IEC 60287-2-3

Edition 1.0 2017-04

INTERNATIONAL STANDARD

NORME INTERNATIONALE

Electric cables – Calculation of the current rating –
Part 2-3: Thermal resistance – Cables installed in ventilated tunnels

Câbles électriques – Calcul du courant admissible –
Partie 2-3: Résistance thermique – Câbles posés dans les tunnels ventilés

IEC 60287-2-3:2017-04(en-fr)

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INTERNATIONAL
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FOREWORD

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International Standard IEC 60287-2-3 has been prepared by IEC technical committee 20: Electric cables.

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

FDIS	Report on voting
20/1707/FDIS	20/1720/RVD

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

This document 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 document will remain unchanged until the stability date indicated on the IEC website under "http://webstore.iec.ch" in the data related to the specific document. At this date, the document will be

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- withdrawn,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

INTRODUCTION

In the IEC 60287 series, IEC 60287-1 provides general formulae for ratings and power losses of electric cables.

IEC 60287-2 presents formulae or calculation methods for thermal resistances.

IEC 60287-2-1 provides calculation methods for dealing with cables installed in free air (see IEC 60287-2-1:2015,4.2.1).

IEC 60287-2-2 provides a method and data for calculating reduction factors for cables in groups running horizontally in free air.

IEC 60287-2-1 and IEC 60287-2-2 consider heat transfer only in a plane perpendicular to the cables; they assume there is no longitudinal heat transfer.

This part of IEC 60287 deals with the rating for cables installed in ventilated tunnels. In such situations, consideration of longitudinal temperature gradients is involved as the air flowing in the tunnel removes some heat from the cables.

Heat transfer with the moving air is convective and is assumed to be either laminar or turbulent depending on the air velocity. The transition situation between laminar and turbulent air flows is ignored.

A general simplified method is provided to estimate the permissible current-carrying capacity of cables installed in ventilated tunnels, the ventilation being either natural or forced.

Only steady states are considered, where the inlet air temperature and the cable loading are constant for a sufficient time for steady temperatures to be achieved.

Where multiple circuits are involved, their characteristics are assumed to be identical.

The main features of the calculation method for cables in tunnels with forced ventilation can be found in Electra n°143 – 144 (1992)[1][1], as the report of a CIGRE working group, including the erratum in Electra n°209 (2003).

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

ELECTRIC CABLES – CALCULATION OF THE CURRENT RATING –

Part 2-3: Thermal resistance – Cables installed in ventilated tunnels

1 Scope

This part of IEC 60287 describes a method for calculating the continuous current rating factor for cables of all voltages installed in ventilated tunnels. The method is applicable to any type of cable.

The method applies to natural as well as forced ventilation.

Longitudinal heat transfer within the cables and the surroundings of the tunnel is assumed to be negligible.

All cables are assumed to be identical within the tunnel and it is assumed that the tunnel cross-section does not change with distance along the tunnel.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

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

IEC 60287-2-1:2015, *Electric cables – Calculation of the current rating – Part 2-1: Thermal resistance – Calculation of thermal resistance*

3 Terms, definitions and symbols

3.1 Terms and definitions

No terms and definitions are listed in this document.

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

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

3.2 Symbols

h	heat dissipation coefficient given in IEC 60287-2-1 for cables in still air	$W/m^2 \cdot K^{5/4}$
n	number of conductors in a cable	-
z	coordinate corresponding to the tunnel axis	m
A_t	inner tunnel cross-sectional area	m^2
C_{av}	heat capacity of the air flow	W/K

C_{vair}	volumetric heat capacity of air	Ws/(m^3·K)
D_e^*	external diameter of cable	m
D_t	inner diameter of the tunnel	m
F_m	coefficient for the calculation of radiation shape factor	-
I	current in one conductor (r.m.s. value)	A
k_{air}	thermal conductivity for air	W/(m·K)
K_{cv}	convection factor	-
K_r	radiation shape factor	-
K_t	effective emissivity	-
L	length of the tunnel	m
L_t	depth of tunnel axis	m
N	number of cables	-
Pr	Prandtl number	-
R	alternating current resistance of conductor at its maximum operating temperature	Ω/m
Re	Reynolds number	-
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_{4t}	equivalent thermal resistance of cable surrounding	K·m/W
T_{as}	convection thermal resistance between cable and air	K·m/W
T_{at}	convection thermal resistance between air and inner wall of the tunnel	K·m/W
T_{st}	radiation thermal resistance between cable and inner wall of the tunnel	K·m/W
T_a	equivalent star thermal resistance of air	K·m/W
T_e	external thermal resistance of the tunnel	K·m/W
T_s	equivalent star thermal resistance of cable	K·m/W
T_t	equivalent star thermal resistance of tunnel wall	K·m/W
V	air velocity	m/s
W_a(z)	heat removed by the air, at the point z in the cable route	W/m
W_a(L)	heat removed by the air, at tunnel outlet	W/m
W_c	losses in a conductor per unit length, assuming maximum conductor temperature	W/m
W_d	dielectric losses per unit length per phase	W/m
W_k	total heat generated by cable	W/m
λ_1	ratio of the total losses in metallic sheaths to the total conductor losses (sheath/screen loss factor)	-
λ_2	ratio of the total losses in armour to the total conductor losses (armour loss factor)	-
ν	kinematic viscosity for air	m^2/s
ρ_{soil}	soil thermal resistivity	K·m/W
L_0	reference length (see Formula (16))	m
σ_b	Stefan-Boltzmann constant	W/(m^2·K^4)
$\Delta\theta_0$	fictitious increase of ambient temperature to account for the ventilation	K
θ_{max}	maximum permissible conductor temperature	°C

$\theta_{at}(z)$	air temperature, at the point z in the cable route	°C
$\theta_{at}(0)$	air temperature at tunnel inlet	°C
$\theta_{at}(L)$	air temperature at tunnel outlet	°C
$\theta(z)$	conductor temperature, at the point z in the cable route	°C
$\theta_{e}(z)$	temperature at the star point after delta-star transformation	°C
$\theta_{s}(z)$	temperature of the cable surface, at the point z in the cable route	°C
$\theta_{s}(L)$	temperature of the cable surface, at tunnel outlet	°C
$\theta_{t}(z)$	temperature of the inner tunnel wall, at the point z in the cable route	°C
$\theta_{t}(L)$	temperature of the inner tunnel wall, at tunnel outlet	°C
θ_{a}	temperature at ground level	°C

4 Description of method

4.1 General description

The method is based on the calculation of the temperature of the cable surface, the air in the tunnel and the tunnel wall, as a function of the heat generated by the cables.

For any location along the cable route, a set of formulae is developed, involving:

- heat transfer formulae describing heat transfer mechanisms by radiation and convection between the cables, the air in the tunnel and the tunnel wall;
- energy balance formulae for cables, air in the tunnel and tunnel wall;
- heat transfer formulae for conduction in the surroundings of the tunnel.

This set of formulae may be written in such a way that:

- the heat removed by the air, $W_a(z)$, is linked to the derivative of the air temperature with respect to the longitudinal coordinate of the tunnel;
- every other formula is approximated as a thermal Ohm's law linking temperature drop and heat flow through a thermal resistance; the heat flow is derived from the heat generated by the cables, W_k, and the heat removed by the air, $W_a(z)$.

Some of the thermal resistances depend on the air temperature and consequently on the distance along the tunnel.

This may be dealt with by dividing the tunnel route into elementary lengths, so that:

- the heat removed by the air is proportional to the difference in the air temperature between elementary length outlet and inlet;
- the thermal resistances may be considered constant for the elementary length.

For typical installations considered in the CIGRE work [1], it was recognized that assuming constant thermal resistances along the tunnel route, computed using temperatures at the tunnel outlet, does not lead to a serious error.

With this assumption, solving the set of formulae is straightforward and the temperatures of the cable surface, air and tunnel wall are easily derived as a function of the cable losses.

The permissible current is then derived from the heat transfer formula for conduction within the cable linking the temperature drop between the conductor and the cable surface to the losses in the cables.

As temperatures at the tunnel outlet are not known, an iterative process is necessary.

The heat generated by a cable, W_k, is assumed to be constant along the cable route and is calculated for the maximum permissible conductor temperature, leading to an estimate of the current rating that is on the safe side.

$$W_k = n \cdot [W_c \cdot (1 + \lambda_1 + \lambda_2) + W_d] \tag{1}$$

$$W_c = R \cdot I^2 \tag{2}$$

where

W_k is the total heat generated by a cable (W/m);

n is the number of conductors in a cable;

W_c is the losses in a conductor per unit length, assuming maximum conductor temperature (W/m);

λ_1 is the ratio of the total losses in metallic sheaths to the total conductor losses;

λ_2 is the ratio of the total losses in armour to the total conductor losses;

W_d is the dielectric losses per unit length per phase (W/m);

R is the alternating current resistance of conductor at its maximum operating temperature (Ω/m);

I is the current in one conductor (r.m.s. value) (A).

4.2 Basic formulae

4.2.1 General

The following heat transfer mechanisms are taken into account:

- radial heat transfer by conduction within the cable,
- heat transfer by radiation from the cable surface to the tunnel wall,
- heat transfer by convection from the cable surface to the air inside the tunnel,
- heat transfer by convection from the air inside the tunnel to the tunnel wall,
- longitudinal heat transfer by convection resulting from the forced or natural flow of air along the tunnel.

4.2.2 Radial heat transfer by conduction within the cable

The conductor temperature is derived from the formula given in IEC 60287-1-1.

$$\theta(z) = \theta_s(z) + W_c \cdot [T_1 + n \cdot (1 + \lambda_1) \cdot T_2 + n \cdot (1 + \lambda_1 + \lambda_2) \cdot T_3] + W_d \cdot \left[\frac{T_1}{2} + n \cdot (T_2 + T_3)\right] \tag{3}$$

where

$\theta(z)$ is the conductor temperature, at the point z in the cable route (°C);

$\theta_s(z)$ is the temperature of the cable surface, at the point z in the cable route (°C);

T_1 is the thermal resistance per core between conductor and sheath (K·m/W);

T_2 is the thermal resistance between sheath and armour (K·m/W);

T_3 is the thermal resistance of external serving (K·m/W).

The loss coefficients and thermal resistances are defined in IEC 60287-1-1 and IEC 60287-2-1.

4.2.3 Heat transfer by radiation from the cable surface to the inner wall of the tunnel

This heat transfer is modelled by Ohm's thermal law, characterized by a thermal resistance:

$$T_{st} = \frac{1}{\pi \cdot D_e^* \cdot K_t \cdot K_r \cdot \sigma_b \cdot \left[\left(\theta_s(\mathrm{L})+273\right)^2 + \left(\theta_t(\mathrm{L})+273\right)^2\right]} \cdot \frac{1}{\left[\left(\theta_s(\mathrm{L})+273\right)+\left(\theta_t(\mathrm{L})+273\right)\right]} \qquad (4)$$

where

D_e^*	is the cable diameter (m);
σ_b	is Stefan-Boltzmann constant, 5,67x10^{-8} (W/m^2·K^4);
θ_s(L) and θ_t(L)	are the cable surface and tunnel surface temperatures at the tunnel outlet (°C);
K_t	is the emissivity of the cable surface (typically 0,9 for served cable);
K_r	is the radiation shape factor taking into account the radiation areas.

K_r may be expressed as:

$$K_r = \frac{1 - F_m}{1 - (1 - K_t) \cdot F_m}$$

where

F_m is a coefficient given in Table 1 and in Annex C

Table 1 – F_m coefficient for radiation thermal resistance calculation

Installation	F_m
Single cable	0
Two cables touching	0,182
Two cables spaced 2 x D_e*	0,081
Two cables spaced 3 x D_e*	0,054
Three cables touching	M: 0,363 O: 0,182
Three cables spaced 2 x D_e*	M: 0,163 O: 0,081
Three cables spaced 3 x D_e*	M: 0,107 O: 0,054
Trefoil touching	0,348
Key M: Middle cable O Outer cable	

4.2.4 Heat transfer by convection from the cable surface to the air inside the tunnel

The convective heat transfer from the cable surface to the air in the tunnel depends on the air flow characteristics, the velocity of the air being the leading parameter.

Where laminar air flow occurs, the convection thermal resistance is given by Formula (5):

$$T_{as} = \frac{1}{\left[\pi \cdot D_e^* \cdot h - \frac{1}{30^{0,25} \cdot T_{st}}\right] \cdot \left[\theta_s(L) - \theta_{at}(L)\right]^{0,25}} \qquad (5)$$

where

h is the heat dissipation coefficient given in IEC 60287-2-1 for cables in still air (W/(m^2·K$^{5/4}$));

θ_{at}(L) is the air temperature at the tunnel outlet (°C).

Formula (5) applies if the Reynolds number is less than 2 000.

If the Reynolds number is higher, the thermal resistance is first assumed to be given by Formula (6), valid for turbulent air flow.

$$T_{as} = \frac{1}{\pi \cdot k_{air} \cdot K_{cv} \cdot \mathrm{Re}^{0,65}} \qquad (6)$$

where

Re is the Reynolds number

$$\mathrm{Re} = \frac{V \cdot D_e^*}{\nu}$$

ν is the kinematic viscosity for air (m^2/s);

k_{air} is the thermal conductivity for air (W/(m·K));

V is the air velocity (m/s).

K_{cv} is an experimentally determined constant for which values are given in Table 2.

Table 2 – Value of parameter K_{cv}

Cable Arrangement	K_{cv}
Single cable	0,130
3 cables touching horizontally[b]	0,086
3 cables spaced horizontally[a]	0,115
3 cables touching vertically[b]	0,086
3 cables spaced vertically[a]	0,115
3 cables touching in trefoil	0,070
[a] to be used where the spacing is larger than 2 x D_e^*	
[b] to be used where the spacing is smaller or equal to 2 x D_e^*	

The values from Formulae (5) and (6) are compared and the higher of the two values is used.

4.2.5 Heat transfer by convection from the air inside the tunnel to the inner tunnel wall

This transfer is modelled by Ohm's thermal law, characterized by a thermal resistance:

If the Reynolds number is greater than 2 500, the air flow is assumed turbulent and the following relationship applies:

$$T_{at} = \frac{1}{\pi \cdot k_{air} \cdot 0{,}023 \cdot \mathrm{Re}^{0{,}8} \cdot \mathrm{Pr}^{0{,}4}} \quad (7)$$

where

Re is the Reynolds number

$$\mathrm{Re} = \frac{V \cdot D_t}{\nu}$$

Pr is the Prandtl number

$$\mathrm{Pr} = C_{vair} \cdot \frac{\nu}{k_{air}}$$

C_{vair} is the specific heat of air per unit volume (J/(m^3·K));

D_t is the inner diameter of the tunnel (m).

If the Reynolds number is less than 2 500, the thermal resistance is considered negligible.

4.2.6 Longitudinal heat transfer by convection resulting from the forced or natural flow of air along the tunnel

The heat removed by the air, $W_a(z)$, is linked to the air temperature variations according to:

$$W_a(z) = C_{av} \cdot \frac{\partial \theta_{at}(z)}{\partial z} \quad (8)$$

where

C_{av} is the heat capacity of the air flow (W/K)

$$C_{av} = C_{vair} \cdot V \cdot A_t \quad (9)$$

A_t is the inner tunnel cross-sectional area (m^2).

4.2.7 Radial heat conduction in the soil surrounding the tunnel

For circular tunnels the thermal resistance of the surrounding soil is expressed by:

$$T_e = \frac{\rho_{soil}}{2 \cdot \pi} \cdot \ln\left[u + \sqrt{u^2 - 1}\right] \quad (10)$$

where

$$u = \frac{2 \cdot L_t}{D_t}$$

ρ_{soil} is the soil thermal resistivity (K·m/W);

L_t is the depth of the tunnel axis (m).

For rectangular tunnels the thermal resistance of the surrounding soil is expressed by:

$$T_e = \frac{\rho_{soil}}{2 \cdot \pi} \cdot \ln\left[3{,}388 \cdot \frac{L_t}{\sqrt{A_t}}\right] \quad (11)$$