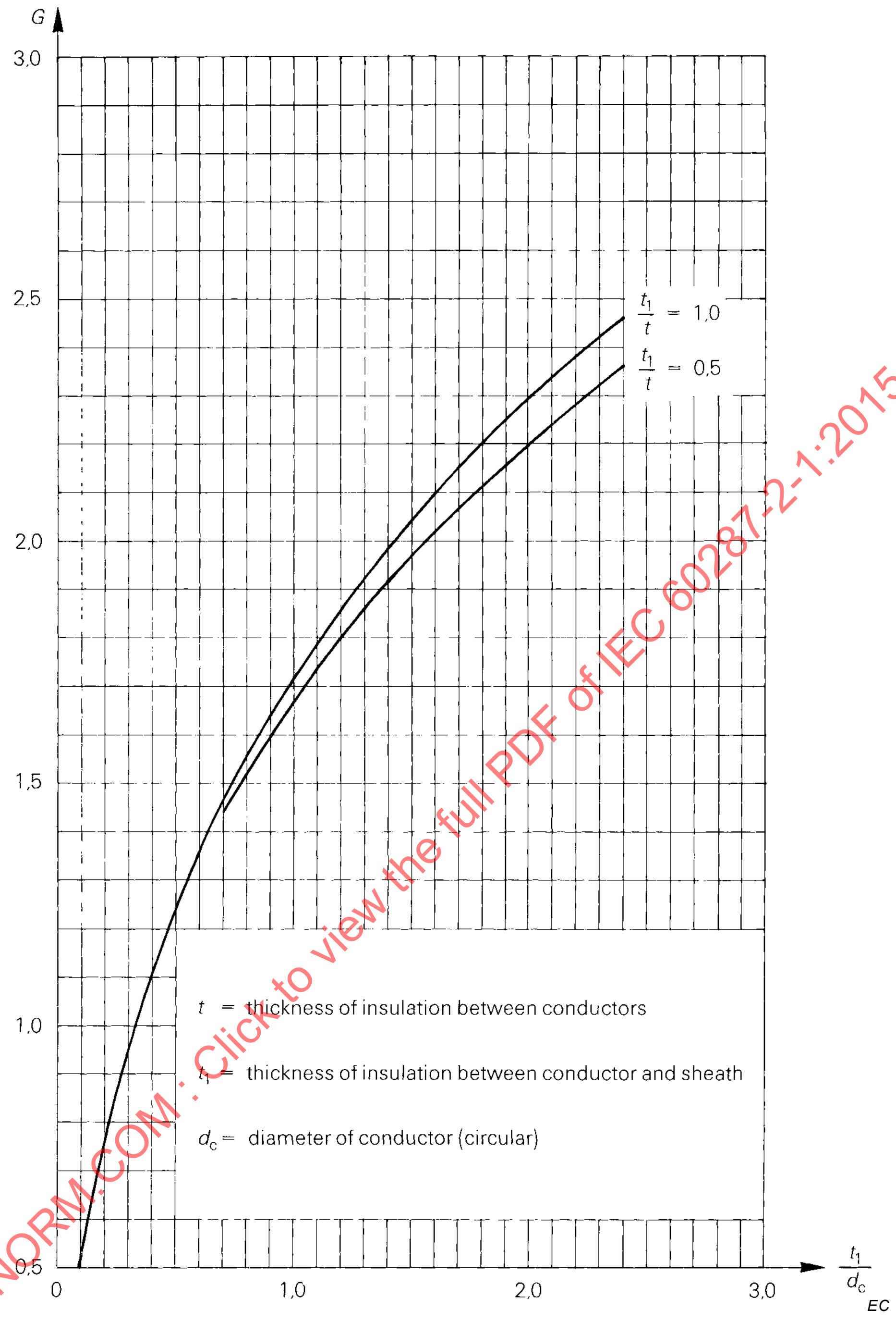


Figure 2 – Geometric factor *G* for two-core belted cables with circular conductors (see 4.1.2.2.2)

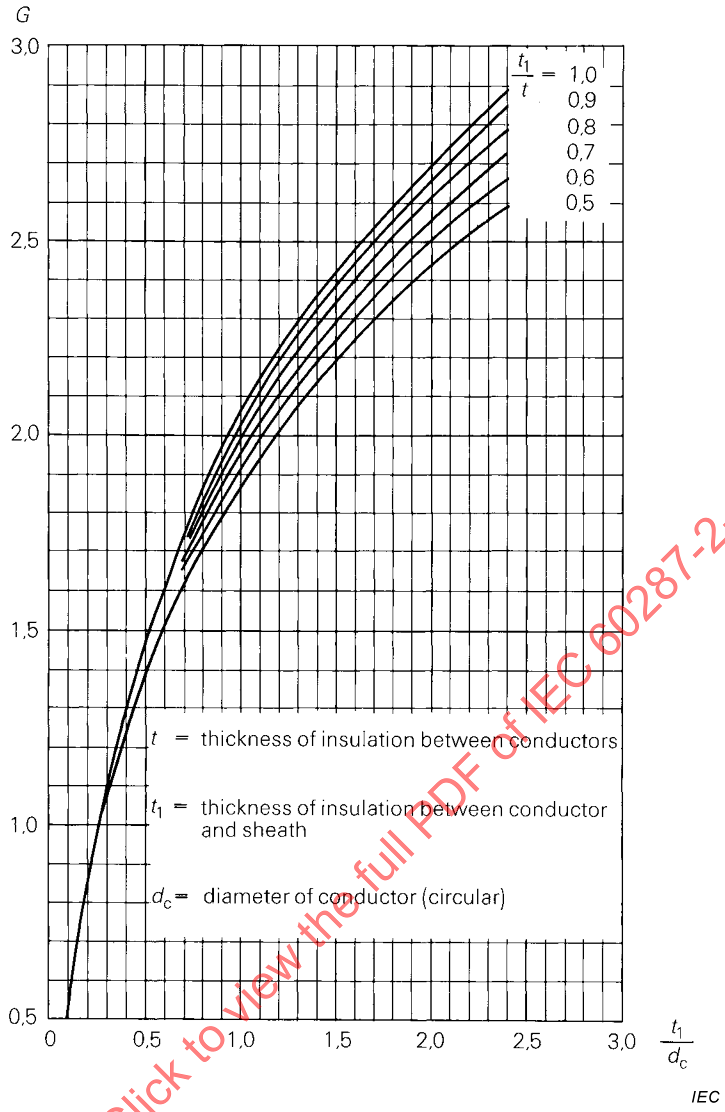


Figure 3 – Geometric factor *G* for three-core belted cables with circular conductors (see 4.1.2.2.4)

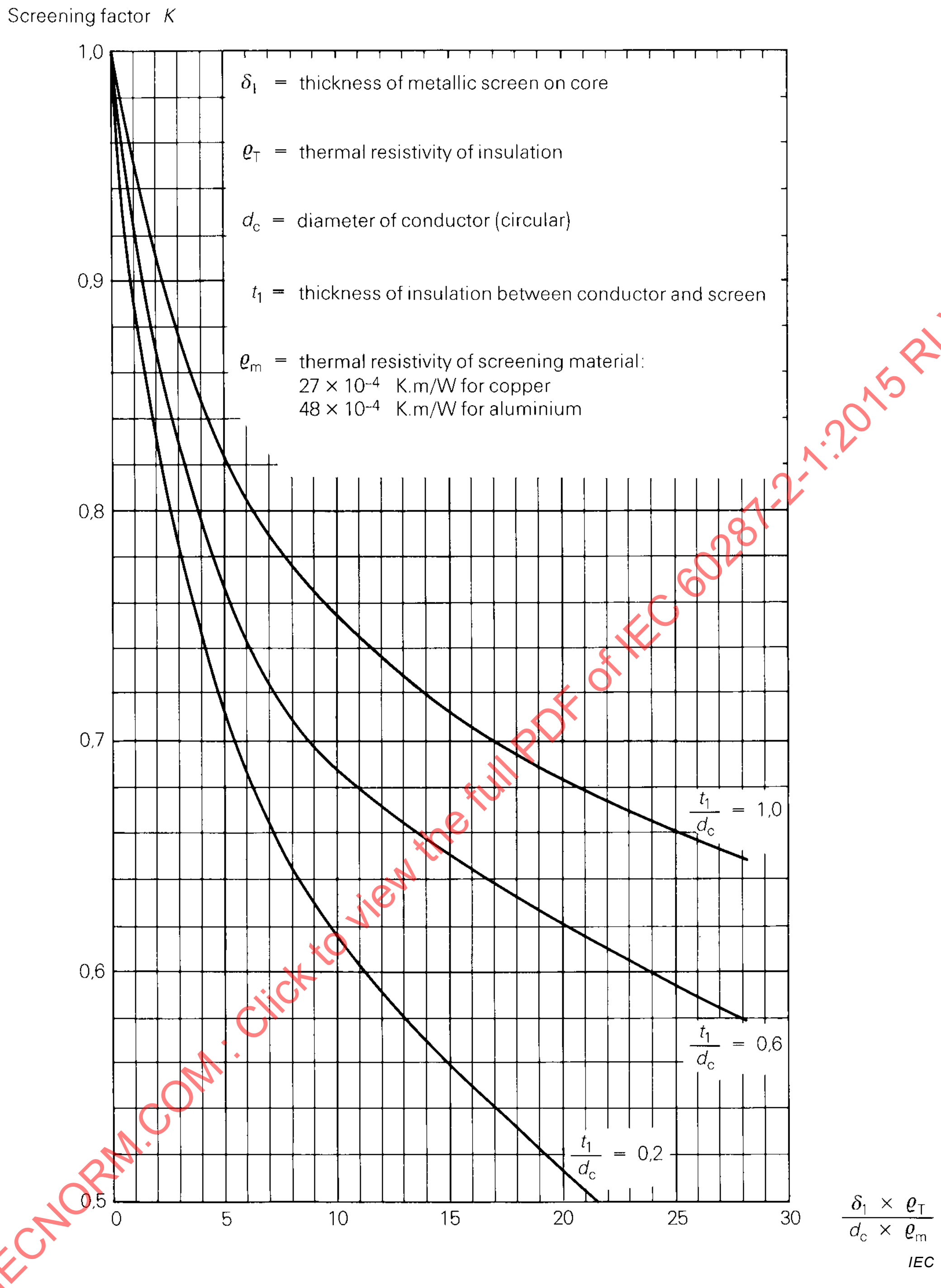


Figure 4 – Thermal resistance of three-core screened cables with circular conductors compared to that of a corresponding unscreened cable (see 4.1.2.3.1)

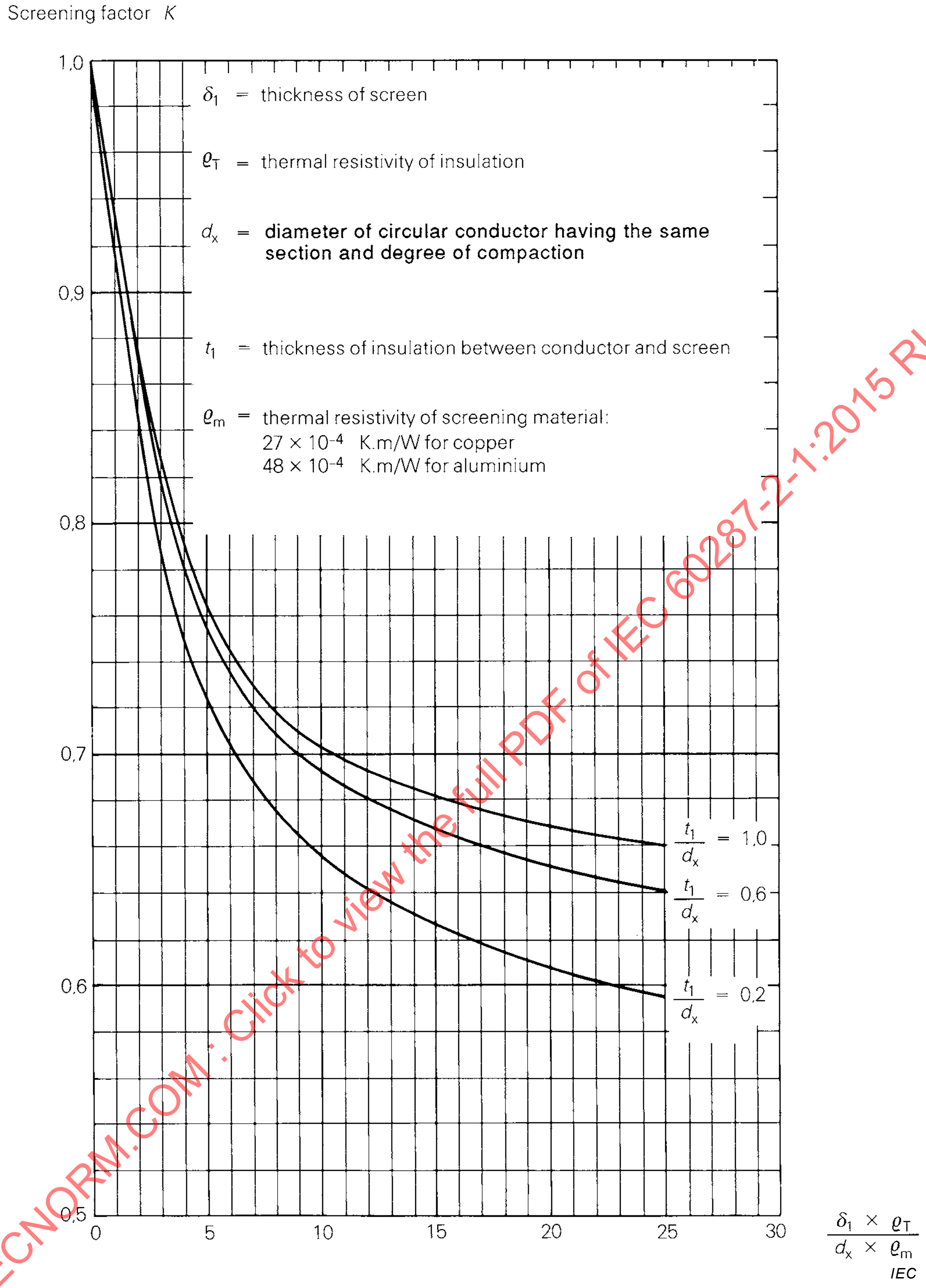


Figure 5 – Thermal resistance of three-core screened cables with sector-shaped conductors compared with that of a corresponding unscreened cable (see 4.1.2.3.3)

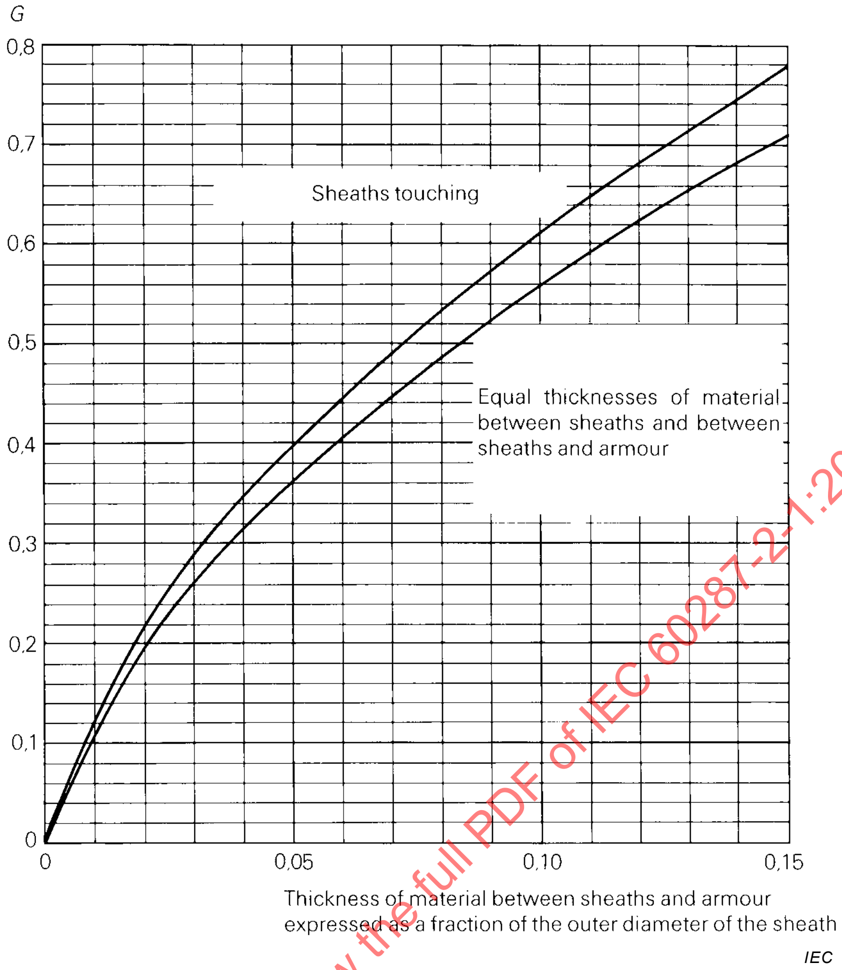


Figure 6 – Geometric factor $\overline{G}$ for obtaining the thermal resistances of the filling material between the sheaths and armour of SL and SA type cables (see 4.1.3.2)

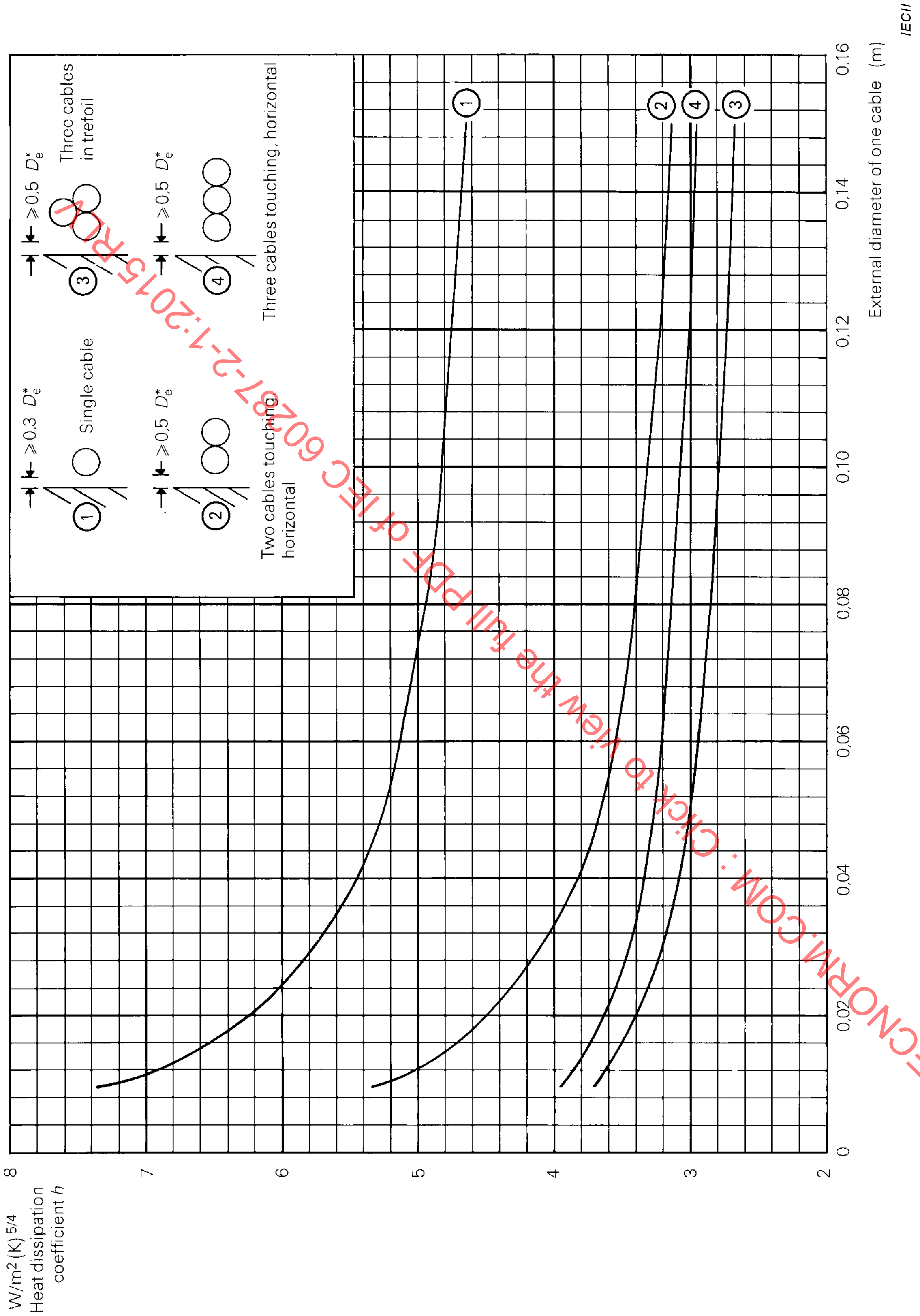


Figure 7 – Heat dissipation coefficient for black surfaces of cables in free air, laying condition #1 to #4

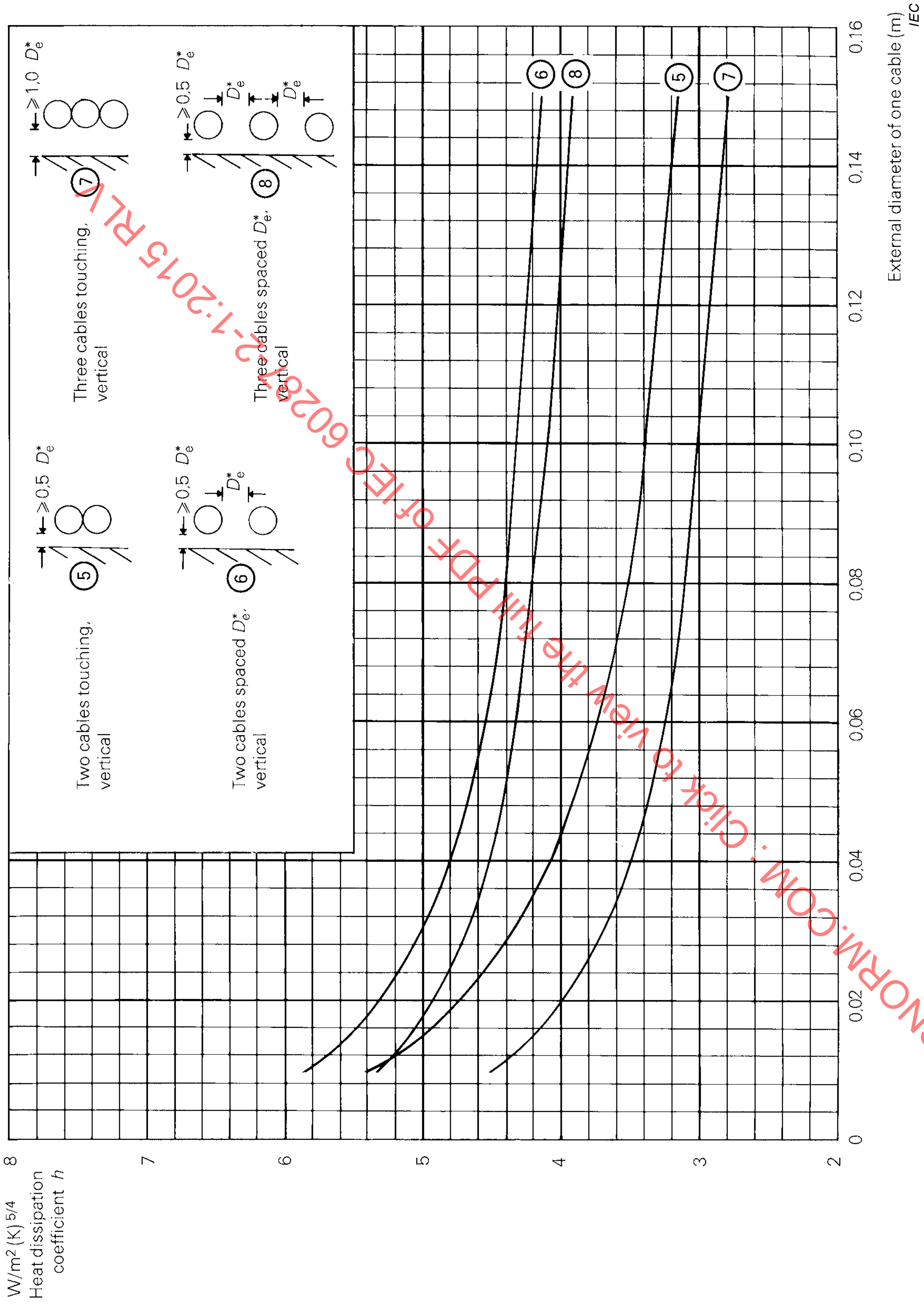


Figure 8 – Heat dissipation coefficient for black surfaces of cables in free air, laying condition #5 to #8

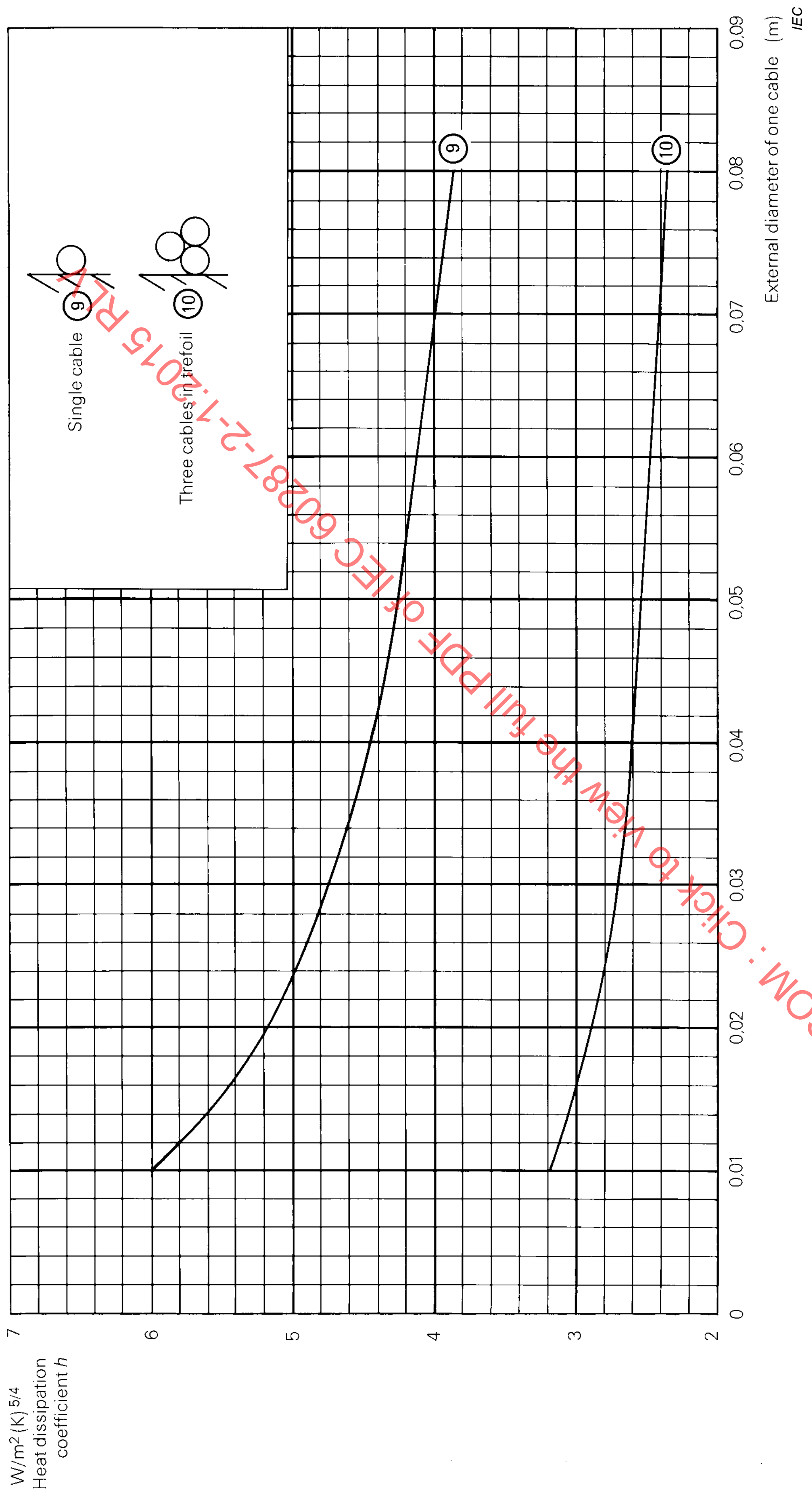


Figure 9 – Heat dissipation coefficient for black surfaces of cables in free air, laying condition #9 to #10

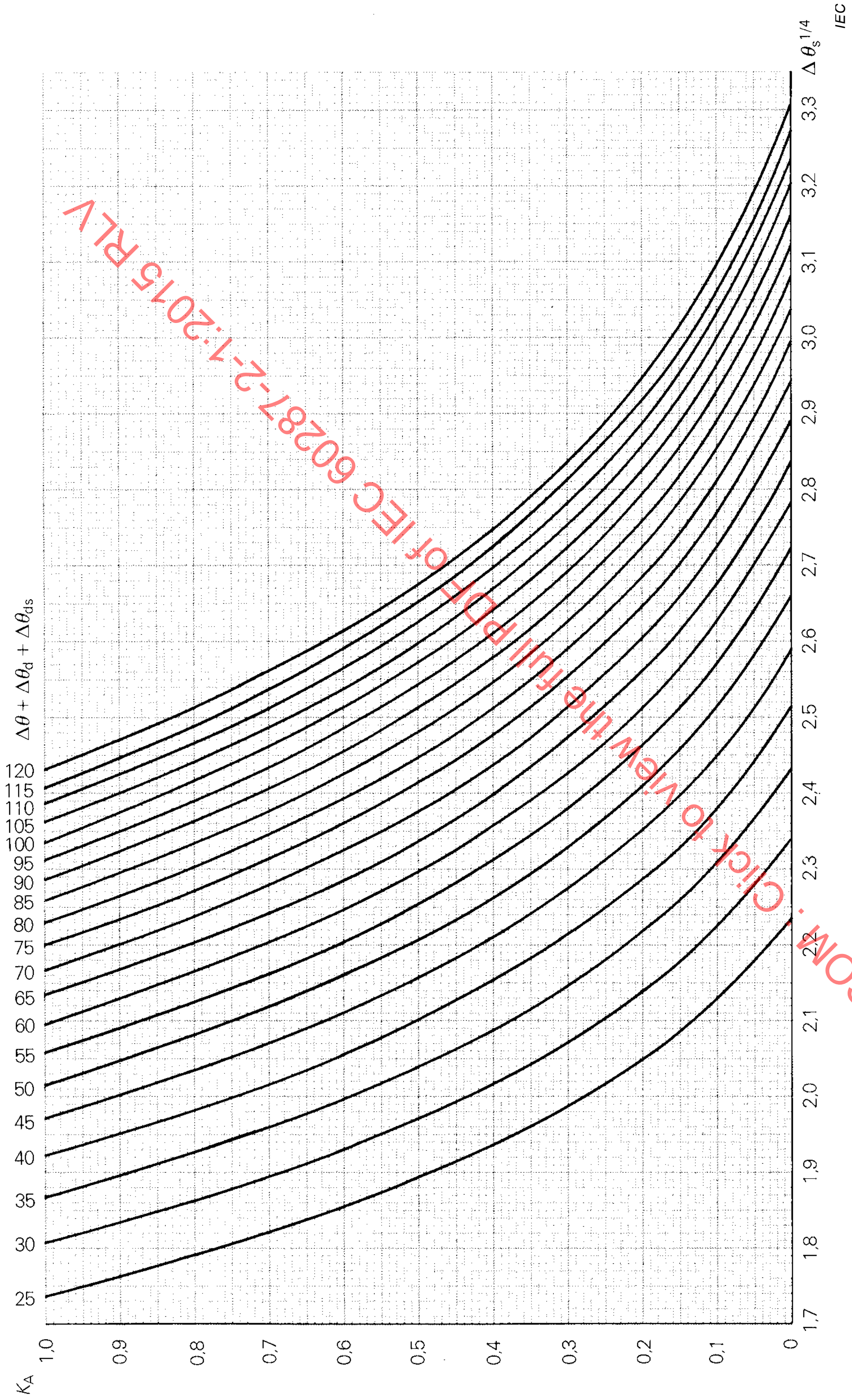


Figure 10 – Graph for the calculation of external thermal resistance of cables in air

Bibliography

IEC 60287-3-1, *Electric cables – Calculation of the current rating – Part 3: Sections on operating conditions – Section 1: Reference operating conditions and selection of cable type*

IEC TR 62095, *Electric cables – Calculations for current ratings – Finite element method*

___

IEC

IEC 60287-2-1

Edition 2.0 2015-04

INTERNATIONAL STANDARD

NORME INTERNATIONALE

Electric cables – Calculation of the current rating –
Part 2-1: Thermal resistance – Calculation of thermal resistance

Câbles électriques – Calcul du courant admissible –
Partie 2-1: Résistance thermique – Calcul de la résistance thermique

IEC 60287-2-1:2015-04(en-fr)

CONTENTS

INTERNATIONAL ELECTROTECHNICAL COMMISSION

ELECTRIC CABLES – CALCULATION OF THE CURRENT RATING –

Part 2-1: Thermal resistance – Calculation of thermal resistance

FOREWORD

1) The International Electrotechnical Commission (IEC) is a worldwide organization for standardization comprising all national electrotechnical committees (IEC National Committees). The object of IEC is to promote international co-operation on all questions concerning standardization in the electrical and electronic fields. To this end and in addition to other activities, IEC publishes International Standards, Technical Specifications, Technical Reports, Publicly Available Specifications (PAS) and Guides (hereafter referred to as "IEC Publication(s)"). Their preparation is entrusted to technical committees; any IEC National Committee interested in the subject dealt with may participate in this preparatory work. International, governmental and non-governmental organizations liaising with the IEC also participate in this preparation. IEC collaborates closely with the International Organization for Standardization (ISO) in accordance with conditions determined by agreement between the two organizations.
2) The formal decisions or agreements of IEC on technical matters express, as nearly as possible, an international consensus of opinion on the relevant subjects since each technical committee has representation from all interested IEC National Committees.
3) IEC Publications have the form of recommendations for international use and are accepted by IEC National Committees in that sense. While all reasonable efforts are made to ensure that the technical content of IEC Publications is accurate, IEC cannot be held responsible for the way in which they are used or for any misinterpretation by any end user.
4) In order to promote international uniformity, IEC National Committees undertake to apply IEC Publications transparently to the maximum extent possible in their national and regional publications. Any divergence between any IEC Publication and the corresponding national or regional publication shall be clearly indicated in the latter.
5) IEC itself does not provide any attestation of conformity. Independent certification bodies provide conformity assessment services and, in some areas, access to IEC marks of conformity. IEC is not responsible for any services carried out by independent certification bodies.
6) All users should ensure that they have the latest edition of this publication.
7) No liability shall attach to IEC or its directors, employees, servants or agents including individual experts and members of its technical committees and IEC National Committees for any personal injury, property damage or other damage of any nature whatsoever, whether direct or indirect, or for costs (including legal fees) and expenses arising out of the publication, use of, or reliance upon, this IEC Publication or any other IEC Publications.
8) Attention is drawn to the Normative references cited in this publication. Use of the referenced publications is indispensable for the correct application of this publication.
9) Attention is drawn to the possibility that some of the elements of this IEC Publication may be the subject of patent rights. IEC shall not be held responsible for identifying any or all such patent rights.

International Standard IEC 60287-2-1 has been prepared by IEC technical committee 20: Electric cables.

This second edition of IEC 60287-2-1 cancels and replaces the first edition, published in 1994, Amendment 1:2001, Amendment 2:2006 and Corrigendum 1:2008. The document 20/1448/CDV, circulated to the National Committees as Amendment 3, led to the publication of this new edition. This edition constitutes a technical revision.

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

a) inclusion of a reference to the use of finite element methods where analytical methods are not available for the calculation of external thermal resistance;
b) explanation about SL and SA type cables;

c) calculation method for T3 for unarmoured three-core cables with extruded insulation and individual copper tape screens on each core;

d) change of condition for X in 5.4;

e) inclusion of constants or installation conditions for water filled ducts in Table 4.

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

FDIS	Report on voting
20/1561/FDIS	20/1588/RVD

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

This publication has been drafted in accordance with the ISO/IEC Directives, Part 2.

A list of all parts 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 publication will remain unchanged until the stability date indicated on the IEC website under "http://webstore.iec.ch" in the data related to the specific publication. At this date, the publication will be

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

INTRODUCTION

IEC 60287 has been divided into three parts so that revisions of, and additions to the document can be carried out more conveniently.

Each part is subdivided into subparts which are published as separate standards.

Part 1: Formulae of ratings and power losses

Part 2: Formulae for thermal resistance

Part 3: Operating conditions

This part of IEC 60287-2 contains methods for calculating the internal thermal resistance of cables and the external thermal resistance for cables laid in free air, ducts and buried.

The formulae in this standard 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 may be obtained, the current ratings should be calculated with the values given in this standard. 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 may lead to erroneous conclusions if they are not based on common criteria: for example, there may 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 may 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 may 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.

ELECTRIC CABLES –
CALCULATION OF THE CURRENT RATING –

Part 2-1: Thermal resistance –
Calculation of thermal resistance

1 Scope

This part of IEC 60287 is solely 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, in 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 part of IEC 60287 provides formulae for thermal resistance.

The formulae given are essentially literal and designedly leave open the selection of certain important parameters. These may 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 may vary widely, the selection of which depends on the country in which the cables are used or are to 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).

Equations given in this part of IEC 60287 for calculating the external thermal resistance of a cable buried directly in the ground or in a buried duct are for a limited number of installation conditions. Where analytical methods are not available for calculation of external thermal resistance finite element methods may be used. Guidance on the use of finite element methods for calculating cable current ratings is given in IEC TR 62095.

2 Normative references

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

IEC 60287-1-1:2006, *Electric cables – Calculation of the current rating – Part 1-1: Current rating equations (100 % load factor) and calculation of losses – General*
IEC 60287-1-1:2006/AMD1:2014

IEC 60853-2, *Calculation of the cyclic and emergency current rating of cables – Part 2: Cyclic rating of cables greater than 18/30 (36) kV and emergency ratings for cables of all voltages*

3 Symbols

The symbols used in this part of IEC 60287 and the quantities which they represent are given in the following list:

D'_a	external diameter of armour	mm
D_d	internal diameter of duct	mm
D_e	external diameter of cable, or equivalent diameter of a group of cores in pipe-type cable	mm
D_e^*	external diameter of cable (used in 4.2.1)	m
D_o	external diameter of duct	mm
D_s	external diameter of metal sheath	mm
D_{oc}	the diameter of the imaginary coaxial cylinder which just touches the crests of a corrugated sheath	mm
D_{ot}	the diameter of the imaginary coaxial cylinder which would just touch the outside surface of the troughs of a corrugated sheath = $D_{it} + 2t_s$	mm
D_{ic}	the diameter of the imaginary cylinder which would just touch the inside surface of the crests of a corrugated sheath = $D_{oc} - 2t_s$	mm
D_{it}	the diameter of the imaginary cylinder which just touches the inside surface of the troughs of a corrugated sheath	mm
E	constant used in 4.2.1.1	
F_1	coefficient for belted cables defined in 4.1.2.2.3	
F_2	coefficient for belted cables defined in 4.1.2.2.6	
G	geometric factor for belted cables	
$\overline{G}$	geometric factor for SL and SA type cables	
H	intensity of solar radiation (see 4.2.1.2)	W/m^2
K	screening factor for the thermal resistance of screened cables	
K_A	coefficient used in 4.2.1	
L	depth of laying, to cable axis or centre of trefoil	mm
L_G	distance from the soil surface to the centre of a duct bank	mm
N	number of loaded cables in a duct bank (see 4.2.7.4)	
T_1	thermal resistance per core between conductor and sheath	K·m/W
T_2	thermal resistance between sheath and armour	K·m/W
T_3	thermal resistance of external serving	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^*	external 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	constant used in 4.2.7.2	
V	constant used in 4.2.7.2	
W_d	dielectric losses per unit length per phase	W/m
W_k	losses dissipated by cable k	W/m
W_{TOT}	total power dissipated in the trough per unit length	W/m
Y	coefficient used in 4.2.7.2	
Z	coefficient used in 4.2.1.1	

d_a	external diameter of belt insulation	mm
d_c	external diameter of conductor	mm
d_{cm}	minor diameter of an oval conductor	mm
d_{cM}	major diameter of an oval 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
g	coefficient used in 4.2.1.1	
h	heat dissipation coefficient	$W/m^2K^{5/4}$
ln	natural logarithm (logarithm to base e)	
n	number of conductors in a cable	
p	the part of the perimeter of the cable trough which is effective for heat dissipation (see 4.2.6.2)	m
r_1	circumscribing radius of two or three-sector shaped conductors	mm
s_1	axial separation of two adjacent cables in a horizontal group of three, not touching	mm
t	insulation thickness between conductors	mm
t_1	insulation thickness between conductors and sheath	mm
t_2	thickness of the bedding	mm
t_3	thickness of the serving	mm
t_i	thickness of core insulation, including screening tapes plus half the thickness of any non-metallic tapes over the laid up cores	mm
t_s	thickness of the sheath	mm
u	$\frac{2L}{D_e}$ in 4.2.	
u	$\frac{L_G}{r_b}$ in 4.2.7.4	
x, y	sides of duct bank ($y>x$) (see 4.2.7.4)	mm
θ_m	mean temperature of medium between a cable and duct or pipe	°C
$\Delta\theta$	permissible temperature rise of conductor above ambient temperature	K
$\Delta\theta_d$	factor to account for dielectric loss for calculating T_4 for cables in free air	K
$\Delta\theta_{ds}$	factor to account for both dielectric loss and direct solar radiation for calculating T_4^* for cables in free air using Figure 10	K
$\Delta\theta_{duct}$	difference between the mean temperature of air in a duct and ambient temperature	K
$\Delta\theta_s$	difference between the surface temperature of a cable in air and ambient temperature	K
$\Delta\theta_{tr}$	temperature rise of the air in a cable trough	K
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'_{1m}	loss factor for the middle cable	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	
λ'_{12}	loss factor for the outer cable with the least losses	
ρ_i	thermal resistivity of the insulation	K·m/W
ρ_f	thermal resistivity of the filler material	K·m/W
ρ_e	thermal resistivity of earth surrounding a duct bank	K·m/W
ρ_c	thermal resistivity of concrete used for a duct bank	K·m/W
ρ_m	thermal resistivity of metallic screens on multicore cables	K·m/W
ρ_T	thermal resistivity of material	K·m/W
σ	absorption coefficient of solar radiation for the cable surface	

4 Calculation of thermal resistances

4.1 Thermal resistance of the constituent parts of a cable, T_1, T_2 and T_3

4.1.1 General

Clause 4 gives the formulae for calculating the thermal resistances per unit length of the different parts of the cable T_1, T_2 and T_3 (see 1.4 of IEC 60287-1-1:2006 and IEC 60287-1-1:2006/AMD1:2014). The thermal resistivities of materials used for insulation and for protective coverings are given in Table 1.

Where screening layers are present, for thermal calculations metallic tapes are considered to be part of the conductor or sheath while semi-conducting layers (including metallized carbon paper tapes) are considered as part of the insulation. The appropriate component dimensions shall be modified accordingly.

4.1.2 Thermal resistance between one conductor and sheath T_1

4.1.2.1 Single-core cables

The thermal resistance between one conductor and the sheath T_1 is given by:

$$T_1 = \frac{\rho_T}{2\pi} \ln\left[1 + \frac{2\,t_1}{d_c}\right]$$

where

ρ_T is the thermal resistivity of insulation (K·m/W);

d_c is the diameter of conductor (mm);

t_1 is the thickness of insulation between conductor and sheath mm).

NOTE For corrugated sheaths, t_1 is based on the mean internal diameter of the sheath which is given by:

$$\left(\frac{D_{it} + D_{oc}}{2}\right) - t_s$$

4.1.2.2 Belted cables

4.1.2.2.1 General

The thermal resistance T_1 between one conductor and sheath is given by:

$$T_1 = \frac{\rho_T}{2\pi} G$$

where

G is the geometric factor

NOTE For corrugated sheaths, t_1 is based on the mean internal diameter of the sheath which is given by:

$$\left(\frac{D_{it} + D_{oc}}{2}\right) - t_s$$

4.1.2.2.2 Two-core belted cables with circular conductors

The geometric factor G is given in Figure 2.

4.1.2.2.3 Two-core belted cables with sector-shaped conductors

The geometric factor G is given by:

$$G = 2\, F_1 \ln\left[\frac{d_a}{2\, r_1}\right]$$

where

$$F_1 = 1 + \frac{2{,}2\, t}{2\pi\, (d_x + t) - t}$$

d_a is the external diameter of the belt insulation (mm);

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

d_x is the diameter of a circular conductor having the same cross-sectional area and degree of compaction as the shaped one (mm);

t is the insulation thickness between conductors (mm).

4.1.2.2.4 Three-core belted cables with circular conductors

For three-core belted cables with circular conductors

$$T_1 = \frac{\rho_i}{2\pi} G + 0{,}031(\rho_f - \rho_i) e^{0{,}67 \frac{t_1}{d_c}}$$

where

ρ_i is the thermal resistivity of the insulation (K·m/W);

ρ_f is the thermal resistivity of the filler material (K·m/W).

The geometric factor G is given in Figure 3.

NOTE For paper-insulated cables ρ_f = ρ_i and, hence, the second term on the right hand side of the above equation can be ignored.

For cables with extruded insulation, the thermal resistivity of the filler material is likely to be between 6 K·m/W and 13 K·m/W, depending on the filler material and its compaction. A value of 10 K·m/W is suggested for fibrous polypropylene fillers.

The above equation is applicable to cables with extruded insulation where each core has an individual screen of spaced wires and to cables with a common metallic screen over all three cores. For unarmoured cables of this design t_1 is taken to be the thickness of the material between the conductors and outer covering (serving).

4.1.2.2.5 Three-core belted cables with oval conductors

The cable shall be treated as an equivalent circular conductor cable with an equivalent diameter $d_c = \sqrt{d_{cM} \times d_{cm}}$ (mm)

where

d_{cM} is the major diameter of the oval conductor (mm);

d_{cm} is the minor diameter of the oval conductor (mm).

4.1.2.2.6 Three-core belted cables with sector-shaped conductors

The geometric factor G for these cables depends on the shape of the sectors, which varies from one manufacturer to another. A suitable formula is:

$$G = 3F_2 \ln\left[\frac{d_a}{2r_1}\right]$$

where

$$F_2 = 1 + \frac{3t}{2\pi(d_x + t) - t}$$

d_a is the external diameter of the belt insulation (mm);

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

d_x is the diameter of a circular conductor having the same cross-sectional area and degree of compaction as the shaped one (mm);

t is the insulation thickness between conductors (mm).

4.1.2.3 Three-core cables, metal tape screened type

4.1.2.3.1 Screened cables with circular conductors

Paper insulated of this type may be first considered as belted cables for which $\frac{t_1}{t}$ is 0,5. Then, in order to take account of the thermal conductivity of the metallic screens, the result shall be multiplied by a factor K, called the screening factor, which is given in Figure 4 for different values of $\frac{t_1}{d_c}$ and different cable specifications.

Thus:

$$T_1 = K \frac{\rho_T}{2\pi} G$$

Three-core cables with extruded insulation and individual copper tape screens on each core should be treated as SL type cables (see 4.1.2.5 and 4.1.3.2).

See 4.1.2.2.4 for three-core cables with extruded insulation and an individual screen of spaced copper wires on each core or a common metallic screen over all three cores.

4.1.2.3.2 Screened cables with oval-shaped conductors

The cable shall be treated as an equivalent circular conductor cable with an equivalent diameter $d_c = \sqrt{d_{cM} \cdot d_{cm}}$.

4.1.2.3.3 Screened cables with sector-shaped conductors

T_1 is calculated for these cables in the same way as for belted cables with sector-shaped conductors, but d_a is taken as the diameter of a circle which circumscribes the core assembly. The result is multiplied by a screening factor given in Figure 5.

4.1.2.4 Oil-filled cables

4.1.2.4.1 Three-core cables with circular conductors and metallized paper core screens and circular oil ducts between the cores

The thermal resistance between one conductor and the sheath T_1 is given by:

$$T_1 = 0{,}385\,\rho_T \left(\frac{2\,t_i}{d_c + 2\,t_i} \right)$$

where

d_c is the conductor diameter (mm);

t_i is the thickness of core insulation including carbon black and metallized paper tapes plus half of any non-metallic tapes over the three laid up cores (mm);

ρ_T is the thermal resistivity of insulation (K·m/W).

This formula assumes that the space occupied by the metal ducts and the oil inside them has a thermal conductance very high compared with the insulation, it therefore applies irrespective of the metal used to form the duct or its thickness.

4.1.2.4.2 Three-core cables with circular conductors and metal tape core screens and circular oil ducts between the cores

The thermal resistance T_1 between one conductor and the sheath is given by:

$$T_1 = 0{,}35\,\rho_T \left(0{,}923 - \frac{d_c}{d_c + 2\,t_i} \right)$$

where

t_i is the thickness of core insulation including the metal screening tapes and half on any non-metallic tapes over the three laid up cores (mm).

NOTE This formula is independent of the metals used for the screens and for the oil ducts.

4.1.2.4.3 Three-core cables with circular conductors, metal tape core screens, without fillers and oil ducts, having a copper woven fabric tape binding the cores together and a corrugated aluminium sheath

The thermal resistance T_1 between one conductor and the sheath is given by:

$$T_1 = \frac{475}{D_c^{1{,}74}} \left[\frac{t_g}{D_c} \right]^{0{,}62} + \frac{\rho_T}{2\pi} \ln \left(\frac{d_c - 2\,\delta_1}{d_c} \right)$$

where

$$t_g = 0{,}5 \left(\left[\frac{D_{it} + D_{ic}}{2} \right] - 2{,}16\,D_c \right)$$

D_c is the diameter of a core over its metallic screen tapes (mm);

t_g is the average nominal clearance between the core metallic screen tapes and the average inside diameter of the sheath (mm);

δ_1 is the thickness of metallic tape core screen (mm).

NOTE The formula is independent of the metal used for the screen tapes.

4.1.2.5 SL and SA type cables

An SL or SA type cable is a three-core cable where each core has an individual lead or aluminium sheath. The sheath is considered to be sufficiently substantial so as to provide an isotherm at the outer surface of the insulation.

The thermal resistance T_1 is calculated in the same way as for single-core cables.

4.1.3 Thermal resistance between sheath and armour T_2

4.1.3.1 Single-core, two-core and three-core cables having a common metallic sheath

The thermal resistance between sheath and armour, T_2, is given by:

$$T_2 = \frac{1}{2\pi} \rho_T \ln\left[1 + \frac{2t_2}{D_s}\right]$$

where

t_2 is the thickness of the bedding (mm);

D_s is the external diameter of the sheath (mm).

NOTE For unarmoured cables with extruded insulation where each core has an individual screen of spaced wires and for unarmoured cables with a common metallic screen over all three cores $T_2 = 0$.

4.1.3.2 SL and SA type cables

The thermal resistance of fillers and bedding under the armour is given by:

$$T_2 = \frac{\rho_T}{6\pi} \overline{G}$$

where

$\overline{G}$ is the geometric factor given in Figure 6.

4.1.4 Thermal resistance of outer covering (serving) T_3

4.1.4.1 General case

The external servings are generally in the form of concentric layers and the thermal resistance T_3 is given by:

$$T_3 = \frac{1}{2\pi} \rho_T \ln\left(1 + \frac{2t_3}{D'_a}\right)$$

where

t_3 is the thickness of serving (mm);

D'_a is the external diameter of the armour (mm).

NOTE For unarmoured cables D'_a is taken as the external diameter of the component immediately beneath it, i.e. sheath, screen or bedding.

For corrugated sheaths:

$$T_3 = \frac{1}{2\pi}\rho_T \ln\left[\frac{D_{oc}+2\,t_3}{\left(\frac{D_{oc}+D_{it}}{2}\right)+t_s}\right]$$

4.1.4.2 Unarmoured three-core cables with extruded insulation and individual copper tape screens on each core

The thermal resistance of the fillers, binder and external serving is given by:

$$T_3 = \frac{\rho_T}{2\pi}\ln\left(1+\frac{2t_3}{D'_a}\right)+\frac{\rho_f}{6\pi}\overline{G}$$

where

ρ_f is the thermal resistivity of filler (K·m/W);

$\overline{G}$ is the geometric factor given in Figure 6 based on the thickness of material between the copper tape screen and the outer covering (serving);

D'_a is taken as the diameter over the binder tape.

4.1.5 Pipe-type cables

For these three-core cables, we have:

a) The thermal resistance T_1 of the insulation of each core between the conductor and the screen. This is calculated by the method set out in 4.1.2 for single-core cables.

b) The thermal resistance T_2 is made up of two parts:

1) The thermal resistance of any serving over the screen or sheath of each core. The value to be substituted for part of T_2 in the rating equation of 1.4 of IEC 60287-1-1:2006 and IEC 60287-1-1:2006/AMD1:2014 is the value per cable, i.e. the value for a three-core cable is one-third the value of a single core.

   The value per core is calculated by the method given in 4.1.3 for the bedding of single-core cables. For oval cores, the geometric mean of the major and minor diameter $\sqrt{d_M \cdot d_m}$ shall be used in place of the diameter for a circular core assembly.

2) The thermal resistance of the gas or oil between the surface of the cores and the pipe. This resistance is calculated in the same way as that part of T_4 which is between a cable and the internal surface of a duct, as given in 4.2.7.2.

   The value calculated will be per cable and should be added to the quantity calculated in 4.1.5 b)1) above, before substituting for T_2 in the rating equation of 1.4 of IEC 60287-1-1:2006 and IEC 60287-1-1:2006/AMD1:2014.

c) The thermal resistance T_3 of any external covering on the pipe is dealt with as in 4.1.4. The thermal resistance of the metallic pipe itself is negligible.

4.2 External thermal resistance T_4

4.2.1 Cables laid in free air

4.2.1.1 Cables protected from direct solar radiation

The thermal resistance T_4 of the surroundings of a cable in air and protected from solar radiation is given by the formula:

$$T_4 = \frac{1}{\pi D_e^* h (\Delta\theta_s)^{1/4}}$$

where

$$h = \frac{Z}{(D_e^*)^g} + E$$

D_e^* is the external diameter of cable (m)

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

NOTE Throughout 4.2.1 D_e^* is expressed in metres.

h is the heat dissipation coefficient obtained either from the above formula using the appropriate values of constants Z, E and g given in Table 2, or from the curves in Figures 7, 8 and 9, which are reproduced for convenience (W/m² *(K)*$^{5/4}$);

served cables and cables having a non-metallic surface should be considered to have a black surface. Unserved cables, either plain lead or armoured should be given a value of h equal to 88 % of the value for a black surface;

$\Delta\theta_s$ is the excess of cable surface temperature above ambient temperature (see hereinafter for method of calculation) *(K)*.

For cables in unfilled troughs, see 4.2.6.

Calculation of $(\Delta\theta_s)^{1/4}$:

A simple iterative method of calculating $(\Delta\theta_s)^{1/4}$ is given below. The alternative graphical method is described in 5.7.

Calculate

$$K_A = \frac{\pi D_e^* h}{(1+\lambda_1+\lambda_2)}\left[\frac{T_1}{n} + T_2\ (1+\lambda_1) + T_3\ (1+\lambda_1+\lambda_2)\right]$$

then

$$(\Delta\theta_s)_{n+1}^{1/4} = \left[\frac{\Delta\theta + \Delta\theta_d}{1 + K_A\ (\Delta\theta_s)_n^{1/4}}\right]^{0,25}$$

Set the initial value of $(\Delta\theta_s)^{1/4} = 2$ and reiterate until $(\Delta\theta_s)_{n+1}^{1/4} - (\Delta\theta_s)_n^{1/4} \leq 0{,}001$

where

$$\Delta\theta_d = W_d \left[\left(\frac{1}{1+\lambda_1+\lambda_2} - \frac{1}{2}\right) T_1 - \frac{n\,\lambda_2\,T_2}{1+\lambda_1+\lambda_2}\right]$$

This is a factor, having the dimensions of temperature difference, accounts for the dielectric losses. If the dielectric losses are neglected, $\Delta\theta_d$ = 0.

$\Delta\theta$ is the permissible conductor temperature rise above ambient temperature.

4.2.1.2 Cables directly exposed to solar radiation – External thermal resistance T_4^*

Where cables are directly exposed to solar radiation, T_4^* is calculated by the method given in 4.2.1.1 except that in the iterative method $(\Delta\theta_s)^{1/4}$ is calculated using the following formula:

$$(\Delta\theta_s)_{n+1}^{1/4} = \left[\frac{\Delta\theta + \Delta\theta_d + \Delta\theta_{ds}}{1 + K_A\ (\Delta\theta_s)_n^{1/4}}\right]^{0,25}$$

where

$$\Delta\theta_{ds} = \frac{\sigma D_e^* H}{(1+\lambda_1+\lambda_2)}\left[\frac{T_1}{n} + T_2\ (1+\lambda_1) + T_3\ (1+\lambda_1+\lambda_2)\right]$$

This is a factor which, having the dimensions of temperature difference, accounts for direct solar radiation.

where

σ is the absorption coefficient of solar radiation for the cable surface (see Table 3);

H is the intensity of solar radiation which should be taken as 10^3 W/m² for most latitudes; it is recommended that the local value should be obtained where possible;

D_e^* is the external diameter of cable (m)

for corrugated sheaths $D_e^* = (D_{oc} + 2\ t_3) \cdot 10^{-3}$ (m).

The alternative graphical method is included in Figure 10.

4.2.2 Single isolated buried cable

$$T_4 = \frac{1}{2\pi}\rho_T \ln\left(u + \sqrt{u^2 - 1}\right)$$

where

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

$u = \dfrac{2L}{D_e}$;

L is the distance from the surface of the ground to the cable axis (mm);

D_e is the external diameter of the cable (mm)
for corrugated sheaths $D_e = D_{oc} + 2\ t_3$.

When the value of u exceeds 10, a good approximation (closer than 1 part in 1 000) is:

$$T_4 = \frac{1}{2\pi}\rho_T \ln(2u)$$

For cable circuits installed at laying depths of more than 10 m, an alternative approach for calculating the current rating is to determine the continuous current rating for a designated time period (usually 40 years) by applying the formulae given in IEC 60853-2, taking into account as far as is practical seasonal variations in load and ground conditions, if any. Finite element modelling may provide a more versatile model for such a lifetime assessment. This subject is under consideration.

4.2.3 Groups of buried cables (not touching)

4.2.3.1 General

Such cases may be solved by using superposition, assuming that each cable acts as a line source and does not distort the heat field due to the other cables.

These cables are of two main types: the first, and most general type, is a group of unequally loaded cables of different construction, and for this problem a general indication of the method only can be given. The second type, which is a more particular one, is a group of equally loaded identical cables, and for this problem a fairly simple solution can be derived.

4.2.3.2 Unequally loaded cables

The method suggested for groups of unequally loaded dissimilar cables is to calculate the temperature rise at the surface of the cable under consideration caused by the other cables of the group, and to subtract this rise from the value of $\Delta\theta$ used in the equation for the rated current in 1.4 of IEC 60287-1-1:2006 and IEC 60287-1-1:2006/AMD1:2014. An estimate of the power dissipated per unit length of each cable shall be made beforehand, and this can be subsequently amended as a result of the calculation where this becomes necessary.

Thus, the temperature rise $\Delta\theta_p$ above ambient at the surface of the p^{th} cable, whose rating is being determined, caused by the power dissipated by the other (q – 1) cables in the group, is given by:

$$\Delta\theta_p = \Delta\theta_{1p} + \Delta\theta_{2p} + \ldots \Delta\theta_{kp} + \ldots \Delta\theta_{qp}$$

(the term $\Delta\theta_{pp}$ is excluded from the summation)

where

$\Delta\theta_{kp}$ is the temperature rise at the surface of the cable produced by the power W_k watt per unit length dissipated in cable k:

$$\Delta\theta_{kp} = \frac{1}{2\pi} \rho_T W_k \ln\left(\frac{d'_{pk}}{d_{pk}}\right)$$

The distances d_{pk} and d'_{pk} are measured from the centre of the p^{th} cable to the centre of cable k, and to the centre of the reflection of cable k in the ground-air surface respectively (see Figure 1).

The value of $\Delta\theta$ in the equation for the rated current in 1.4 of IEC 60287-1-1:2006 and IEC 60287-1-1:2006/AMD1:2014 is then reduced by the amount $\Delta\theta_p$ and the rating of the p^{th} cable is determined using a value T_4 corresponding to an isolated cable at position p.

This calculation is performed for all cables in the group and is repeated where necessary to avoid the possibility of overheating any cable.

4.2.3.3 Equally loaded identical cables

4.2.3.3.1 General

The second type of grouping is where the rating of a number of equally loaded identical cables is determined by the rating of the hottest cable. It is usually possible to decide from the configuration of the installation which cable will be the hottest, and to calculate the rating for this one. In cases of difficulty, a further calculation for another cable may be necessary. The method is to calculate a modified value of T_4 which takes into account the mutual heating of the group and to leave unaltered the value of $\Delta\theta$ used in the rating equation of 1.4 of IEC 60287-1-1:2006 and IEC 60287-1-1:2006/AMD1:2014.

The modified value of the external thermal resistance T_4 of the p^{th} cable is given by:

$$T_4 = \frac{1}{2\pi}\rho_T \ln\left\{\left(u+\sqrt{u^2-1}\right)\left[\left(\frac{d'_{p1}}{d_{p1}}\right)\left(\frac{d'_{p2}}{d_{p2}}\right)\cdots\left(\frac{d'_{pk}}{d_{pk}}\right)\cdots\left(\frac{d'_{pq}}{d_{pq}}\right)\right]\right\}$$

There are $(q - 1)$ terms, with the term $\frac{d'_{pp}}{d_{pp}}$ excluded.

The distances d_{pk}, etc., are the same as those shown in Figure 1, for the first method.

The simpler version 2 u may be used instead of $u+\sqrt{u^2-1}$ if suitable (see 4.2.2).

For simple configurations of cables, this formula may be simplified considerably. The following examples were obtained by the use of superposition.

4.2.3.3.2 Two cables having equal losses, laid in a horizontal plane, spaced apart

$$T_4 = \frac{1}{2\pi}\rho_T \left\{\ln\left(u+\sqrt{u^2-1}\right) + \frac{1}{2}\ln\left[1+\left(\frac{2L}{s_1}\right)^2\right]\right\}$$

where

$u = \frac{2L}{D_e}$;

L is the distance from the surface of the ground to the cables axis (mm);

D_e is the external diameter of one cable (mm);

s_1 is the axial separation between two adjacent cables (mm).

When the value of u exceeds 10, the term $(u+\sqrt{u^2-1})$ may be replaced by $(2u)$.

4.2.3.3.3 Three cables having approximately equal losses, laid in a horizontal plane; equally spaced apart

$$T_4 = \frac{1}{2\pi}\rho_T \left\{\ln\left(u+\sqrt{u^2-1}\right) + \ln\left[1+\left(\frac{2L}{s_1}\right)^2\right]\right\}$$

The value T_4 is that of the centre cable of the group and is used directly in the equation of 1.4.1 of IEC 60287-1-1:2006.

4.2.3.3.4 Three cables having unequal sheath losses, laid in a horizontal plane; equally spaced apart

When the losses in the sheaths of single-core cables laid in a horizontal plane are appreciable, and the sheaths are laid without transposition and/or the sheaths are bonded at all joints, their inequality affects the external thermal resistances of the hottest cable. In such cases the value of T_4 to be used in the numerator of the rating equation in 1.4.1 of IEC 60287-1-1:2006 is as given in 4.2.3.3.3, but a modified value of T_4 shall be used in the denominator, and is given by:

$$T_4 = \frac{1}{2\pi}\rho_T \left\{ \ln\left(u+\sqrt{u^2-1}\right) + \left[\frac{1+0{,}5(\lambda'_{11}+\lambda'_{12})}{1+\lambda'_{lm}}\right] \ln\left[1+\left(\frac{2L}{s_1}\right)^2\right] \right\}$$

This assumes that the centre cable is the hottest cable. The value of λ_1 to be used in the rating equation of 1.4.1 of IEC 60287-1-1:2006 is that for the centre cable,

where

$u = \frac{2L}{D_e}$;

L is the distance from the surface of the ground to the cables axis (mm);

D_e is the external diameter of one cable (mm);

s_1 is the axial separation between two adjacent cables (mm);

λ'_{11} is the sheath loss factor for an outer cable of the group;

λ'_{12} is the sheath loss factor for the other outer cable of the group;

λ'_{lm} is the sheath loss factor for the middle cable of the group.

When the value of u exceeds 10, the term $(u+\sqrt{u^2-1})$ may be replaced by $(2u)$.

4.2.4 Groups of buried cables (touching) equally loaded

4.2.4.1 Two single-core cables, flat formation

4.2.4.1.1 Metallic sheathed cables

Metallic sheathed cables are taken to be cables where it can be assumed that there is a metallic layer that provides an isotherm at, or immediately under, the outer sheath of the cable.

$$T_4 = \frac{\rho_T}{\pi}\left(\ln(2u) - 0{,}451\right) \quad \text{for } u \geq 5$$

4.2.4.1.2 Non-metallic sheathed cables

Non-metallic sheathed cables are taken to be cables where any metallic layer at, or immediately under, the outer sheath of the cable is not sufficient to provide an isotherm.

$$T_4 = \frac{\rho_T}{\pi}\left(\ln(2u) - 0{,}295\right) \quad \text{for } u \geq 5$$

This formula is used for non-metallic sheathed cables having a copper wire screen and for the external thermal resistance of non-metallic touching ducts (see 4.2.7.4).

4.2.4.2 Three single-core cables, flat formation

4.2.4.2.1 Metallic sheathed cables

Metallic sheathed cables are taken to be cables where it can be assumed that there is a metallic layer that provides an isotherm at, or immediately under, the outer sheath of the cable. The value of λ_1 used in the rating equation of 1.4.1.1 of IEC 60287-1-1:2006 is the average of the λ_1 values for the three cables.

$$T_4 = \rho_T \left(0{,}475 \ \ln(2u) - 0{,}346\right) \quad \text{for } u \geq 5$$

4.2.4.2.2 Non-metallic sheathed cables

Non-metallic sheathed cables are taken to be cables where any metallic layer at, or immediately under, the outer sheath of the cable is not sufficient to provide an isotherm.

$$T_4 = \rho_T \left(0{,}475 \ \ln(2u) - 0{,}142\right) \quad \text{for } u \geq 5$$

This formula is used for non-metallic sheathed cables having a copper wire screen and for the external thermal resistance of non-metallic touching ducts (see 4.2.7.4).

4.2.4.3 Three single-core cables, trefoil formation

4.2.4.3.1 General

For this configuration, L is measured to the centre of the trefoil group and D_e is the diameter of one cable. T_4 is the external thermal resistance of any one of the cables and the configuration may be with the apex either at the top or at the bottom of the group.

For corrugated sheaths, $D_e = D_{oc} + 2\ t_3$.

4.2.4.3.2 Metallic sheathed cables

$$T_4 = \frac{1{,}5}{\pi} \rho_T \left[\ln(2u) - 0{,}630\right]$$

In this case, the thermal resistance of the serving over the sheath or armour, T_3, as calculated by the method given in 4.1.4 shall be multiplied by a factor of 1,6.

4.2.4.3.3 Part-metallic covered cables (where helically laid armour or screen wires cover from 20 % to 50 % of the cable circumference)

This formula is based on long lay (15 times the diameter under the wire screen) 0,7 mm diameter, individual copper wires having a total cross-sectional area of between 15 mm^2 and 35 mm^2.

$$T_4 = \frac{1{,}5}{\pi} \rho_T \left[\ln(2u) - 0{,}630\right]$$

In this case, the thermal resistance of the insulation T_1, as calculated by the method given in 4.1.2.1 and the thermal resistance of the serving T_3, as calculated by the method given in 4.1.3 shall be multiplied by the following factors:

T_1: by 1,07 for cables up to 35 kV

by 1,16 for cables from 35 kV to 150 kV

T_3: by 1,6.

4.2.4.3.4 Non-metallic sheathed cables

$$T_4 = \frac{1}{2\pi} \rho_T \left[\ln(2u) + 2\ln(u)\right]$$

This formula is used for non-metallic sheathed cables having a screen of spaced copper wires and for the external thermal resistance of touching ducts (see 4.2.7.4).

4.2.5 Buried pipes

The external thermal resistance of buried pipes used for pipe-type cables is calculated as for ordinary cables, using the formula in 4.2.2. In this case, the depth of laying L is measured to the centre of the pipe and D_e is the external diameter of the pipe, including anti-corrosion covering.

4.2.6 Cables in buried troughs

4.2.6.1 Buried troughs filled with sand

Where cables are installed in sand-filled troughs, either completely buried or with the cover flush with the ground surface, there is danger that the sand will dry out and remain dry for long periods. The cable external thermal resistance may then be very high and the cable may reach undesirably high temperatures. It is advisable to calculate the cable rating using a value of 2,5 K·m/W for the thermal resistivity of the sand filling unless a specially selected filling has been used for which the dry resistivity is known.

4.2.6.2 Unfilled troughs of any type, with the top flush with the soil surface and exposed to free air

An empirical formula is used which gives the temperature rise of the air in the trough above the air ambient as:

$$\Delta\theta_{tr} = \frac{W_{TOT}}{3\,p}$$

where

W_{TOT} is the total power dissipated in the trough per metre length (W/m);

p is that part of the trough perimeter which is effective for heat dissipation (m).

Any portion of the perimeter, which is exposed to sunlight, is therefore not included in the value of p. The rating of a particular cable in the trough is then calculated as for a cable in free air (see 4.2.1), but the ambient temperature shall be increased by $\Delta\theta_{tr}$.

4.2.7 Cables in ducts or pipes

4.2.7.1 General

The external thermal resistance of a cable in a duct consists of three parts.

a) The thermal resistance of the air space between the cable surface and duct internal surface T_4'.

b) The thermal resistance of the duct itself, T_4''. The thermal resistance of a metal pipe is negligible.

c) The external thermal resistance of the duct T_4''.

The value of T_4 to be substituted in the equation for the permissible current rating in 1.4 of IEC 60287-1-1:2006 and IEC 60287-1-1:2006/AMD1:2014 will be the sum of the individual parts, i.e.:

$$T_4 = T_4' + T_4'' + T_4'''$$

Cables in ducts which have been completely filled with a pumpable material having a thermal resistivity not exceeding that of the surrounding soil, either in the dry state or when sealed to preserve the moisture content of the filling material, may be treated as directly buried cables.

4.2.7.2 Thermal resistance between cable and duct (or pipe) T_4'

For the cable diameters in the range 25 mm to 100 mm the following formula shall be used for ducted cable. It shall also be used for the thermal resistance of the space between cores and pipe surface of a pipe-type cable (see 4.1.5 b)), when the equivalent diameter of the three cores in the pipe is within the range 75 mm to 125 mm. The equivalent diameter is defined below:

$$T_4' = \frac{U}{1 + 0{,}1\,(V + Y\theta_m)\,D_e}$$

where

U, V, Y are constants, depending on the installations the values of which are given in Table 4;

D_e is the external diameter of the cable (mm);

when the formula is used for pipe-type cables (see 4.1.5 b)), D_e becomes the equivalent diameter of the group of cores as follows:

- two cores: D_e = 1,65 × core outside diameter (mm);
- three cores: D_e = 2,15 × core outside diameter (mm);
- four cores: D_e = 2,50 × core outside diameter (mm);

θ_m is the mean temperature of the medium filling the space between cable and duct. An assumed value has to be used initially and the calculation repeated with a modified value if necessary (°C).

4.2.7.3 Thermal resistance of the duct (or pipe) itself T_4''

The thermal resistance (T_4'') across the wall of a duct shall be calculated from:

$$T_4'' = \frac{1}{2\pi}\,\rho_T \ln\left(\frac{D_o}{D_d}\right)$$

where

D_o is the outside diameter of the duct (mm);

D_d is the inside diameter of the duct (mm);

ρ_T is the thermal resistivity of duct material (K·m/W).

The value of ρ_T can be taken as zero for metal ducts, for other materials, see Table 1.

4.2.7.4 External thermal resistance of the duct (or pipe) T_4'''

This shall be determined for single-way duct(s) not embedded in concrete in the same way as for cable, using the appropriate formulae given in 4.2.1, 4.2.2, 4.2.3 or 4.2.4, and the external radius of the duct or pipe including any protective covering thereon, replacing the external radius of the cable. When the ducts are embedded in concrete, the calculation of the thermal resistance outside the ducts is first of all made assuming a uniform medium outside the ducts having a thermal resistivity equal to the concrete. A correction is then added algebraically to take account of the difference, if any, between the thermal resistivities of concrete and soil for that part of the thermal circuit exterior to the duct bank.

The correction to the thermal resistance is given by:

$$\frac{N}{2\pi}(\rho_e - \rho_c)\ln\left(u + \sqrt{u^2 - 1}\right)$$

where

N is the number of loaded cables in the duct bank;

ρ_e is the thermal resistivity of earth around bank (K·m/W);

ρ_c is the thermal resistivity of concrete (K·m/W);

$u = \dfrac{L_G}{r_b}$

L_G is the depth of laying to centre of duct bank (mm);

r_b is the equivalent radius of concrete bank (mm) given by:

$$\ln r_b = \frac{1}{2}\frac{x}{y}\left(\frac{4}{\pi} - \frac{x}{y}\right)\ln\left(1+\frac{y^2}{x^2}\right) + \ln\frac{x}{2}$$

The quantities x and y are the shorter and longer sides, respectively, of the duct bank section irrespective of its position, in millimetres.

This formula is only valid for ratios of $\frac{y}{x}$ less than 3.

5 Digital calculation of quantities given graphically

5.1 General

Clause 5 gives formulae and methods suitable for digital calculation for those quantities given in Figures 2 to 6 and the procedure for calculating $\Delta\theta_s$ by means of Figure 10. The method used is approximation by algebraic expressions, followed by quadratic or linear interpolation where necessary. The maximum percentage error prior to interpolation is given for each case.

5.2 Geometric factor G for two-core belted cables with circular conductors

See Figure 2.

Denote $X = t_1/d_c$

$Y = (2t_1/t) - 1$

then $G = MG_s$

where

$$M = \text{formule Mie} = \ln\left[\frac{1-\alpha\beta+\left[(1-\alpha^2)(1-\beta^2)\right]^{0,5}}{\alpha-\beta}\right]$$

$$\alpha = \frac{1}{\left[1+\dfrac{X}{1+X/(1+Y)}\right]^2}$$

$$\frac{\beta}{\alpha} = \frac{\dfrac{X}{1+Y}-\dfrac{1}{2}}{\dfrac{X}{1+Y}+\dfrac{3}{2}}$$

$G_s = G_s(X, Y)$, i.e. is a function of both X and Y.

Calculate the three quantities $G_s\ (X,\ 0)$, $G_s\ (X,\ 0{,}5)$ and $G_s\ (X,\ 1)$

where:

$G_s\ (X,\ 0) = 1{,}060\ 19 - 0{,}067\ 177\ 8\ X + 0{,}017\ 952\ 1\ X^2$

$G_s\ (X,\ 0{,}5) = 1{,}067\ 98 - 0{,}065\ 164\ 8\ X + 0{,}015\ 812\ 5\ X^2$

$G_s\ (X,\ 1) = 1{,}067\ 00 - 0{,}055\ 715\ 6\ X + 0{,}012\ 321\ 2\ X^2$

$G_s\ (X,\ Y)$ may be obtained by quadratic interpolation using the following formula:

$$G_s\ (X,\ Y) = G_s\ (X,\ 0) + Y\ [-3\ G_s\ (X,\ 0) + 4\ G_s\ (X,\ 0{,}5) - G_s\ (X,\ 1)] + Y^2\ [\ 2\ G_s\ (X,\ 0) - 4\ G_s\ (X,\ 0{,}5) + 2\ G_s\ (X,\ 1)]$$

The maximum percentage error in the calculation of $G_s\ (X,\ 0)$, $G_s\ (X,\ 0{,}5)$ and $G_s\ (X,\ 1)$ is less than 0,5 % compared with corresponding graphical values.

5.3 Geometric factor G for three-core belted cables with circular conductors

See Figure 3.

Denote $X = t_1/d_c$

$Y = (2t_1/t) - 1$

and $G = MG_s$

where

$$M = \text{formule Mie} = \ln\left[\frac{1-\alpha\beta+\left[(1-\alpha^2)(1-\beta^2)\right]^{0,5}}{\alpha-\beta}\right]$$

$$\alpha = \frac{1}{\left[1+\dfrac{2X}{1+\dfrac{2}{\sqrt{3}}\left(1+\dfrac{2X}{1+Y}\right)}\right]^3}$$

$$\frac{\beta}{\alpha} = \frac{\dfrac{2}{\sqrt{3}}\left(1+\dfrac{2X}{1+Y}\right)-3}{\dfrac{2}{\sqrt{3}}\left(1+\dfrac{2X}{1+Y}\right)+3}$$

$G_s = G_s\ (X,\ Y)$, i.e., is a function of both X and Y.

Calculate the three quantities $G_s\ (X,\ 0)$, $G_s\ (X,\ 0{,}5)$ and $G_s\ (X,\ 1)$

where

$G_s\ (X,\ 0) = 1{,}094\ 14 - 0{,}094\ 404\ 5\ X + 0{,}023\ 446\ 4\ X^2$

$G_s\ (X,\ 0{,}5) = 1{,}096\ 05 - 0{,}080\ 185\ 7\ X + 0{,}017\ 691\ 7\ X^2$

$G_s\ (X,\ 1) = 1{,}098\ 31 - 0{,}072\ 063\ 1\ X + 0{,}014\ 590\ 9\ X^2$

and obtain $G_s\ (X,\ Y)$ by quadratic interpolation between the three calculated values.

This may be done by substituting $G_s\ (X,\ 0)$, $G_s\ (X,\ 0{,}5)$ and $G_s\ (X,\ 1)$ in the following formula:

$$G_s(X, Y) = G_s(X, 0) + Y\,[-3\,G_s(X, 0) + 4\,G_s(X, 0{,}5) - G_s(X, 1)] + Y^2\,[\,2\,G_s(X, 0) - 4\,G_s(X, 0{,}5) + 2\,G_s(X, 1)]$$

The maximum percentage error in the calculation of G_s (X, 0), G_s (X, 0,5) and G_s (X, 1) is less than 0,5 % compared with corresponding graphical values.

5.4 Thermal resistance of three-core screened cables with circular conductors compared to that of a corresponding unscreened cable

See Figure 4.

Denote $X = (\delta_1\,\rho_T)/(d_c\,\rho_m)$

$Y = t_1/d_c$

The screening factor K is a function of both X and Y. Calculate the three quantities K (X, 0,2), K (X, 0,6) and K (X, 1) from the following formulae according to whether $0 < X \leq 6$ or $6 < X \leq 25$.

$0 < X \leq 6$

$$K(X, 0{,}2) = 0{,}998\,095 - 0{,}123\,369\,X + 0{,}020\,262\,0\,X^2 - 0{,}001\,416\,67\,X^3$$

$$K(X, 0{,}6) = 0{,}999\,452 - 0{,}089\,658\,9\,X + 0{,}012\,023\,9\,X^2 - 0{,}000\,722\,228\,X^3$$

$$K(X, 1) = 0{,}997\,976 - 0{,}052\,857\,1\,X + 0{,}003\,452\,38\,X^2$$

$6 < X \leq 25$

$$K(X, 0{,}2) = 0{,}824\,160 - 0{,}028\,872\,1\,X + 0{,}000\,928\,511\,X^2 - 0{,}000\,013\,712\,1\,X^3$$

$$K(X, 0{,}6) = 0{,}853\,348 - 0{,}024\,687\,4\,X + 0{,}000\,966\,967\,X^2 - 0{,}000\,015\,996\,7\,X^3$$

$$K(X, 1) = 0{,}883\,287 - 0{,}015\,378\,2\,X + 0{,}000\,260\,292\,X^2$$

K (X, Y) is then obtained by quadratic interpolation between the three calculated values. This may be done by substitution in the following formula:

$$K(X, Y) = K(X, 0{,}2) + Z\,[-3\,K(X, 0{,}2) + 4\,K(X, 0{,}6) - K(X, 1)] + Z^2\,[\,2\,K(X, 0{,}2) - 4\,K(X, 0{,}6) + 2\,K(X, 1)]$$

where $Z = 1{,}25\,Y - 0{,}25$

The maximum percentage error in the calculation of the sector correction factor is less than 0,5 % compared with graphical values.

5.5 Thermal resistance of three-core screened cables with sector-shaped conductors compared to that of a corresponding unscreened cable

See Figure 5.

Denote $X = (\delta_1\,\rho_T)/(d_x\,\rho_m)$

$Y = t_1/d_x$

The screening factor K is a function of both X and Y. Calculate the three quantities K (X, 0,2), K (X, 0,6) and K (X, 1) from the following formulae according to whether $0 < X \leq 3$, $3 < X \leq 6$, or $6 < X \leq 25$.

$0 < X \leq 3$

$$K(X, 0{,}2) = 1{,}001\,69 - 0{,}094\,5\,X + 0{,}007\,523\,81\,X^2$$

$$K(X, 0{,}6) = 1{,}001\,71 - 0{,}076\,928\,6\,X + 0{,}005\,357\,14\,X^2$$

$$K(X, 1) = K(X, 0{,}6)$$

$3 < X \leq 6$ $K(X, 0{,}2)$ and $K(X, 0{,}6)$ are given by the same formula as for $0 < X \leq 3$

$K(X, 1) = 1{,}001\,17 - 0{,}075\,214\,3\,X + 0{,}005\,333\,34\,X^2$

$6 < X \leq 25$ $K(X, 0{,}2) = 0{,}811\,646 - 0{,}023\,841\,3\,X + 0{,}000\,994\,933\,X^2 - 0{,}000\,015\,515\,2\,X^3$

$K(X, 0{,}6) = 0{,}833\,598 - 0{,}022\,315\,5\,X + 0{,}000\,978\,956\,X^2 - 0{,}000\,015\,831\,1\,X^3$

$K(X, 1) = 0{,}842\,875 - 0{,}022\,725\,5\,X + 0{,}001\,058\,25\,X^2 - 0{,}000\,017\,742\,7\,X^3$

For $0 < X \leq 3$ and $0{,}2 < Y \leq 0{,}6$, $K(X, Y)$ is obtained by linear interpolation between $K(X, 0{,}2)$ and $K(X, 0{,}6)$ as follows:

$$K(X, Y) = K(X, 0{,}2) + 2{,}5\,(Y - 0{,}2)\,[K(X, 0{,}6) - K(X, 0{,}2)]$$

For $3 < X < 25$, $K(X, Y)$ is obtained by quadratic interpolation between the three calculated values. The relevant formula is:

$$K(X, Y) = K(X, 0{,}2) + Z\,[-3\,K(X, 0{,}2) + 4\,K(X, 0{,}6) - K(X, 1)] + Z^2\,[\,2\,K(X, 0{,}2) - 4\,K(X, 0{,}6) + 2\,K(X, 1)]$$

where $Z = 1{,}25\,Y - 0{,}25$

The maximum percentage error in the calculation of the sector correction factor is less than 1 % compared with graphical values.

5.6 Curve for $\overline{G}$ for obtaining the thermal resistance of the filling material between the sheaths and armour of SL and SA type cables

See Figure 6.

Denote X = thickness of material between sheaths and armour expressed as a fraction of the outer diameter of the sheath.

The lower curve is given by:

$0 < X \leq 0{,}03$ $\overline{G} = 2\pi\,(0{,}000\,202\,380 + 2{,}032\,14\,X - 21{,}666\,7\,X^2)$

$0{,}03 < X \leq 0{,}15$ $\overline{G} = 2\pi\,(0{,}012\,652\,9 + 1{,}101\,X - 4{,}561\,04\,X^2 + 11{,}509\,3\,X^3)$

The maximum percentage error in the calculation of $\overline{G}$ is less than 1 %.

The upper curve is given below:

$0 < X \leq 0{,}03$ $\overline{G} = 2\pi\,(0{,}000\,226\,19 + 2{,}114\,29\,X - 20{,}476\,2\,X^2)$

$0{,}03 < X \leq 0{,}15$ $\overline{G} = 2\pi\,(0{,}014\,210\,8 + 1{,}175\,33\,X - 4{,}497\,37\,X^2 + 10{,}635\,2\,X^3)$

The maximum percentage error in the calculation of $\overline{G}$ is less than 1 %.

5.7 Calculation of $\Delta\theta_s$ by means of a diagram

See Figure 10.

The procedure is as follows:

a) calculate the value of K_A using the formula:

$$K_A = \frac{\pi D_e^* h}{1+\lambda_1+\lambda_2}\left[\frac{T_1}{n}+T_2\,(1+\lambda_1)+T_3\,(1+\lambda_1+\lambda_2)\right]$$

b) locate the line on Figure 10 with the value of a) above as ordinate, and then locate the point on this line for the appropriate value of:

$$\Delta\theta + \Delta\theta_d + \Delta\theta_{ds} = \text{constant}$$

c) read off the abscissa of this point to obtain:

$$(\Delta\theta_s)^{1/4}$$

1) cables protected from solar radiation

$$\Delta\theta_d = W_d\left[\left(\frac{1}{1+\lambda_1+\lambda_2} - \frac{1}{2}\right)T_1 - \frac{n\lambda_2\,T_2}{1+\lambda_1+\lambda_2}\right]$$

if the dielectric losses are neglected, $\Delta\theta_d = 0$
$\Delta\theta_{ds} = 0$

2) cables subjected to solar radiation

$$\Delta\theta_d = W_d\left[\left(\frac{1}{1+\lambda_1+\lambda_2} - \frac{1}{2}\right)T_1 - \frac{n\lambda_2\,T_2}{1+\lambda_1+\lambda_2}\right]$$

if the dielectric losses are neglected, $\Delta\theta_d = 0$

$$\Delta\theta_{ds} = \sigma D_e^* H\left[\frac{T_1+n\,(1+\lambda_1)\,T_2+n\,(1+\lambda_1+\lambda_2)\,T_3}{n\,(1+\lambda_1+\lambda_2)}\right]$$

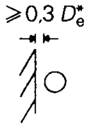
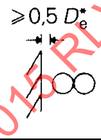
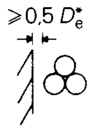
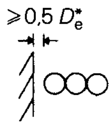
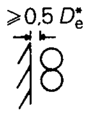
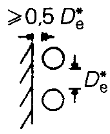
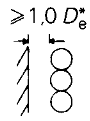
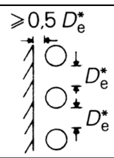
Table 1 – Thermal resistivities of materials

Material	Thermal resistivity (ρ_T) K·m/W
Insulating materials[a]	
Paper insulation in solid type cables	6,0
Paper insulation in oil-filled cables	5,0
Paper insulation in cables with external gas pressure	5,5
Paper insulation in cables with internal gas pressure:	
a) pre-impregnated	5,5
b) mass-impregnated	6,0
PE	3,5
XLPE	3,5
PPL	5,5
Polyvinyl chloride:	
up to and including 3 kV cables	5,0
greater than 3 kV cables	6,0
EPR:	
up to and including 3 kV cables	3,5
greater than 3 kV cables	5,0
Butyl rubber	5,0
Rubber	5,0
Protective coverings	
Compounded jute and fibrous materials	6,0
Rubber sandwich protection	6,0
Polychloroprene	5,5
PVC:	
up to and including 35 kV cables	5,0
greater than 35 kV cables	6,0
PVC/bitumen on corrugated aluminium sheaths	6,0
PE	3,5
Materials for duct installations	
Concrete	1,0
Fibre	4,8
Asbestos	2,0
Earthenware	1,2
PVC	6,0
PE	3,5

[a] For the purposes of current rating calculations, the semiconducting screening materials are assumed to have the same thermal properties as the adjacent dielectric materials.

Where plastic or elastomeric materials are used for protective coverings, the thermal resistivities shall be taken to be the same as those for the insulating grades of the materials given in this table.

Table 2 – Values for constants *Z*, *E* and *g* for black surfaces of cables in free air

No.	Installation	*Z*	*E*	*d*	Mode
Installation on non-continuous brackets, ladder supports or cleats, D_e^* not greater than 0,15 m					
1	Single cable[a]	0,21	3,94	0,60	
2	Two cables touching, horizontal	0,29	2,35	0,50	
3	Three cables in trefoil	0,96	1,25	0,20	
4	Three cables touching, horizontal	0,62	1,95	0,25	
5	Two cables touching, vertical	1,42	0,86	0,25	
6	Two cables spaced, D_e^* vertical	0,75	2,80	0,30	
7	Three cables touching, vertical	1,61	0,42	0,20	
8	Three cables spaced, D_e^* vertical	1,31	2,00	0,20	
Installation clipped direct to a vertical wall (D_e^* not greater than 0,08 m)					
9	Single cable	1,69	0,63	0,25	
10	Three cables in trefoil	0,94	0,79	0,20	

[a] Values for a “single cable” also apply to each cable of a group when they are spaced horizontally with a clearance between cables of at least 0,75 times the cable overall diameter.

Table 3 – Absorption coefficient of solar radiation for cable surfaces

Material	σ
Bitumen/jute serving	0,8
Polychloroprene	0,8
PVC	0,6
PE	0,4
Lead	0,6

Table 4 – Values of constants *U, V* and *Y*

Installation condition	*U*	*V*	*Y*
In metallic conduit	5,2	1,4	0,011
In fibre duct in air	5,2	0,83	0,006
In fibre duct in concrete	5,2	0,91	0,010
In asbestos cement:			
duct in air	5,2	1,2	0,006
duct in concrete	5,2	1,1	0,011
Gas pressure cable in pipe	0,95	0,46	0,002 1
Oil pressure pipe-type cable	0,26	0,0	0,002 6
Plastic ducts	1,87	0,312	0,003 7
Earthenware ducts	1,87	0,28	0,003 6
Water filled ducts	0,1	0,03	0,001

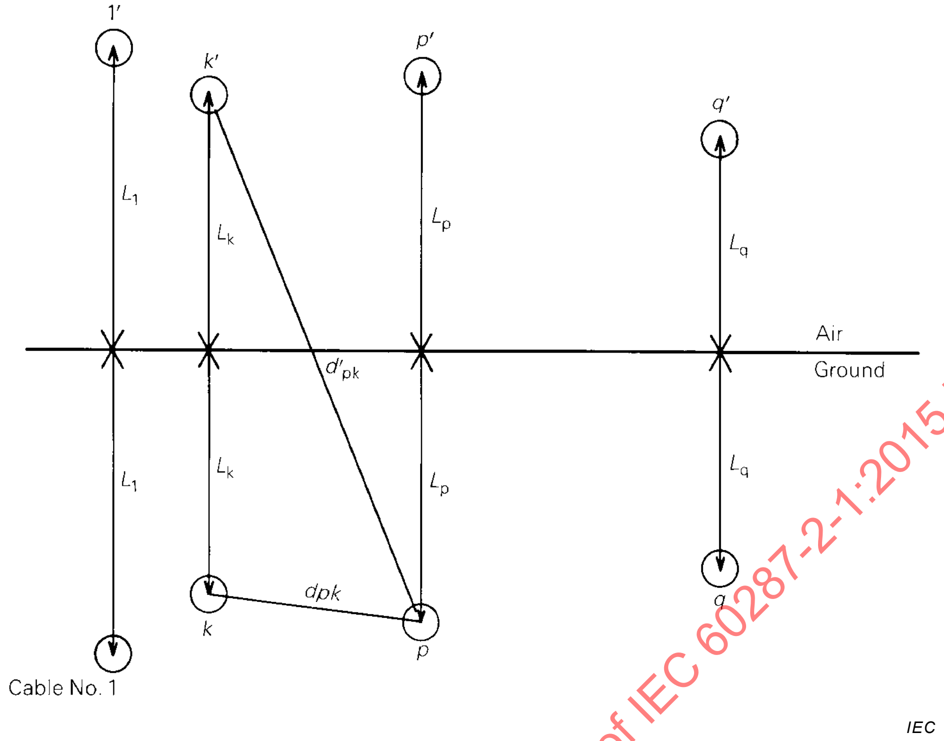


Figure 1 – Diagram showing a group of *q* cables and their reflection in the ground-air surface

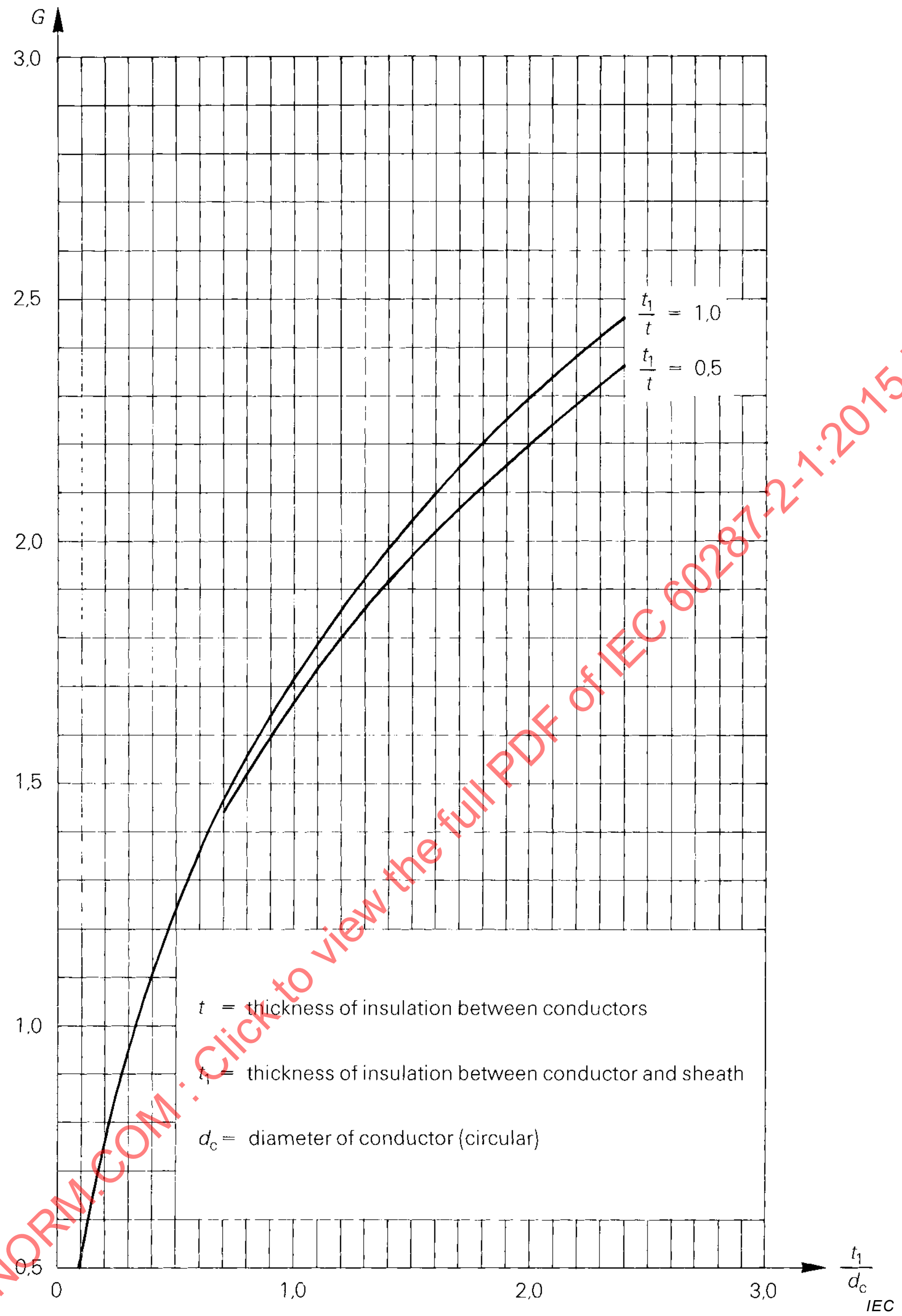


Figure 2 – Geometric factor *G* for two-core belted cables with circular conductors (see 4.1.2.2.2)

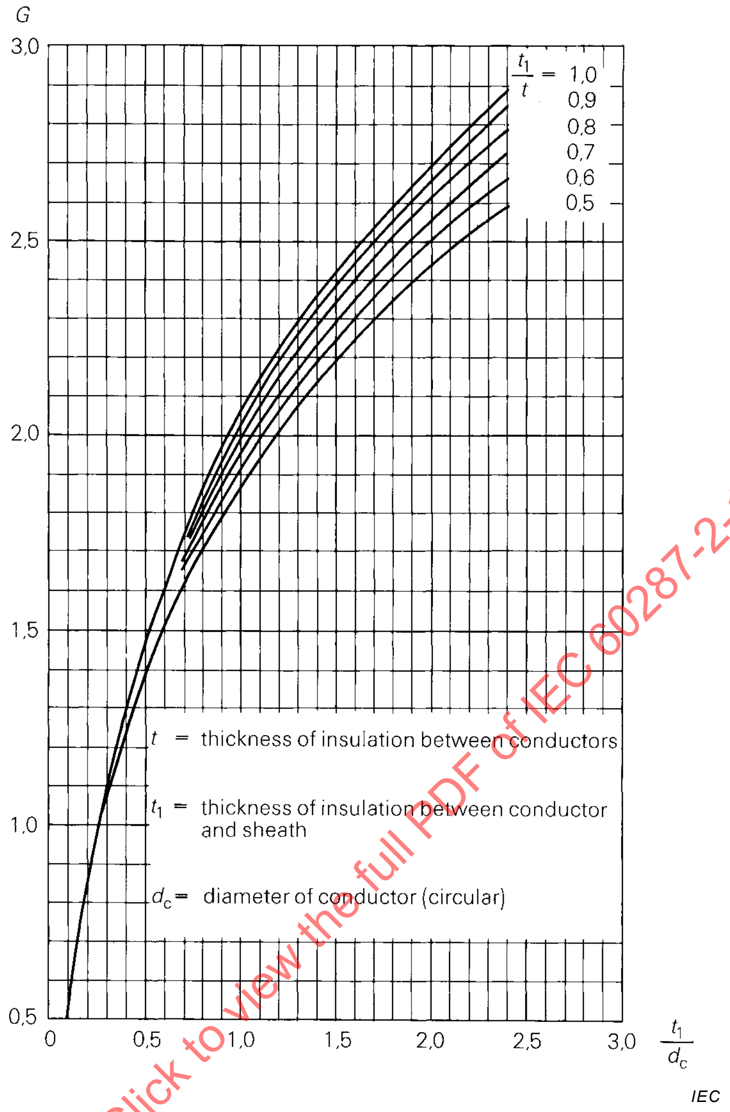


Figure 3 – Geometric factor *G* for three-core belted cables with circular conductors (see 4.1.2.2.4)

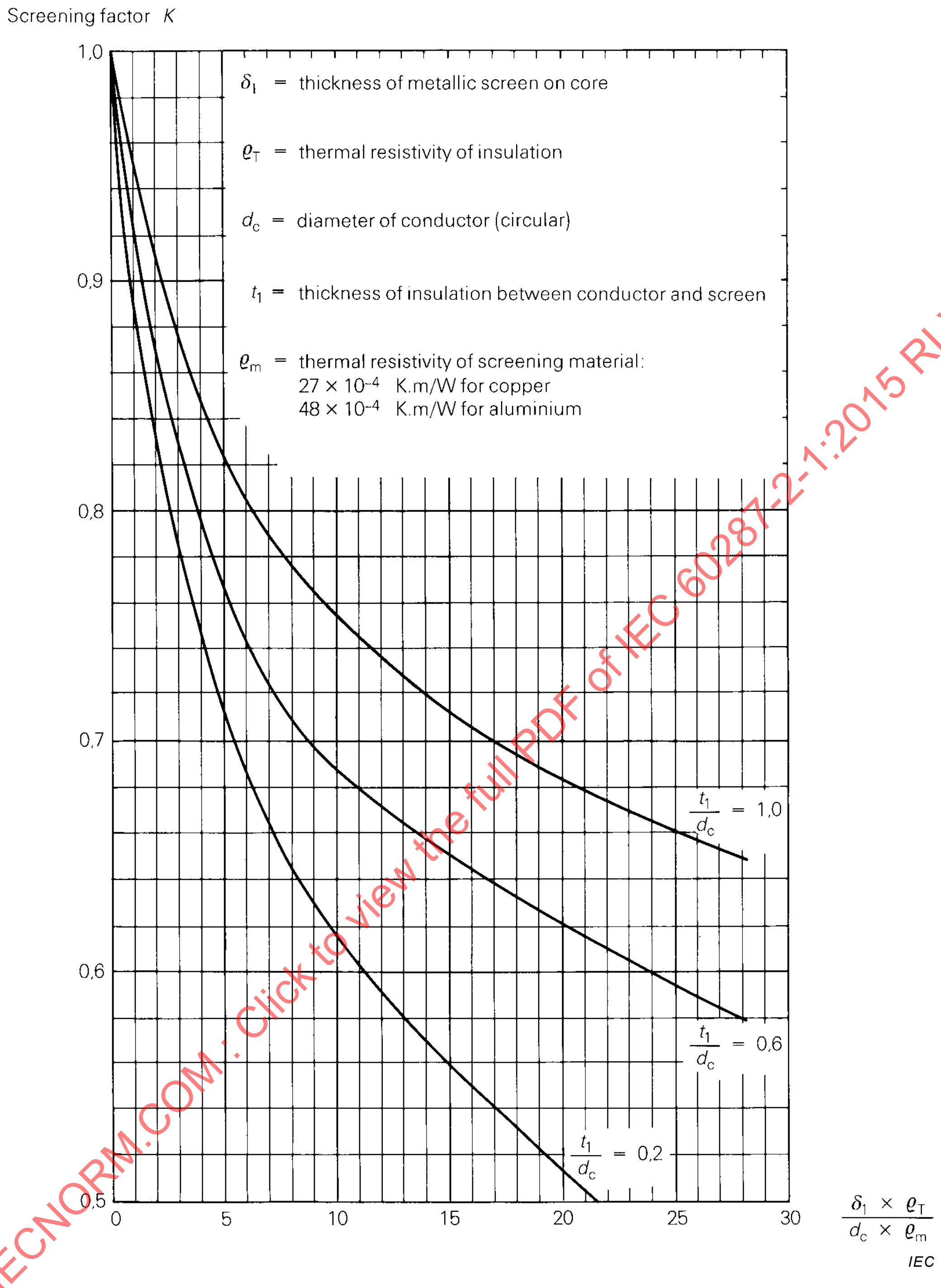


Figure 4 – Thermal resistance of three-core screened cables with circular conductors compared to that of a corresponding unscreened cable (see 4.1.2.3.1)

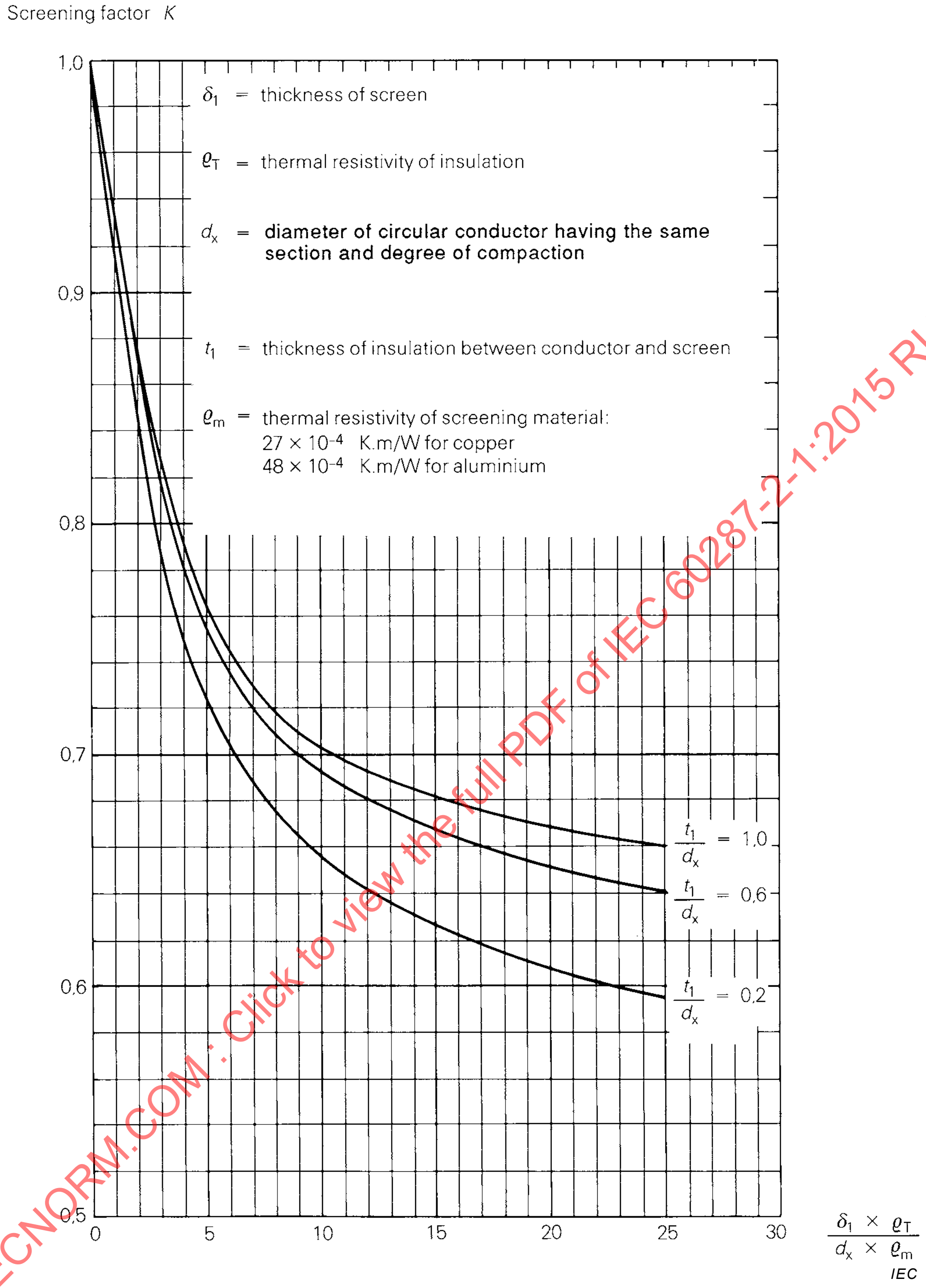


Figure 5 – Thermal resistance of three-core screened cables with sector-shaped conductors compared with that of a corresponding unscreened cable (see 4.1.2.3.3)

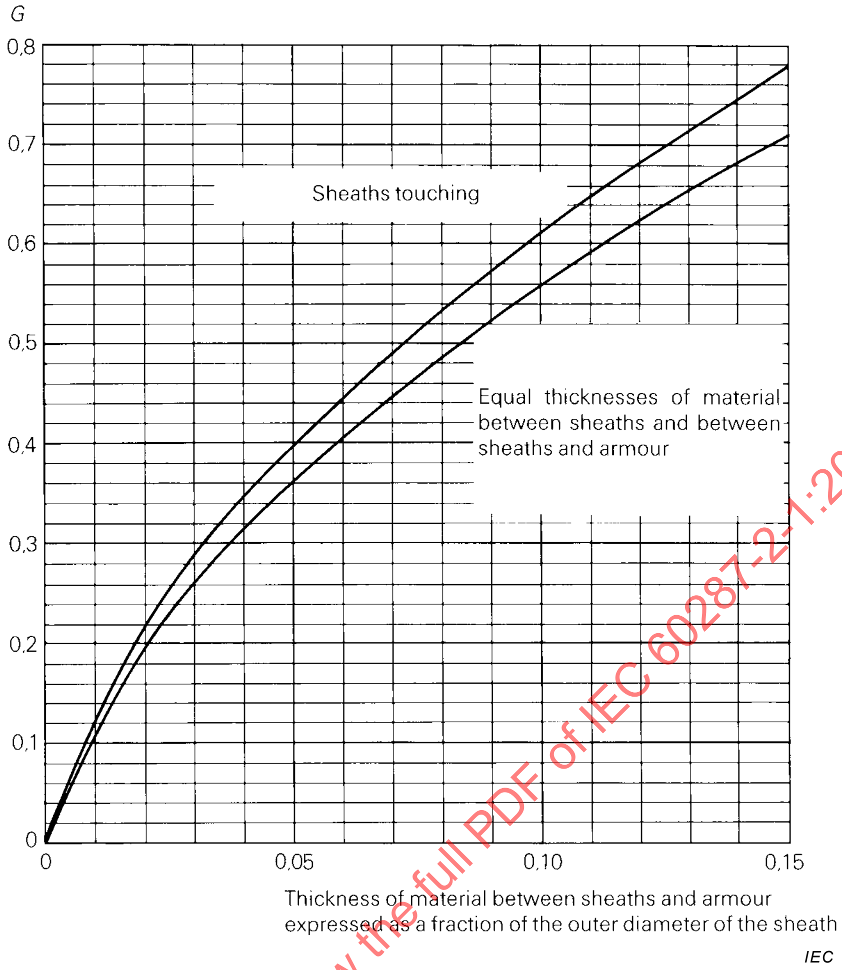


Figure 6 – Geometric factor $\overline{G}$ for obtaining the thermal resistances of the filling material between the sheaths and armour of SL and SA type cables (see 4.1.3.2)

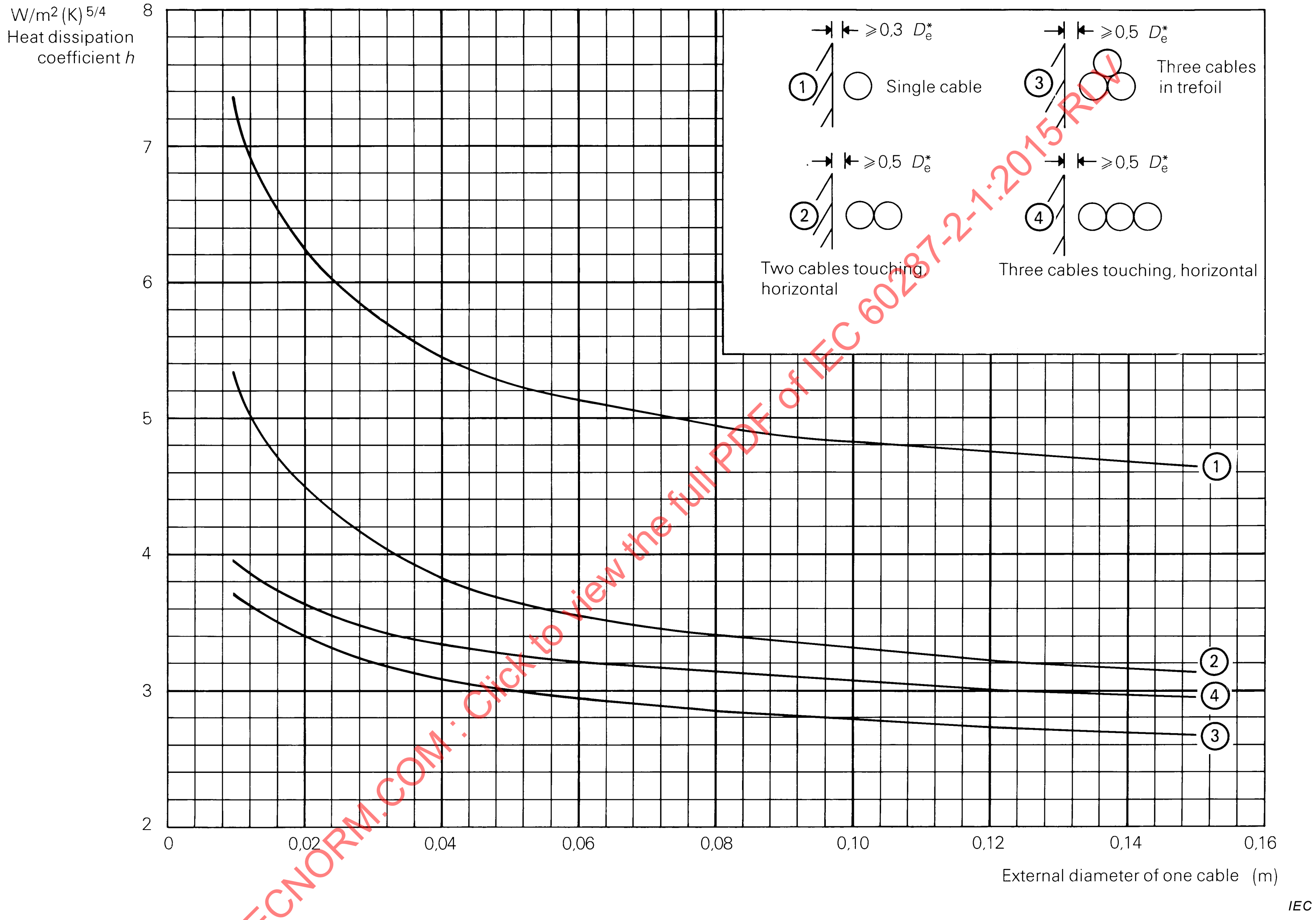


Figure 7 – Heat dissipation coefficient for black surfaces of cables in free air, laying condition #1 to #4

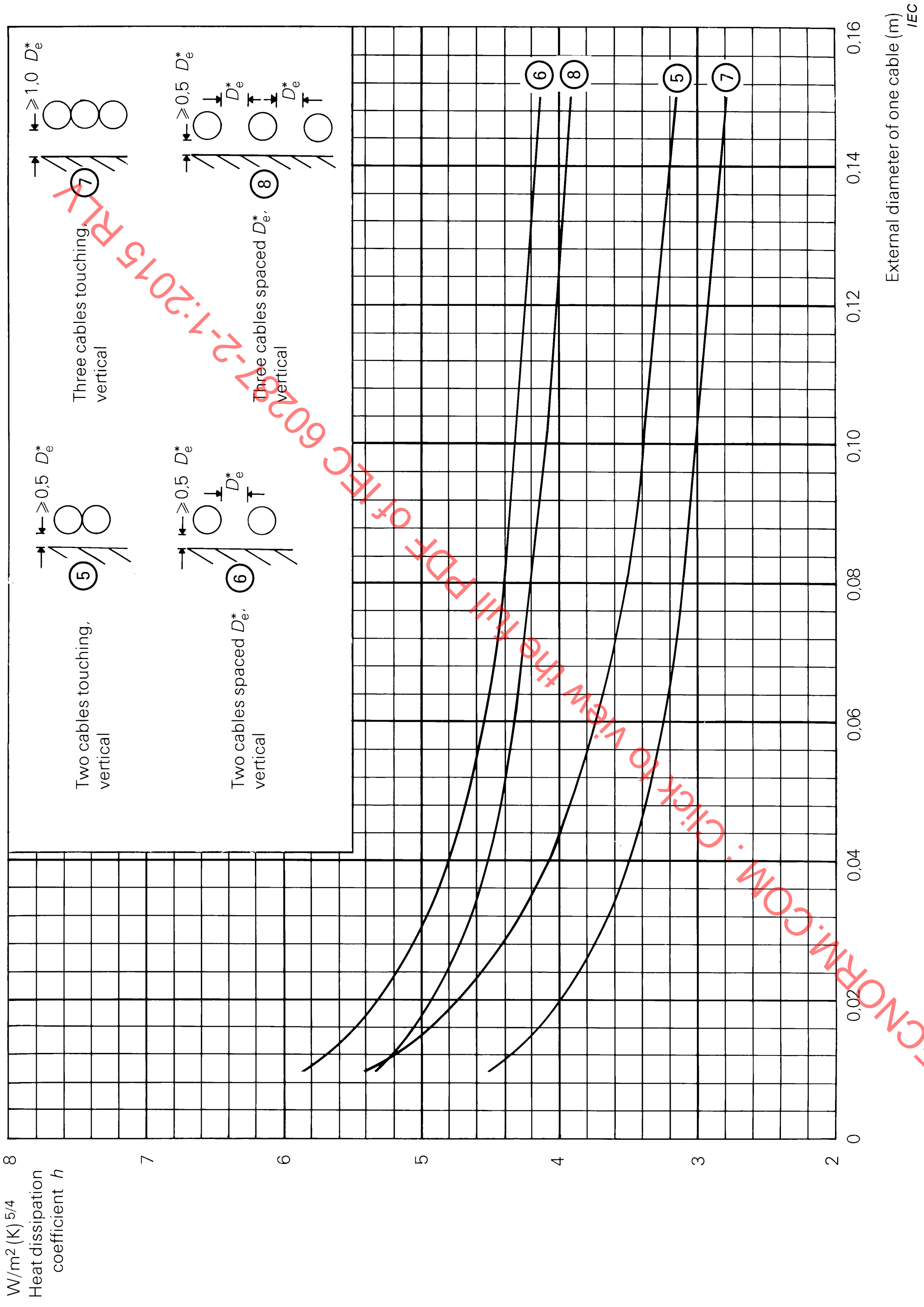


Figure 8 – Heat dissipation coefficient for black surfaces of cables in free air, laying condition #5 to #8

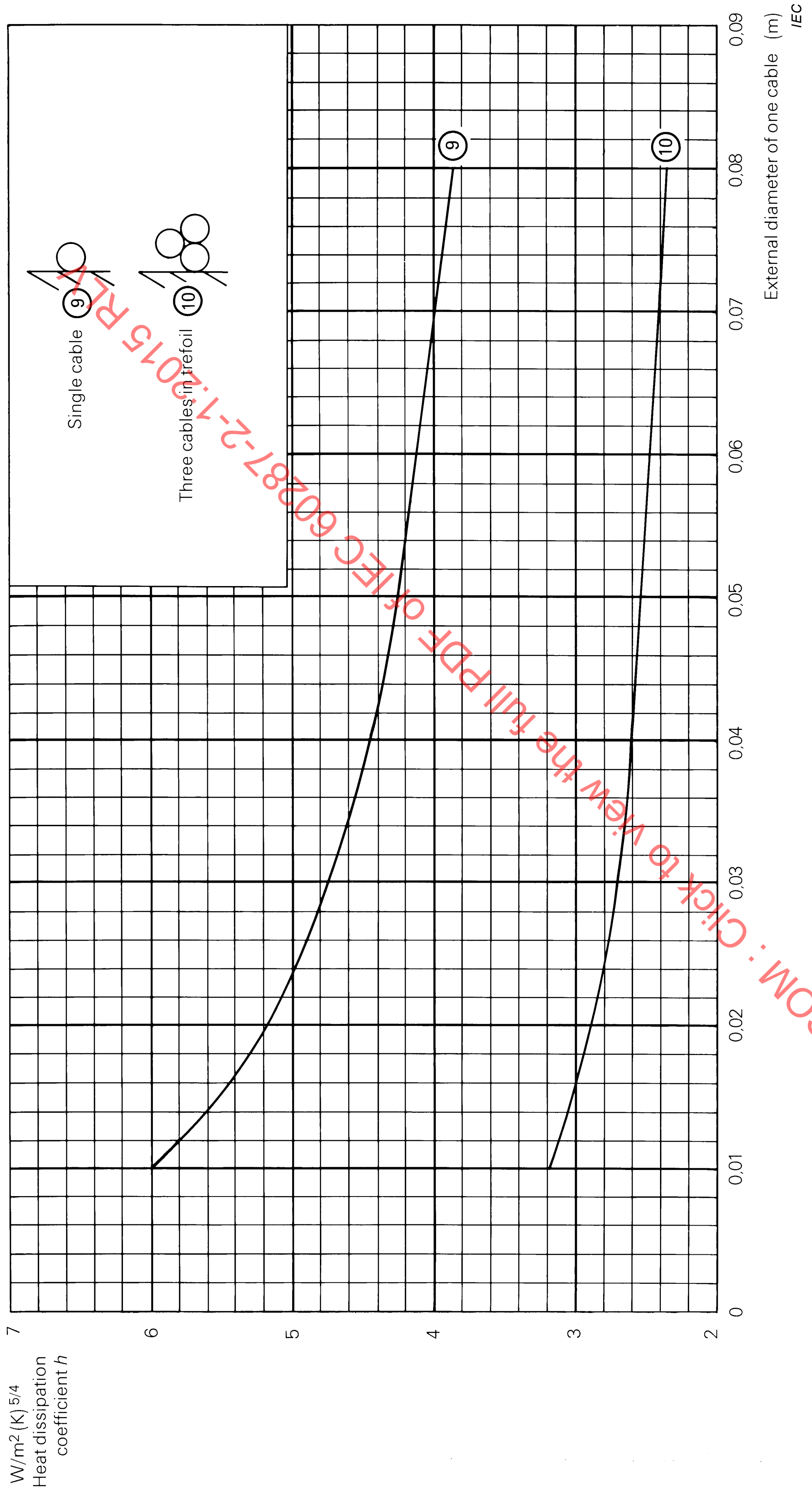


Figure 9 – Heat dissipation coefficient for black surfaces of cables in free air, laying condition #9 to #10

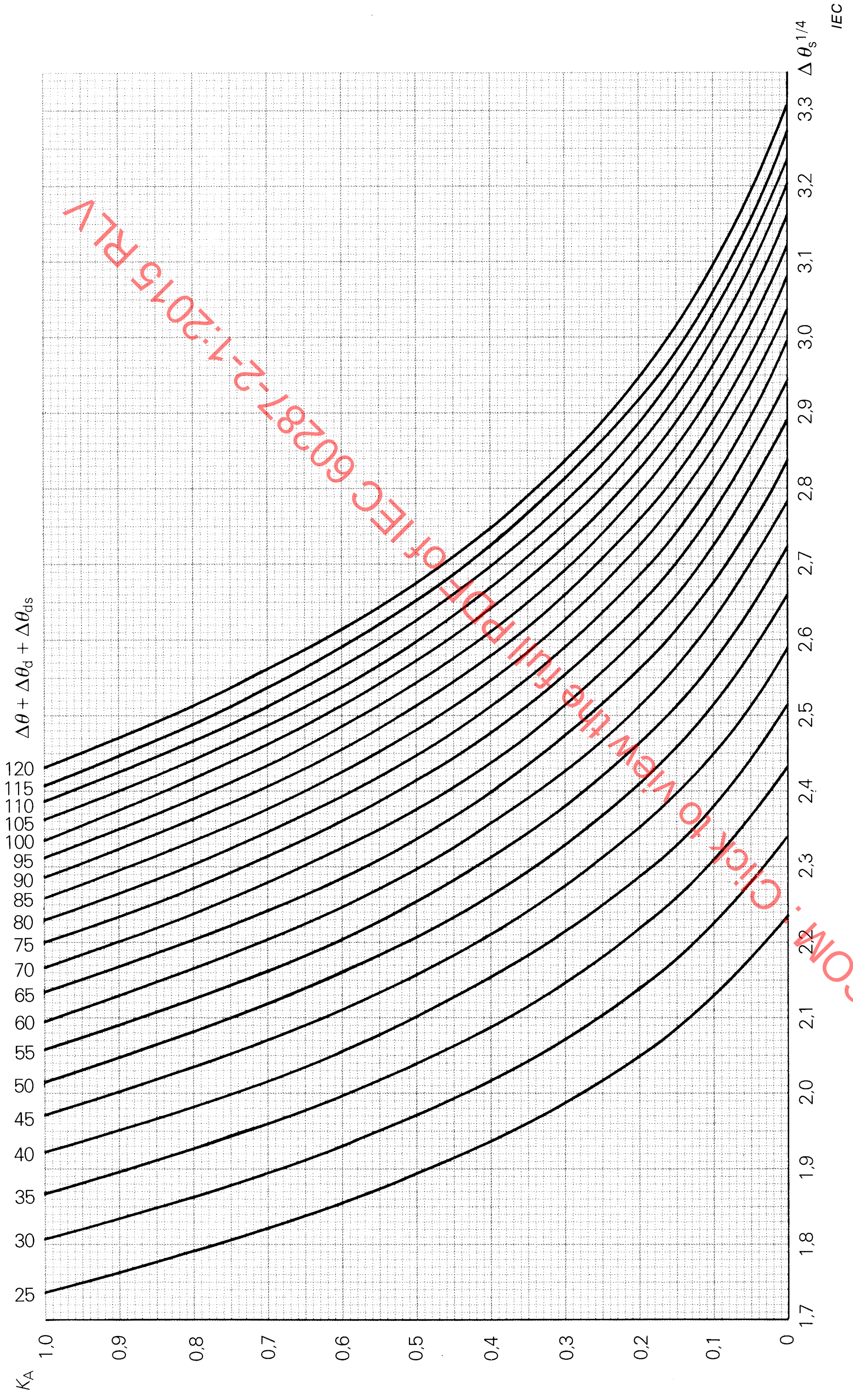


Figure 10 – Graph for the calculation of external thermal resistance of cables in air

Bibliography

IEC 60287-3-1, *Electric cables – Calculation of the current rating – Part 3: Sections on operating conditions – Section 1: Reference operating conditions and selection of cable type*

IEC TR 62095, *Electric cables – Calculations for current ratings – Finite element method*

___

SOMMAIRE

COMMISSION ÉLECTROTECHNIQUE INTERNATIONALE

____

CÂBLES ÉLECTRIQUES – CALCUL DU COURANT ADMISSIBLE –

Partie 2-1: Résistance thermique – Calcul de la résistance thermique

AVANT-PROPOS

1) La Commission Electrotechnique Internationale (IEC) est une organisation mondiale de normalisation composée de l'ensemble des comités électrotechniques nationaux (Comités nationaux de l'IEC). L'IEC a pour objet de favoriser la coopération internationale pour toutes les questions de normalisation dans les domaines de l'électricité et de l'électronique. A cet effet, l'IEC – entre autres activités – publie des Normes internationales, des Spécifications techniques, des Rapports techniques, des Spécifications accessibles au public (PAS) et des Guides (ci-après dénommés "Publication(s) de l'IEC"). Leur élaboration est confiée à des comités d'études, aux travaux desquels tout Comité national intéressé par le sujet traité peut participer. Les organisations internationales, gouvernementales et non gouvernementales, en liaison avec l'IEC, participent également aux travaux. L'IEC collabore étroitement avec l'Organisation Internationale de Normalisation (ISO), selon des conditions fixées par accord entre les deux organisations.
2) Les décisions ou accords officiels de l'IEC concernant les questions techniques représentent, dans la mesure du possible, un accord international sur les sujets étudiés, étant donné que les Comités nationaux de l'IEC intéressés sont représentés dans chaque comité d'études.
3) Les Publications de l'IEC se présentent sous la forme de recommandations internationales et sont agréées comme telles par les Comités nationaux de l'IEC. Tous les efforts raisonnables sont entrepris afin que l'IEC s'assure de l'exactitude du contenu technique de ses publications; l'IEC ne peut pas être tenue responsable de l'éventuelle mauvaise utilisation ou interprétation qui en est faite par un quelconque utilisateur final.
4) Dans le but d'encourager l'uniformité internationale, les Comités nationaux de l'IEC s'engagent, dans toute la mesure possible, à appliquer de façon transparente les Publications de l'IEC dans leurs publications nationales et régionales. Toutes divergences entre toutes Publications de l'IEC et toutes publications nationales ou régionales correspondantes doivent être indiquées en termes clairs dans ces dernières.
5) L'IEC elle-même ne fournit aucune attestation de conformité. Des organismes de certification indépendants fournissent des services d'évaluation de conformité et, dans certains secteurs, accèdent aux marques de conformité de l'IEC. L'IEC n'est responsable d'aucun des services effectués par les organismes de certification indépendants.
6) Tous les utilisateurs doivent s'assurer qu'ils sont en possession de la dernière édition de cette publication.
7) Aucune responsabilité ne doit être imputée à l'IEC, à ses administrateurs, employés, auxiliaires ou mandataires, y compris ses experts particuliers et les membres de ses comités d'études et des Comités nationaux de l'IEC, pour tout préjudice causé en cas de dommages corporels et matériels, ou de tout autre dommage de quelque nature que ce soit, directe ou indirecte, ou pour supporter les coûts (y compris les frais de justice) et les dépenses découlant de la publication ou de l'utilisation de cette Publication de l'IEC ou de toute autre Publication de l'IEC, ou au crédit qui lui est accordé.
8) L'attention est attirée sur les références normatives citées dans cette publication. L'utilisation de publications référencées est obligatoire pour une application correcte de la présente publication.
9) L'attention est attirée sur le fait que certains des éléments de la présente Publication de l'IEC peuvent faire l'objet de droits de brevet. L'IEC ne saurait être tenue pour responsable de ne pas avoir identifié de tels droits de brevets et de ne pas avoir signalé leur existence.

La présente Norme internationale IEC 60287-2-1 a été établie par le comité d'études 20 de l'IEC: Câbles électriques.

Cette seconde édition de l'IEC 60287-2-1 annule et remplace la première édition, publiée en 1994, l'Amendement 1:2001, l'Amendement 2:2006 et le Corrigendum 1:2008. Le document 20/1448/CDV, circulé comme Amendement 3 auprès des Comités nationaux de l'IEC, a conduit à la publication de cette nouvelle édition.

Cette édition inclut les modifications techniques majeures suivantes par rapport à l'édition précédente:

a) ajout d'une référence à l'utilisation des méthodes des éléments finis dans le cas où des méthodes analytiques ne sont pas disponibles pour le calcul de la résistance thermique externe;
b) explication sur les câbles triplombs et sous gaines d'aluminium individuelles;
c) méthode de calcul de T3 pour les câbles tripolaires non armés à isolation extrudée et écrans individuels constitués de bandes en cuivre disposés sur chaque conducteur;
d) changement de condition de X en 5.4;
e) ajout des valeurs des constantes ou conditions d'installation des fourreaux remplis d'eau au Tableau 4.

Le texte de cette norme est issu des documents suivants:

FDIS	Rapport de vote
20/1561/FDIS	20/1588/RVD

Le rapport de vote indiqué dans le tableau ci-dessus donne toute information sur le vote ayant abouti à l'approbation de cette norme.

Cette publication a été rédigée selon les Directives ISO/IEC, Partie 2.

Une liste de toutes les parties de la série IEC 60287, publiées sous le titre général *Câbles électriques – Calcul du courant admissible*, peut être consultée sur le site web de l'IEC.

Le comité a décidé que le contenu de cette publication ne sera pas modifié avant la date de stabilité indiquée sur le site web de l'IEC sous "http://webstore.iec.ch" dans les données relatives à la publication recherchée. A cette date, la publication sera

- reconduite,
- supprimée,
- remplacée par une édition révisée, ou
- amendée.

INTRODUCTION

L'IEC 60287 a été divisée en trois parties de manière à faciliter les révisions et les adjonctions au document.

Chaque partie est subdivisée en sous-parties qui sont publiées en tant que normes séparées.

Partie 1: Formules de l'intensité du courant admissible et pertes de puissance

Partie 2: Formules relatives à la résistance thermique

Partie 3: Conditions de fonctionnement

La présente partie de l'IEC 60287-2 contient des méthodes de calcul de la résistance thermique interne des câbles, et de la résistance thermique externe des câbles posés à l'air libre, des câbles enterrés et des canaux.

Les formules de cette norme contiennent des paramètres variant avec la spécification du câble et les matériaux utilisés. Les valeurs données dans les tableaux sont soit approuvées au niveau international, comme les résistivités électriques et les coefficients de température à résistance, soit les valeurs généralement acceptées dans la pratique, comme les résistivités thermiques et les permittivités des matériaux. Certaines des valeurs de la dernière catégorie ne sont pas caractéristiques de la qualité des câbles neufs, mais de celles des câbles ayant déjà subi une longue période d'utilisation. Dans le but d'obtenir des résultats comparables et reproductibles, il convient de calculer les caractéristiques assignées du courant avec les valeurs indiquées dans la présente norme. Toutefois, lorsqu'on sait avec certitude que d'autres valeurs sont plus appropriées aux matériaux et à leur conception, ces dernières peuvent alors être utilisées en déclarant les caractéristiques assignées correspondantes du courant, à condition que les différentes valeurs soient indiquées.

Les grandeurs relatives aux conditions de fonctionnement des câbles sont susceptibles de varier considérablement d'un pays à l'autre. Par exemple, pour ce qui est de la température ambiante et de la résistivité thermique du sol, les valeurs sont régies dans les différents pays par diverses considérations. Des comparaisons hâtives entre les valeurs utilisées dans les différents pays peuvent donner lieu à des conclusions erronées, si elles ne reposent pas sur des critères communs; par exemple, on peut prévoir différentes valeurs d'espérance de vie des câbles; de même, dans certains pays, la conception est fondée sur la valeur maximale de la résistivité thermique du sol, tandis que dans d'autres c'est la valeur moyenne qui est utilisée. En particulier, dans le cas de la résistivité thermique du sol, il est bien connu que celle-ci est très sensible au taux d'humidité et peut varier sensiblement dans le temps suivant le type de sol, les conditions topographiques et météorologiques et la charge du câble.

Il convient dès lors d'effectuer le choix des valeurs des différents paramètres de la façon suivante:

Les valeurs numériques devront, de préférence, être basées sur des résultats de mesures valables. De tels résultats sont déjà souvent inclus dans les spécifications nationales sous forme de valeurs recommandées, de telle sorte que le calcul peut être exécuté sur la base de ces valeurs généralement utilisées dans le pays en question; un examen de ces valeurs figure dans l'IEC 60287-3-1.

On trouvera un choix d'informations nécessaires pour sélectionner le type de câble approprié dans l'IEC 60287-3-1.

CÂBLES ÉLECTRIQUES – CALCUL DU COURANT ADMISSIBLE –

Partie 2-1: Résistance thermique – Calcul de la résistance thermique

1 Domaine d'application

La présente partie de l'IEC 60287 s'applique uniquement au fonctionnement en régime permanent des câbles de toutes tensions alternatives et de tensions continues jusqu'à 5 kV, enterrés directement dans le sol, placés dans des fourreaux, des caniveaux ou des tubes d'acier, avec ou sans assèchement partiel du sol, ainsi que les câbles posés à l'air libre. On entend par "régime permanent" la circulation continue d'un courant constant (facteur de charge 100 %) juste suffisant pour atteindre asymptotiquement la température maximale de l'âme en supposant que les conditions du milieu ambiant restent inchangées.

La présente partie de l'IEC 60287 fournit des formules pour la résistance thermique.

Les formules proposées sont essentiellement littérales et laissent en principe libre le choix de certains paramètres importants. Ceux-ci peuvent être divisés en trois groupes:

– les paramètres liés à la constitution du câble (par exemple résistivité thermique de l'isolant) pour lesquels des valeurs représentatives ont été recueillies, à partir des travaux publiés;
– les paramètres liés aux conditions du milieu ambiant qui peuvent varier considérablement, dont le choix dépend du pays dans lequel les câbles sont ou doivent être utilisés;
– les paramètres résultant d'un accord entre fabricant et utilisateur et qui supposent une marge de sécurité en service (par exemple température maximale du conducteur).

Les équations figurant dans cette partie de l'IEC 60287 pour le calcul de la résistance thermique externe d'un câble enterré directement dans le sol, ou dans un conduit enterré concernent un nombre limité de conditions d'installation. Dans le cas où des méthodes analytiques ne sont pas disponibles pour le calcul de la résistance thermique externe, les méthodes des éléments finis peuvent être utilisées. Les lignes directrices relatives à l'utilisation des méthodes des éléments finis pour le calcul des caractéristiques assignées du courant de câble sont fournies dans l'IEC TR 62095.

2 Références normatives

Les documents suivants sont cités en référence de manière normative, en intégralité ou en partie, dans le présent document et sont indispensables pour son application. Pour les références datées, seule l'édition citée s'applique. Pour les références non datées, la dernière édition du document de référence s'applique (y compris les éventuels amendements).

IEC 60287-1-1:2006, *Câbles électriques – Calcul du courant admissible – Partie 1-1: Equations de l'intensité du courant admissible (facteur de charge 100 %) et calcul des pertes – Généralités*
IEC 60287-1-1:2006/AMD1:2014

IEC 60853-2, *Calcul des capacités de transport des câbles pour les régimes de charge cycliques et de surcharge de secours – Partie 2: Régime cyclique pour des câbles de tensions supérieures à 18/30 (36) kV et régimes de secours pour des câbles de toutes tensions*

3 Symboles

Les symboles utilisés dans la présente norme et les grandeurs qu'ils représentent sont donnés dans la liste suivante:

D'_a	diamètre extérieur de l'armure	mm
D_d	diamètre intérieur du fourreau	mm
D_e	diamètre extérieur du câble ou diamètre équivalent d'un groupe de conducteurs isolés pour un câble en tuyau	mm
D_e^*	diamètre extérieur du câble (se reporter au 4.2.1)	m
D_o	diamètre extérieur du fourreau	mm
D_s	diamètre extérieur de la gaine métallique	mm
D_{oc}	diamètre du cylindre coaxial imaginaire tangent aux crêtes d'une gaine ondulée	mm
D_{ot}	diamètre du cylindre coaxial imaginaire tangent à la surface extérieure des caniveaux d'une gaine ondulée = $D_{it} + 2t_s$	mm
D_{ic}	diamètre du cylindre imaginaire tangent à la surface intérieure des crêtes d'une gaine ondulée = $D_{oc} - 2t_s$	mm
D_{it}	diamètre du cylindre imaginaire tangent à la surface intérieure des caniveaux d'une gaine ondulée	mm
E	constante utilisée en 4.2.1.1	
F_1	coefficient pour les câbles à ceinture définis en 4.1.2.2.3	
F_2	coefficient pour les câbles à ceinture définis en 4.1.2.2.6	
G	facteur géométrique pour câbles à ceinture	
$\overline{G}$	facteur géométrique des câbles triplombs et sous gaines d'aluminium individuelles	
H	intensité du rayonnement solaire (se reporter au 4.2.1.2)	W/m^2
K	facteur d'écran pour la résistance thermique des câbles sous écran	
K_A	coefficient utilisé en 4.2.1	
L	profondeur de pose par rapport à l'axe du câble ou au centre de la disposition en trèfle	mm
L_G	distance de la surface du sol au centre d'un fourreau porte-câbles	mm
N	nombre de câbles chargés dans un fourreau porte-câbles (voir 4.2.7.4)	
T_1	résistance thermique par conducteur isolé entre âme et gaine métallique ou écran	K·m/W
T_2	résistance thermique entre gaine et armure	K·m/W
T_3	résistance thermique du revêtement extérieur	K·m/W
T_4	résistance thermique du milieu environnant (rapport de l'échauffement de la surface du câble au-dessus du milieu ambiant aux pertes par unité de longueur)	K·m/W
T_4^*	résistance thermique du milieu extérieur à l'air libre tenant compte du rayonnement solaire	K·m/W
T'_4	résistance thermique entre câble et fourreau (ou tuyau)	K·m/W
T''_4	résistance thermique du fourreau (ou du tuyau)	K·m/W
T'''_4	résistance thermique du milieu environnant du fourreau (ou tuyau)	K·m/W
U	constante utilisée en 4.2.7.2	
V	constante utilisée en 4.2.7.2	
W_d	pertes diélectriques par unité de longueur par	W/m

W_k	pertes dissipées par le câble k	W/m
W_{TOT}	puissance totale dissipée dans un caniveau par unité de longueur	W/m
Y	coefficient utilisé en 4.2.7.2	
Z	coefficient utilisé en 4.2.1.1	
d_a	diamètre extérieur de la ceinture isolante	mm
d_c	diamètre extérieur de l'âme	mm
d_{cm}	est le petit diamètre de l'âme ovale	mm
d_{cM}	plus grand diamètre d'une âme ovale	mm
d_M	plus grand diamètre d'écran ou de gaine d'une âme ovale	mm
d_m	plus petit diamètre d'écran ou de gaine d'une âme ovale	mm
d_x	diamètre d'une âme circulaire équivalente ayant la même section et le même degré de rétreint que l'âme sectorale	mm
g	coefficient utilisé en 4.2.1.1	
h	coefficient de dissipation de chaleur	$W/m^2K^{5/4}$
ln	logarithme naturel (logarithme en base e)	
n	nombre d'âmes dans un câble	
p	partie du périmètre du caniveau qui participe à la dissipation de chaleur (voir 4.2.6.2)	m
r_1	rayon du cercle circonscrit de deux ou trois âmes sectorales	mm
s_1	distance entre axes de deux câbles adjacents dans une nappe horizontale de trois câbles non jointifs	mm
t	épaisseur de l'isolation entre âmes	mm
t_1	épaisseur d'isolant entre âmes et gaine	mm
t_2	épaisseur du matelas	mm
t_3	épaisseur du matelas extérieur	mm
t_i	épaisseur de l'enveloppe isolante d'un conducteur isolé y compris les rubans de blindage plus la moitié de l'épaisseur de tous les rubans non métalliques sur l'assemblage des conducteurs isolés	mm
t_3	épaisseur de la gaine	mm
u	$\frac{2L}{D_e}$ en 4.2.	
u	$\frac{L_G}{r_b}$ en 4.2.7.4	
x, y	côtés d'un fourreau porte-câbles ($y>x$) (voir 4.2.7.4)	mm
θ_m	température moyenne du milieu entre un câble et le fourreau ou le tuyau	°C
$\Delta\theta$	échauffement admissible de l'âme au-dessus de la température ambiante	K
$\Delta\theta_d$	facteur tenant compte des pertes diélectriques dans le calcul de T_4 pour des câbles posés à l'air libre	K
$\Delta\theta_{ds}$	facteur tenant compte des pertes diélectriques et du rayonnement solaire direct pour le calcul de T_4^* pour des câbles posés à l'air libre selon la Figure 10	K
$\Delta\theta_{duct}$	différence entre la température moyenne de l'air dans un fourreau et température ambiante	K
$\Delta\theta_s$	différence entre la température en surface d'un câble placé à l'air libre et la température ambiante	K

$\Delta\theta_{tr}$	échauffement de l'air dans un caniveau de câble	K
λ_1, λ_2	rapport utilisé des pertes totales dans les gaines métalliques et les armures respectivement aux pertes totales des âmes (ou pertes dans une gaine ou armure aux pertes dans une âme)	
λ'_{1m}	facteur de perte du câble médian	Trois câbles posés en nappe non transposés, avec gaines reliées aux deux extrémités
λ'_{11}	facteur de perte du câble extérieur ayant les pertes les plus importantes	
λ'_{12}	facteur de perte du câble extérieur ayant les pertes les plus faibles	
ρ_i	résistivité thermique de l'isolation	K·m/W
ρ_f	résistivité thermique du bourrage	K·m/W
ρ_e	résistivité thermique du sol entourant un fourreau porte-câbles	K·m/W
ρ_c	résistivité thermique du béton constituant un fourreau porte-câbles	K·m/W
ρ_m	résistivité thermique des écrans métalliques dans les câbles multipolaires	K·m/W
ρ_T	résistivité thermique du matériau	K·m/W
σ	coefficient d'absorption du rayonnement solaire par la surface du câble	

4 Calcul des résistances thermiques

4.1 Résistances thermiques des constituants des câbles, T_1, T_2 et T_3

4.1.1 Généralités

L'Article 4 donne les formules pour le calcul des résistances thermiques linéiques des différentes parties de câbles T_1, T_2 et T_3 (voir 1.4 de l'IEC 60287-1-1:2006 et de l'IEC 60287-1-1:2006/AMD1:2014). Les résistivités thermiques des matériaux utilisés comme isolants et revêtements de protection figurent dans le Tableau 1.

Lorsque des couches d'écrantage sont présentes, pour les calculs thermiques les rubans métalliques sont considérés comme faisant partie de l'âme ou de la gaine alors que les couches semi-conductrices (y compris le rubanage en papier carbone métallisé) font partie de l'isolant. Les dimensions appropriées des composants doivent être modifiées en conséquence.

4.1.2 Résistance thermique entre une âme et la gaine T_1

4.1.2.1 Câbles unipolaires

La résistance thermique entre une âme et la gaine T_1 est donnée par:

$$T_1 = \frac{\rho_T}{2\pi} \ln\left[1 + \frac{2\,t_1}{d_c}\right]$$

où

ρ_T est la résistivité thermique de l'isolant (K·m/W);

d_c est le diamètre de l'âme (mm);

t_1 est l'épaisseur de l'isolant entre l'âme et la gaine mm).

NOTE Pour les gaines ondulées, t_1 est mesurée d'après le diamètre intérieur moyen de la gaine qui est donné par:

$$\left(\frac{D_{it} + D_{oc}}{2}\right) - t_s$$

4.1.2.2 Câbles à ceinture

4.1.2.2.1 Généralités

La résistance thermique T_1 entre une âme et la gaine est donnée par:

$$T_1 = \frac{\rho_T}{2\pi} G$$

où

G est le facteur géométrique

NOTE Pour les gaines ondulées, t_1 est mesurée d'après le diamètre intérieur moyen de la gaine qui est donné par:

$$\left(\frac{D_{it} + D_{oc}}{2}\right) - t_s$$

4.1.2.2.2 Câbles bipolaires à ceinture et âmes circulaires

Le facteur géométrique G est représenté à la Figure 2.

4.1.2.2.3 Câbles bipolaires à ceinture et âmes sectorales

Le facteur géométrique G est donné par:

$$G = 2\,F_1 \ln\left[\frac{d_a}{2\,r_1}\right]$$

où

$$F_1 = 1 + \frac{2{,}2\,t}{2\pi\,(d_x + t) - t}$$

d_a est le diamètre extérieur de la ceinture isolante (mm);

r_1 est le rayon du cercle circonscrit aux âmes (mm);

d_x est le diamètre d'une âme circulaire ayant la même section et le même degré de rétreint que l'âme sectorale considérée (mm);

t est l'épaisseur de l'isolation entre les âmes (mm).

4.1.2.2.4 Câbles tripolaires à ceinture et âmes circulaires

Pour les câbles tripolaires à ceinture et âmes circulaires

$$T_1 = \frac{\rho_i}{2\pi} G + 0{,}031(\rho_f - \rho_i) e^{0{,}67\frac{t_1}{d_c}}$$

où

ρ_i est la résistivité thermique de l'isolant (K·m/W);

ρ_f est la résistivité thermique de l'isolant du bourrage (K·m/W).

Le facteur géométrique G est donné par la Figure 3.

NOTE Pour les câbles à isolation papier ρ_f = ρ_i et, par conséquent, le second terme du deuxième membre de l'équation ci-dessus peut être négligé.

Pour les câbles à isolation extrudée, la résistivité thermique du matériau de bourrage est susceptible d'être comprise entre 6 K·m/W et 13 K·m/W, selon le matériau de bourrage et son degré de compression. Une valeur de 10 K·m/W est suggérée pour les bourrages en fibres de polypropylène.

L'équation ci-dessus s'applique aux câbles à isolation extrudée dont chaque conducteur possède un écran individuel de fils espacés et aux câbles ayant un écran métallique commun disposé sur les trois conducteurs. Pour les câbles non armés de cette constitution, la valeur t_1 correspond à l'épaisseur du matériau entre les âmes et le revêtement extérieur (matelas extérieur).

4.1.2.2.5 Câbles tripolaires à ceinture et âmes ovales

Le câble doit être considéré comme un câble à âme circulaire équivalent avec un diamètre équivalent $d_\mathrm{c} = \sqrt{d_\mathrm{cM} \cdot d_\mathrm{cm}}$ (mm)

où

d_cM est le grand diamètre de l'âme ovale (mm);

d_cm est le petit diamètre de l'âme ovale (mm).

4.1.2.2.6 Câbles tripolaires à ceinture et âmes sectorales

Le facteur géométrique G de ces câbles dépend de la forme des secteurs, qui varie d'un fabricant à l'autre. Une formule appropriée est:

$$G = 3F_2 \ln\left[\frac{d_\mathrm{a}}{2r_1}\right]$$

où

$$F_2 = 1 + \frac{3t}{2\pi(d_\mathrm{x} + t) - t}$$

d_a est le diamètre extérieur de la ceinture isolante (mm);

r_1 est le rayon du cercle circonscrit aux âmes (mm);

d_x est le diamètre d'une âme circulaire ayant la même section et le même degré de rétreint que l'âme sectorale considérée (mm);

t est l'épaisseur de l'isolation entre les âmes (mm).

4.1.2.3 Câbles tripolaires, de type écranté en ruban métallique

4.1.2.3.1 Câbles écrantés à âmes circulaires

Les câbles à isolation papier de ce type peuvent être d'abord considérés comme des câbles à ceinture pour lesquels $\frac{t_1}{t}$ est égal à 0,5. Puis, pour tenir compte de la conductivité thermique des écrans métalliques, le résultat doit être multiplié par un facteur K, dit facteur d'écran, donné à la Figure 4 pour différentes valeurs de $\frac{t_1}{d_\mathrm{c}}$ et différentes spécifications de câbles.

Ainsi:

$$T_1 = K \frac{\rho_\mathrm{T}}{2\pi} G$$

Il convient de considérer les câbles tripolaires à isolation extrudée et écrans individuels constitués de feuillards en cuivre disposés sur chaque conducteur, comme les câbles triplombs (voir 4.1.2.5 et 4.1.3.2).

Voir 4.1.2.2.4 pour les câbles tripolaires à isolation extrudée dont chaque conducteur possède un écran individuel de fils espacés en cuivre ou dont l'écran métallique est commun aux trois conducteurs.

4.1.2.3.2 Câbles métallisés à âmes ovales

Le câble doit être considéré comme un câble à âme circulaire équivalent ayant un diamètre équivalent $d_c = \sqrt{d_{cM} \cdot d_{cm}}$.

4.1.2.3.3 Câbles métallisés à âmes sectorales

T_1 est calculée de la même manière que pour les câbles à ceinture à âmes sectorales, mais d_a est égal au diamètre d'un cercle qui circonscrit l'assemblage des conducteurs. Le résultat est multiplié par un facteur d'écran donné à la Figure 5.

4.1.2.4 Câbles à huile fluide

4.1.2.4.1 Câbles tripolaires à âmes circulaires, à écrans sur isolant en papier métallisé et à canaux d'huile circulaires entre les conducteurs

La résistance thermique entre une âme et la gaine T_1 est donnée par:

$$T_1 = 0{,}385 \rho_T \left(\frac{2\, t_i}{d_c + 2\, t_i} \right)$$

où

d_c est le diamètre de l'âme (mm);

t_i est l'épaisseur de l'isolation du conducteur comprenant les rubans de noir de carbone et de papier métallisé et la moitié de tous les rubans non métalliques couvrant l'assemblage des trois conducteurs (mm);

ρ_T est la résistivité thermique de l'isolant (K·m/W).

Cette formule suppose que l'espace occupé par les canaux métalliques et l'huile qui s'y trouve a une conductivité thermique très élevée par rapport à l'isolation et par conséquent s'applique sans tenir compte du métal constituant les canaux d'huile ou de leur épaisseur.

4.1.2.4.2 Câbles tripolaires à âmes circulaires, à écrans sur isolant en ruban métallique et canaux d'huile circulaires entre les conducteurs

La résistance thermique T_1 entre une âme et la gaine est donnée par:

$$T_1 = 0{,}35 \rho_T \left(0{,}923 - \frac{d_c}{d_c + 2\, t_i} \right)$$

où

t_i est l'épaisseur de l'isolation du conducteur comprenant les rubans de noir de carbone et de papier métallisé et la moitié de tous les rubans non métalliques couvrant l'assemblage des trois conducteurs (mm).

NOTE Cette formule est indépendante des métaux utilisés pour les écrans et pour les canaux d'huile.

4.1.2.4.3 Câbles tripolaires à âmes circulaires, à écrans sur isolant en ruban métallique, sans bourrages et canaux d'huile, ayant un ruban en tissu de cuivre textile liant les conducteurs et une gaine ondulée en aluminium

La résistance thermique T_1 entre une âme et la gaine est donnée par:

$$T_1 = \frac{475}{D_c^{1,74}}\left[\frac{t_g}{D_c}\right]^{0,62} + \frac{\rho_T}{2\pi}\ln\left(\frac{d_c - 2\,\delta_1}{d_c}\right)$$

où

$$t_g = 0,5\left(\left[\frac{D_{it}+D_{ic}}{2}\right] - 2,16\,D_c\right)$$

D_c est le diamètre d'un conducteur au-dessus des rubans métalliques de l'écran (mm);

t_g est l'interstice nominal moyen entre les rubans métalliques de l'écran sur isolant et le diamètre intérieur moyen de la gaine (mm);

δ_1 est l'épaisseur de l'écran sur isolant en ruban métallique (mm).

NOTE La formule ne dépend pas du métal utilisé pour les rubans de l'écran.

4.1.2.5 Câbles triplombs et sous gaines d'aluminium individuelles

Un câble de type triplomb ou sous gaine d'aluminium individuelle est un câble tripolaire dans lequel chaque conducteur comporte une gaine individuelle en plomb ou en aluminium. La gaine est considérée comme étant suffisamment substantielle de sorte à fournir une isothermie à la surface extérieure de l'isolation.

La résistance thermique T_1 est calculée de la même manière que pour les câbles unipolaires.

4.1.3 Résistance thermique entre gaine et armure T_2

4.1.3.1 Câbles unipolaires, bipolaires et tripolaires ayant une gaine métallique commune

La résistance thermique entre la gaine et l'armure, T_2, est donnée par:

$$T_2 = \frac{1}{2\pi}\rho_T \ln\left[1 + \frac{2\,t_2}{D_s}\right]$$

où

t_2 est l'épaisseur du matelas (mm);

D_s est le diamètre extérieur de la gaine (mm).

NOTE Pour les câbles non armés à isolation extrudée dont chaque conducteur possède un écran individuel de fils espacés et pour les câbles non armés ayant un écran métallique commun disposé sur les trois conducteurs T_2 = 0.

4.1.3.2 Câbles triplombs et sous gaines d'aluminium individuelles

La résistance thermique des bourrages et revêtements situés sous l'armure est donnée par:

$$T_2 = \frac{\rho_T}{6\pi}\overline{G}$$

où

$\overline{G}$ est le facteur géométrique donné à la Figure 6.

4.1.4 Résistance thermique du revêtement extérieur (matelas extérieur) T_3

4.1.4.1 Cas général

Les revêtements extérieurs sont généralement disposés en couches concentriques et la résistance thermique T_3 est donnée par:

$$T_3 = \frac{1}{2\pi} \rho_T \ln\left(1 + \frac{2\,t_3}{D'_a}\right)$$

où

t_3 est l'épaisseur du matelas extérieur (mm);

D'_a est le diamètre extérieur de l'armure (mm).

NOTE Pour les câbles non armés D'_a est égal au diamètre extérieur du composant immédiatement dessous, c'est-à-dire une gaine, un écran ou un matelas.

Pour les gaines ondulées:

$$T_3 = \frac{1}{2\pi} \rho_T \ln\left[\frac{D_{oc} + 2\,t_3}{\left(\frac{D_{oc} + D_{it}}{2}\right) + t_s}\right]$$

4.1.4.2 Câbles tripolaires non armés à isolation extrudée et écrans individuels constitués de bandes en cuivre disposés sur chaque conducteur

La résistance thermique du bourrage, du frettage et du revêtement extérieur est donnée par:

$$T_3 = \frac{\rho_T}{2\pi} \ln\left(1 + \frac{2t_3}{D'_a}\right) + \frac{\rho_f}{6\pi} \overline{G}$$

où

ρ_f est la résistivité thermique de l'isolant du bourrage (K·m/W);

$\overline{G}$ est le facteur géométrique représenté à la Figure 6 fondé sur l'épaisseur du matériau entre l'écran constitué d'une bande de cuivre et le revêtement extérieur (matelas extérieur);

D'_a correspond au diamètre du ruban de frettage.

4.1.5 Cas des câbles en tuyau

Pour ces câbles tripolaires, nous disposons de:

a) La résistance thermique T_1 de l'isolant de chaque conducteur entre âme et écran. Celle-ci est calculée par la méthode indiquée en 4.1.2 relative aux câbles unipolaires.

b) La résistance thermique T_2 comprend deux parties:

   1) La résistance thermique de chaque matelas extérieur placé sur écran ou sur gaine de chaque conducteur. La valeur à introduire pour remplacer la partie de T_2 dans l'équation du calcul du courant admissible du 1.4 de l'IEC 60287-1-1:2006 et de l'IEC 60287-1-1:2006/AMD1:2014 est la valeur par câble, c'est-à-dire que la valeur d'un câble tripolaire est le tiers de la valeur d'un conducteur seul.

      La valeur par conducteur est calculée par la méthode donnée en 4.1.3 pour le matelas des câbles unipolaires. Dans le cas de conducteurs ovales, la moyenne géométrique du petit diamètre et du grand diamètre $\sqrt{d_M \cdot d_m}$ doit être utilisée à la place du diamètre concernant un assemblage des conducteurs circulaires.

2) La résistance thermique du gaz ou de l'huile comprise entre la surface extérieure des conducteurs et le tuyau. Cette résistance est calculée de la même façon que la partie de T_4 qui se situe entre un câble et la surface intérieure d'un fourreau, tel qu'indiqué en 4.2.7.2.

La valeur calculée sera la valeur par câble et il convient de l'ajouter à la grandeur calculée plus haut en 4.1.5 b)1), avant de l'introduire pour remplacer T_2 dans l'équation du courant admissible du 1.4 de l'IEC 60287-1-1:2006 et de l'IEC 60287-1-1:2006/AMD1:2014.

c) La résistance thermique T_3 de tout type de revêtements extérieurs au tuyau est déterminée comme indiqué en 4.1.4. La résistance thermique du tuyau métallique lui-même est négligeable.

4.2 Résistance thermique extérieure T_4

4.2.1 Câbles posés à l'air libre

4.2.1.1 Câbles protégés du rayonnement solaire direct

La résistance thermique T_4 de l'environnement d'un câble placé à l'air libre, et protégé du rayonnement solaire, est donnée par la formule:

$$T_4 = \frac{1}{\pi D_e^* h (\Delta\theta_s)^{1/4}}$$

où

$$h = \frac{Z}{(D_e^*)^g} + E$$

D_e^* est le diamètre extérieur du câble (m);

pour les gaines ondulées $D_e^* = (D_{oc} + 2\, t_3) \cdot 10^{-3}$ (m);

NOTE Dans l'ensemble de 4.2.1 D_e^* est exprimé en mètres.

h est le coefficient de dissipation de chaleur obtenu soit à partir de la formule ci-dessus utilisant les valeurs appropriées des constantes Z, E et g données figurant dans le Tableau 2, soit à partir des courbes des Figures 7, 8 et 9, reproduites par souci de commodité (W/m² *(K)*$^{5/4}$);

les câbles revêtus de jute et les câbles ayant une surface non métallique doivent être considérés comme ayant une surface noire. Pour les câbles sans revêtement extérieur, à plomb nu ou à armure nue, il convient de prendre une valeur de h égale à 88 % de la valeur donnée pour une surface noire;

$\Delta\theta_s$ est l'échauffement de la surface du câble au-dessus de la température ambiante (voir ci-après pour la méthode de calcul) *(K).*

Pour les câbles en caniveaux non remplis, se reporter en 4.2.6.

Calcul de $(\Delta\theta_s)^{1/4}$:

Une méthode itérative simple de calcul $(\Delta\theta_s)^{1/4}$ est fournie ci-dessous. Une autre méthode graphique est donnée en 5.7.

Calculer

$$K_A = \frac{\pi D_e^* h}{(1+\lambda_1+\lambda_2)}\left[\frac{T_1}{n}+T_2(1+\lambda_1)+T_3(1+\lambda_1+\lambda_2)\right]$$

puis

$$(\Delta\theta_s)_{n+1}^{1/4} = \left[\frac{\Delta\theta + \Delta\theta_d}{1+K_A(\Delta\theta_s)_n^{1/4}}\right]^{0,25}$$

Régler la valeur initiale de $(\Delta\theta_s)^{1/4} = 2$ et réitérer le calcul jusqu'à ce que $(\Delta\theta_s)_{n+1}^{1/4} - (\Delta\theta_s)_n^{1/4} \leq 0{,}001$

où

$$\Delta\theta_d = W_d\left[\left(\frac{1}{1+\lambda_1+\lambda_2}-\frac{1}{2}\right)T_1 - \frac{n\,\lambda_2\,T_2}{1+\lambda_1+\lambda_2}\right]$$

Il s'agit d'un facteur qui, comportant les dimensions d'une différence de température, rend compte des pertes diélectriques. Si les pertes diélectriques sont négligées, $\Delta\theta_d = 0$.

$\Delta\theta$ est l'échauffement admissible de l'âme par rapport à la température ambiante.

4.2.1.2 Câbles soumis au rayonnement solaire direct – Résistance thermique extérieure T_4^*

Lorsque les câbles sont soumis au rayonnement solaire direct, T_4^* est calculé par la méthode donnée en 4.2.1.1, mais dans la méthode itérative $(\Delta\theta_s)^{1/4}$ est calculé en utilisant la formule suivante:

$$(\Delta\theta_s)_{n+1}^{1/4} = \left[\frac{\Delta\theta + \Delta\theta_d + \Delta\theta_{ds}}{1+K_A(\Delta\theta_s)_n^{1/4}}\right]^{0,25}$$

où

$$\Delta\theta_{ds} = \frac{\sigma D_e^* H}{(1+\lambda_1+\lambda_2)}\left[\frac{T_1}{n}+T_2(1+\lambda_1)+T_3(1+\lambda_1+\lambda_2)\right]$$

Il s'agit d'un facteur qui, ayant les dimensions d'une différence de température, rend compte de l'influence du rayonnement solaire.

où

σ est le coefficient d'absorption du rayonnement solaire par la surface du câble (voir le Tableau 3);

H est l'intensité du rayonnement solaire qu'il convient de prendre égale à 10^3 W/m² sous la plupart des latitudes; il est recommandé d'obtenir la valeur locale lorsque cela est possible;

D_e^* est le diamètre extérieur du câble (m)

pour les gaines ondulées $D_e^* = (D_{oc} + 2\,t_3) \cdot 10^{-3}$ (m).

Une autre méthode graphique est donnée à la Figure 10.

4.2.2 Un seul câble isolé enterré

$$T_4 = \frac{1}{2\pi} \rho_T \ln\left(u + \sqrt{u^2 - 1}\right)$$

où

ρ_T est la résistivité thermique du sol (K·m/W);

$u = \frac{2L}{D_e}$;

L est la distance de la surface du sol à l'axe du câble (mm);

D_e est le diamètre extérieur du câble (mm);
pour les gaines ondulées $D_e = D_{oc} + 2\, t_3$.

Quand la valeur de u dépasse 10, une bonne approximation (proche de 1 pour 1 000) est obtenue en utilisant la formule:

$$T_4 = \frac{1}{2\pi} \rho_T \ln(2\,u)$$

Pour les circuits de câbles installés à des profondeurs de pose de plus de 10 m, une autre approche pour calculer l'intensité du courant admissible consiste à déterminer l'intensité du courant en régime permanent pour une période de temps désignée (généralement 40 ans) en appliquant les formules figurant dans l'IEC 60853-2, prenant en compte dans la mesure du possible, les variations saisonnières des conditions de charge et la nature du sol, le cas échéant. La modélisation par éléments finis peut fournir un modèle plus polyvalent pour cette évaluation de la durée de vie. Ce thème est à l'étude.

4.2.3 Groupe de câbles enterrés (non jointifs)

4.2.3.1 Généralités

Ces cas peuvent être résolus par l'application du principe de superposition, en supposant que chaque câble est assimilable à une source de chaleur rectiligne ne perturbant pas le flux thermique dû aux autres câbles.

Ils sont de deux types principaux: le premier cas, le plus général, est celui d'un groupe de câbles inégalement chargés et de construction différente, pour lequel on ne peut donner qu'une indication sur la méthode à suivre. Le deuxième cas, qui est plus particulier, est celui d'un groupe de câbles identiques et également chargés et pour lequel une solution simple peut être proposée.

4.2.3.2 Câbles inégalement chargés

La méthode suggérée, pour un groupe de câbles inégalement chargés et de construction différente, consiste à calculer l'échauffement à la surface du câble en question, provoqué par les autres câbles du groupe, et à retrancher cette valeur d'échauffement de celle de $\Delta\theta$ utilisée dans l'équation du courant assigné du 1.4 de l'IEC 60287-1-1:2006 et de l'IEC 60287-1-1:2006/AMD1:2014. Il faut donc estimer auparavant la puissance linéique dissipée par chaque câble, quitte à corriger ultérieurement ces valeurs suivant les calculs, si nécessaire.

Ainsi, l'échauffement $\Delta\theta_p$ au-dessus de la température ambiante à la surface du $p^{ème}$ câble, dont les caractéristiques assignées sont déterminées, provoqué par la puissance dissipée par les autres (q – 1) câbles du groupe, est fourni par:

$$\Delta\theta_p = \Delta\theta_{1p} + \Delta\theta_{2p} + \ldots \Delta\theta_{kp} + \ldots \Delta\theta_{qp}$$