IEC 60287-2-3

Edition 2.0 2024-06

# INTERNATIONAL STANDARD

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



IEC 60287-2-3:2024-06(en)

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

This second edition cancels and replaces the first edition published in 2017. This edition constitutes a technical revision.

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

a) symbols alignment with other parts of the IEC 60287 series.

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

| Draft | Report on voting |
|---|---|
| 20/2175/FDIS | 20/2182/RVD |

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

The language used for the development of this International Standard is English.

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

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

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

- reconfirmed,
- withdrawn, or
- revised.

# INTRODUCTION

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

The IEC 60287-2 series 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, *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 terminology databases for use in standardization at the following addresses:

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

## 3.2 Symbols

| | | |
|---|---|---|
| $A_t$ | inner tunnel cross-sectional area | $m^2$ |
| $C_{av}$ | heat capacity of the air flow | W/K |
| $C_{vair}$ | volumetric heat capacity of air | $W \cdot s/(m^3 \cdot K)$ |
| $D_e^*$ | external diameter of cable | m |
| $D_t$ | inner diameter of the tunnel | m |
| $C_{Fm}$ | coefficient for the calculation of radiation shape factor | - |
| $I$ | current in one conductor (RMS value) | A |
| $K_{cv}$ | convection factor | - |
| $K_r$ | radiation shape factor | - |
| $K_t$ | effective emissivity | - |
| $L^*_t$ | depth of tunnel axis | m |
| $N$ | number of cables | - |
| $P_r$ | Prandtl number | - |
| Re | Reynolds number | - |
| $R_R$ | alternating current resistance of conductor with sustained application of a rated current $I_R$ i.e. at standard maximum permissible temperature | Ω/m |
| $T_1$ | 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 |
| $T_e$ | external thermal resistance 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 |
| $T^*_s$ | equivalent star thermal resistance of cable | K · m/W |
| $T^*_t$ | equivalent star thermal resistance of tunnel wall | K · m/W |
| $V_{air}$ | air velocity | m/s |
| $W_a(z_t)$ | heat removed by the air, at the point $z_t$ on the cable route | W/m |
| $W_a(z_{tot})$ | 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 |
| $W_{ktot}$ | total heat generated by cable | W/m |
| $h$ | heat dissipation coefficient given in IEC 60287-2-1 for cables in still air | $W/(m^2 \cdot K^{5/4})$ |
| $k_{air}$ | thermal conductivity for air | $W/(m \cdot K)$ |
| $n$ | number of conductors or cores in a cable | |
| $s_1$ | axial separation between two adjacent cables (mm) | mm |
| $s_r$ | ratio between spacing and cable diameter | - |
| $z_0$ | reference length (see Formula (16)) | m |

| | | |
|---|---|---|
| $z_t$ | coordinate corresponding to the tunnel axis | m |
| $z_{tot}$ | length of the tunnel | m |
| $\Delta\theta_0$ | fictitious increase of ambient temperature to account for the ventilation | K |
| $\theta_a$ | temperature at ground level | °C |
| $\theta_{at}(0)$ | air temperature at tunnel inlet | °C |
| $\theta_{at}(z_t)$ | air temperature, at the point $z_t$ on the cable route | °C |
| $\theta_{at}(z_{tot})$ | air temperature at tunnel outlet | °C |
| $\theta_c(z_t)$ | conductor temperature, at the point $z_t$ on the cable route | °C |
| $\theta_{c\_max}$ | maximum permissible conductor temperature | °C |
| $\theta_e(z_t)$ | temperature at the star point after delta-star transformation | °C |
| $\theta_s(z_t)$ | temperature of the cable surface, at the point $z_t$ on the cable route | °C |
| $\theta_s(z_{tot})$ | temperature of the cable surface, at tunnel outlet | °C |
| $\theta_t(z_t)$ | temperature of the inner tunnel wall, at the point $z_t$ on the cable route | °C |
| $\theta_t(z_{tot})$ | temperature of the inner tunnel wall, at tunnel outlet | °C |
| $\lambda_1$ | ratio of the total losses in metallic sheaths to the total conductor losses (sheath or screen loss factor) | - |
| $\lambda_2$ | ratio of the total losses in armour to the total conductor losses (armour loss factor) | - |
| $\nu$ | kinematic viscosity for air | $m^2/s$ |
| $\rho$ | soil thermal resistivity | K · m/W |
| $\sigma_B$ | Stefan-Boltzmann constant | $W/(m^2 \cdot K^4)$ |



# 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, $W_a(z_t)$, 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, $W_{ktot}$, and the heat removed by the air, $W_a(z_t)$.

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, $W_{\mathrm{ktot}}$, 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.

$$W_{\mathrm{ktot}} = n \cdot \left[ W_{\mathrm{c}} \cdot (1 + \lambda_1 + \lambda_2) + W_{\mathrm{d}} \right] \tag{1}$$

$$W_{\mathrm{c}} = R_{\mathrm{R}} \cdot I^2 \tag{2}$$

where

$W_{\mathrm{ktot}}$ is the total heat generated by a cable (W/m);

$n$ is the number of conductors in a cable;

$W_{\mathrm{c}}$ is the losses in a conductor per unit length, assuming maximum conductor temperature (W/m);

$\lambda_1$ is the ratio of the total losses in metallic sheaths to the total conductor losses;

$\lambda_2$ is the ratio of the total losses in armour to the total conductor losses;

$W_{\mathrm{d}}$ is the dielectric losses per unit length per phase (W/m);

$R_{\mathrm{R}}$ is the alternating current resistance of conductor with sustained application of a rated $I_{\mathrm{R}}$ current i.e. at standard maximum permissible temperature (Ω/m);

$I$ is the current in one conductor (RMS 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.

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

where

$\theta_c(z_t)$ is the conductor temperature, at the point $z_t$ on the cable route (°C);

$\theta_s(z_t)$ is the temperature of the cable surface, at the point $z_t$ on 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);

$z_t$ is the coordinate corresponding to the tunnel axis (m).

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:

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

where

$D_e^*$ is the cable diameter (m);

$\sigma_B$ is Stefan-Boltzmann constant, 5,67 × $10^{-8}$ (W/m$^2$ · K$^4$);

$\theta_s(z_{tot})$ is the cable surface at the tunnel outlet (°C);

$\theta_t(z_{tot})$ is the 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;

$z_{tot}$ is the length of the tunnel (m).

$K_r$ may be expressed as:

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

where

$C_{Fm}$ is a coefficient given in Table 1 and in Annex C.

**Table 1 – $C_{F_m}$ coefficient for radiation thermal resistance calculation**

| **Installation** | $C_{Fm}$ |
|---|---|
| Single cable | 0 |
| Two cables touching | 0,182 |
| Two cables spaced 2 × $D_e$* | 0,081 |
| Two cables spaced 3 × $D_e$* | 0,054 |
| Three cables touching | M: 0,363<br>O: 0,182 |
| Three cables spaced 2 × $D_e$* | M: 0,163<br>O: 0,081 |
| Three cables spaced 3 × $D_e$* | M: 0,107<br>O: 0,054 |
| Trefoil touching | 0,348 |
| **Key**<br>M Middle cable<br>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):

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

where

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

$\theta_{at}(z_{tot})$ is the air temperature at the tunnel outlet (°C);

$\theta_s(z_{tot})$ is the temperature of the cable surface, at tunnel outlet;

$T_{st}$ is the radiation thermal resistance between the cable and inner wall of the tunnel.

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.

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

where

Re is the Reynolds number;

$$Re = \frac{V_{air} \cdot D_e^*}{\nu}$$

$\nu$ is the kinematic viscosity for air ($m^2/s$);

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

$V_{air}$ is the air velocity (m/s);

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

**Table 2 – Values 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 × $D_e$*.

[b] To be used where the spacing is smaller or equal to 2 × $D_e$*.



### 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:

$$T_{at} = \frac{1}{\pi \cdot k_{air} \cdot 0{,}023 \cdot Re^{0,8} \cdot P_r^{0,4}} \tag{7}$$

where

Re is the Reynolds number;

$$Re = \frac{V_{air} \cdot D_t}{\nu}$$

$P_r$ is the Prandtl number;

$$P_r = C_{vair} \cdot \frac{v}{k_{air}}$$

$C_{vair}$ 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, $W_a(z_t)$, is linked to the air temperature variations according to:

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

where

$z_t$ is the coordinate corresponding to the tunnel axis (m);

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

$$C_{av} = C_{vair} \cdot V_{air} \cdot A_t \tag{9}$$

$A_t$ 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:

$$T_e = \frac{\rho}{2 \cdot \pi} \cdot \ln\left[u + \sqrt{u^2 - 1}\right] \tag{10}$$

where

$$u = \frac{2 \cdot L_t^*}{D_t};$$

$\rho$ is the soil thermal resistivity (K · m/W);

$L^*_t$ is the depth of the tunnel axis (m);

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

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

$$T_e = \frac{\rho}{2 \cdot \pi} \cdot \ln\left[3{,}388 \cdot \frac{L_t^*}{\sqrt{A_t}}\right] \tag{11}$$

where

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

For deep tunnels, these formulae will produce conservative results because of soil thermal inertia. This subject is under consideration.

## 4.3 Set of formulae

A delta-star transformation is used to derive the following set of formulae:

$$\begin{aligned}
&\theta_s(z_t) - \theta_e(z_t) = T_s^* \cdot N \cdot W_{ktot} \\
&\theta_e(z_t) - \theta_t(z_t) = T_t^* \cdot (N \cdot W_{ktot} - W_a(z_t)) \\
&\theta_t(z_t) - \theta_a(z_t) = T_e \cdot (N \cdot W_{ktot} - W_a(z_t)) \\
&\theta_{at}(z_t) - \theta_e(z_t) = -T_a^* \cdot W_a(z_t) \\
&W_a(z_t) = C_{av} \cdot \frac{\partial \theta_{at}(z_t)}{\partial z_t}
\end{aligned} \tag{12}$$

where

$z_t$ is the coordinate corresponding to the tunnel axis;

$W_{ktot}$ is the total heat generated by the cable (W/m).

$W_a(z_t)$ is the heat removed by the air, at the point $z_t$ on the cable route (W/m);

$T^*_s$ is the equivalent star thermal resistance of the cable (K · m/W);

$T^*_t$ is the equivalent star thermal resistance of the tunnel wall (K · m/W);

$T^*_a$ is the equivalent star thermal resistance of air (K · m/W);

defined as follows:

$$\begin{aligned}
&T_s^* = \frac{\left(T_{st}/N\right)\cdot\left(T_{as}/N\right)}{\left(T_{st}/N\right)+\left(T_{as}/N\right)+T_{at}} \\
&T_t^* = \frac{T_{at}\cdot\left(T_{st}/N\right)}{\left(T_{st}/N\right)+\left(T_{as}/N\right)+T_{at}} \\
&T_a^* = \frac{T_{at}\cdot\left(T_{as}/N\right)}{\left(T_{st}/N\right)+\left(T_{as}/N\right)+T_{at}}
\end{aligned} \tag{13}$$

The delta-star transformation is shown diagrammatically in Annex B.

## 4.4 Solving

The permissible current rating is obtained from Formula (14) which is similar to the classical formula for cable rating given in IEC 60287-1-1:

$$I = \left[ \frac{\theta_{c\_max} - \left[\theta_a + \Delta\theta_0\right] - W_d \cdot \left[\frac{T_1}{2} + n \cdot \left(T_2 + T_3 + T_{4t}\right)\right]}{R \cdot \left[T_1 + n \cdot \left(1 + \lambda_1\right) \cdot T_2 + n \cdot \left(1 + \lambda_1 + \lambda_2\right) \cdot \left(T_3 + T_{4t}\right)\right]} \right]^{1/2} \tag{14}$$

where

$\Delta\theta_0$ is the fictitious increase of ambient temperature to account for the ventilation (K);

$$\Delta\theta_0 = \left[\theta_{at}(0) - \theta_a\right] \cdot \frac{T_t^* + T_e}{T_a^* + T_t^* + T_e} \cdot e^{-\frac{z_{tot}}{z_0}} \tag{15}$$

$T_{4t}$ is the equivalent thermal resistance of cable surrounding (K · m/W);

$$T_{4t} = N \cdot \left[ T_s^* + \left(T_t^* + T_e\right) \cdot \left(1 - \frac{T_t^* + T_e}{T_a^* + T_t^* + T_e} \cdot e^{-\frac{z_{tot}}{z_0}}\right) \right] \tag{16}$$

$z_0$ is the reference length (m);

$$z_0 = \left(T_a^* + T_t^* + T_e\right) \cdot C_{av} \tag{17}$$

$\theta_{c\_max}$ is the maximum permissible conductor temperature (°C).

The air temperature $\theta_{at}(z_{tot})$ at the tunnel outlet is estimated from:

$$\theta_{at}(z_{tot}) = \theta_{at}(0) + \left[\theta_a + \left(T_t^* + T_e\right) \cdot N \cdot W_{ktot} - \theta_{at}(0)\right] \cdot \left[1 - e^{-\frac{z_{tot}}{z_0}}\right] \tag{18}$$

The cable surface temperature and the tunnel wall temperature at the tunnel outlet are derived from the air temperature by:

$$\theta_s(z_{tot}) = \theta_{at}(z_{tot}) + T_a^* \cdot W_a(z_{tot}) + T_s^* \cdot N \cdot W_{ktot} \tag{19}$$

$$\theta_t(z_{tot}) = \theta_{at}(z_{tot}) + T_a^* \cdot W_a(z_{tot}) - T_t^* \cdot \left[N \cdot W_{ktot} - W_a(z_{tot})\right] \tag{20}$$

where

$W_a(z_{tot})$ is the heat removed by the air at the tunnel outlet, given by:

$$W_a(z_{tot}) = \frac{\left(T_t^* + T_e\right) \cdot N \cdot W_{ktot} - \left[\theta_{at}(z_{tot}) - \theta_a\right]}{T_a^* + T_t^* + T_e} \tag{21}$$

### 4.5 Iterative process

The thermal resistances $T^*_a$, $T^*_s$ and $T^*_t$ are calculated from estimates of the cable surface temperature, the tunnel wall temperature and the air temperature at the tunnel outlet, using Formula (4), Formula (5) or Formula (6), Formula (7) and Formula (13).

The cable permissible current is derived from Formula (14) through Formula (15), Formula (16), Formula (17), $T_e$ being derived from Formula (10) and Formula (11) and $C_{av}$ being derived from Formula (9).

Losses in the cables are calculated with Formula (1) and Formula (2).

The air temperature at the tunnel outlet is calculated with Formula (18), the cable surface temperature and the tunnel wall temperature are calculated with Formula (19) and Formula (20), using Formula (21).

The calculation is repeated using these new estimates of the cable surface temperature, the tunnel wall temperature and the air temperature at the tunnel outlet as input, until convergence.

As first estimates, the temperatures at the tunnel outlet are taken as the air temperature at the tunnel inlet.

## 5 Formulae for air properties

Formula (22) to Formula (25) provide the required properties for air at the appropriate temperature:

The thermal conductivity for air is expressed by:

$$k_{air} = 2{,}42 \cdot 10^{-2} + 7{,}2 \cdot 10^{-5} \cdot \theta_{at}(z_{tot}) \tag{22}$$

The kinematic viscosity for air is expressed by:

$$\nu = 1{,}32 \cdot 10^{-5} + 9{,}5 \cdot 10^{-8} \cdot \theta_{at}\left(z_{tot}\right) \quad (23)$$

The Prandtl number for air is expressed by:

$$P_r = 0{,}715 - 2{,}5 \cdot 10^{-4} \cdot \theta_{at}\left(z_{tot}\right) \quad (24)$$

The volumetric heat capacity of air, $C_{vair}$, being derived from $P_r$, $k_{air}$ and $\nu$ is expressed by:

$$C_{vair} = P_r \cdot \frac{k_{air}}{\nu} \quad (25)$$

## 6 Temperature profile

Formula (26) gives the air temperature $\theta_{at}(z_t)$ in any location $z_t$ along the tunnel.

$$\theta_{at}\left(z_t\right) = \theta_{at}\left(0\right) + \left[\theta_a + \left(T_t^* + T_e\right) \cdot N \cdot W_{ktot} - \theta_{at}\left(0\right)\right] \cdot \left[1 - e^{-\frac{z_t}{z_0}}\right] \quad (26)$$

where

$W_{ktot}$, $T^*_t$, $T_e$ and $z_0$ have been determined according to Clause 4;

$z_t$ is the coordinate corresponding to the tunnel axis (m).

A complete calculation example can be found in Annex A.

# Annex A
(informative)

# Calculation example

## A.1 Cable and installation

The example given in Table A.1 considers three single-core cables without armour ($T_2$ = 0 and $\lambda_2$ = 0) spaced vertically within a circular ventilated tunnel (the spacing between the cables being three times their diameter).

**Table A.1 – Installation data**

| **Cables** | **Symbol** | **Value** | **Unit** |
|---|---|---|---|
| Number of cables | $N$ | 3 | - |
| Number of conductors in a cable | $n$ | 1 | - |
| Cable outer diameter | $D_e$* | 0,122 | m |
| Alternating current resistance of conductor at its maximum operating temperature | $R_R$ | 1,28E-05 | Ω/m |
| Dielectric losses per unit length per phase | $W_d$ | 4,0 | W/m |
| Sheath or screen loss factor | $\lambda_1$ | 0,045 03 | - |
| Maximum permissible conductor temperature | $\theta_{c\_max}$ | 90 | °C |
| Thermal resistance per core between conductor and sheath | $T_1$ | 0,341 | K · m/W |
| Thermal resistance of external serving | $T_3$ | 0,038 | K · m/W |
| **Tunnel and surroundings** | | | |
| Soil thermal resistivity | $\rho$ | 1,0 | K · m/W |
| Depth of tunnel axis | $L^*_t$ | 4,0 | m |
| Inner tunnel diameter | $D_t$ | 3,0 | m |
| Length of the tunnel | $z_{tot}$ | 1 000 | m |
| Temperature at ground level | $\theta_a$ | 20 | °C |
| Air temperature at tunnel inlet | $\theta_{at}(0)$ | 20 | °C |
| Air velocity | $V_{air}$ | 2 | m/s |
| **Constants** | | | |
| Convection factor | $K_{cv}$ | 0,115 | - |
| Radiation shape factor | $K_r$ | 0,90 | - |
| Effective emissivity | $K_t$ | 0,90 | - |



## A.2 Calculated values

The number of significant figures given in Table A.2 does not indicate the accuracy of the calculations but is intended to assist those developing a calculation tool.

**Table A.2 – Iterative process for a 1 km long tunnel**

| Iteration | Formula | 1 | 2 | 3 |
|---|---|---|---|---|
| assumed $\theta_s(z_{tot})$ | | 20 | 52,11 | 52,15 |
| assumed $\theta_t(z_{tot})$ | | 20 | 36,83 | 37,89 |
| assumed $\theta_{at}(z_{tot})$ | | 20 | 36,49 | 37,30 |
| $T_e$ | (10) | 0,261 | 0,261 | 0,261 |
| $T_{st}$ | (4) | 0,564 6 | 0,443 6 | 0,441 3 |
| $k_{air}$ | (22) | 0,026 | 0,027 | 0,027 |
| ν | (23) | $1{,}51 \times 10^{-5}$ | $1{,}666\ 65 \times 10^{-5}$ | $1{,}674\ 34 \times 10^{-5}$ |
| Re | (6) | 16 159 | 14 640 | 14 573 |
| $T_{as}$ | (6) | 0,198 5 | 0,202 3 | 0,202 5 |
| Pr | (24) | 0,710 0 | 0,705 9 | 0,705 7 |
| Re | (7) | 397 351 | 360 003 | 358 351 |
| $T_{at}$ | (7) | 0,020 5 | 0,021 3 | 0,021 3 |
| $T^*_s$ | (13) | 0,045 3 | 0,042 1 | 0,042 1 |
| $T^*_t$ | (13) | 0,014 1 | 0,013 3 | 0,013 3 |
| $T^*_a$ | (13) | 0,004 9 | 0,006 1 | 0,006 1 |
| $C_{vair}$ | (25) | 1 206 | 1 136 | 1 133 |
| $C_{av}$ | (9) | 17 044 | 16 063 | 16 019 |
| $z_0$ | (17) | 4 764 | 4 496 | 4 484 |
| $\Delta\theta_0$ | (15) | 0 | 0 | 0 |
| $T_{4t}$ | (16) | 0,303 7 | 0,304 5 | 0,304 8 |
| $I$ | (14) | 2 758 | 2 756 | 2 755 |
| $W_c$ | (2) | 97,3 | 97,2 | 97,2 |
| $W_{ktot}$ | (1) | 105,7 | 105,6 | 105,6 |
| $\theta_{at}(z_{tot})$ | (18) | 36,49 | 37,30 | 37,33 |
| $W_a(z_{tot})$ | (21) | 252,58 | 248,11 | 247,84 |
| $\theta_s(z_{tot})$ | (19) | 52,11 | 52,15 | 52,17 |
| $\theta_t(z_{tot})$ | (20) | 36,83 | 37,89 | 37,93 |



The temperature profile along the 1 km length of the tunnel is given in Figure A.1.

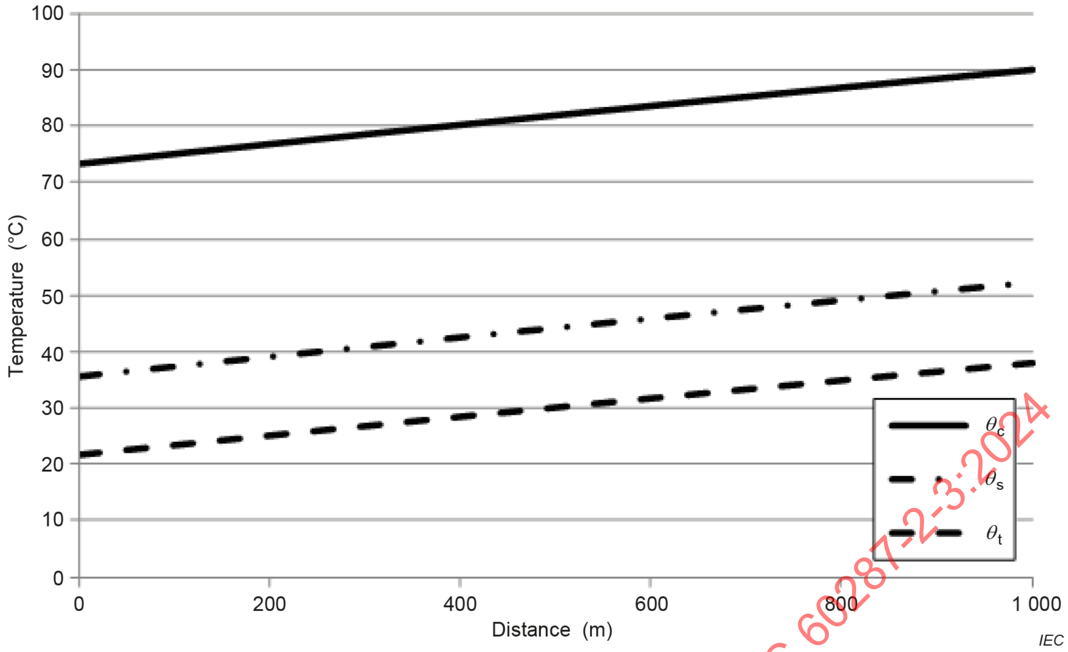


**Figure A.1 – Temperature profile along a 1 km tunnel**



In the example given in Figure A.1 the thermal properties of the air have been determined for the calculated air temperature in the tunnel at each stage in the iteration. If the air thermal properties were determined at a temperature of 30 °C, the current rating would be 2 764 A, compared to 2 755 A calculated above.

Repeating the calculation using the same data, except for a tunnel length of 10 000 m, results in a current rating of 1 999 A. The temperature profile along the 10 km tunnel is shown in Figure A.2.

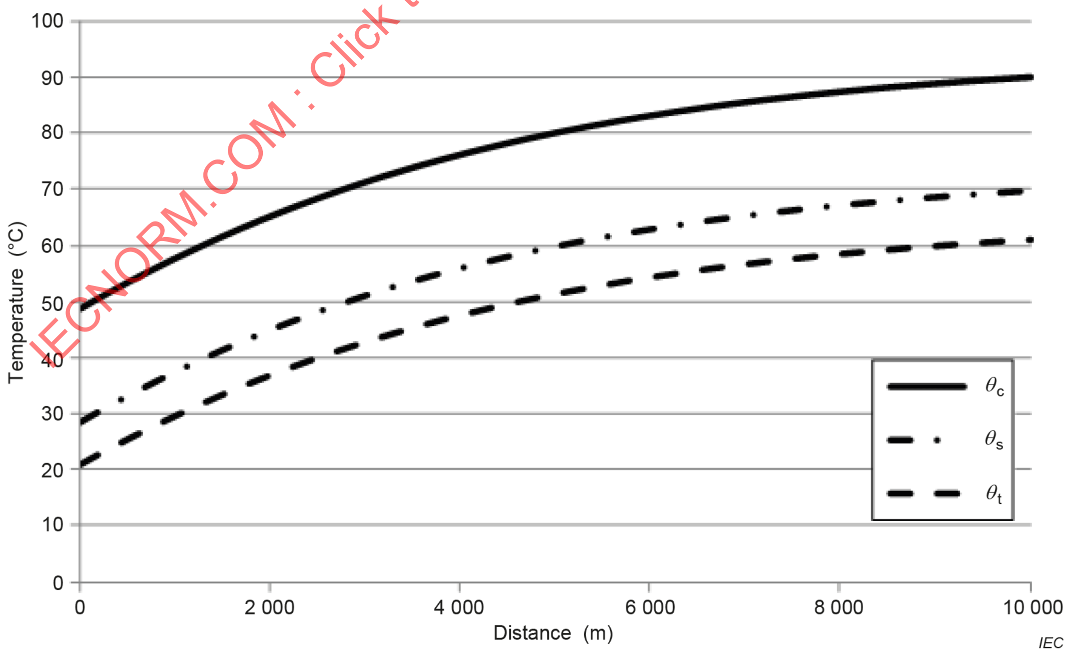


**Figure A.2 – Temperature profile along a 10 km tunnel**

If the air thermal properties are determined for a temperature of 30 °C, the permissible current is found to be 2 018 A, instead of 1 999 A. This difference is considered to be insignificant.

# Annex B
(informative)

## Delta-star transformation

The heat transfer mechanism in the tunnel and the delta-star given in 4.3 is shown in Figure B.1.

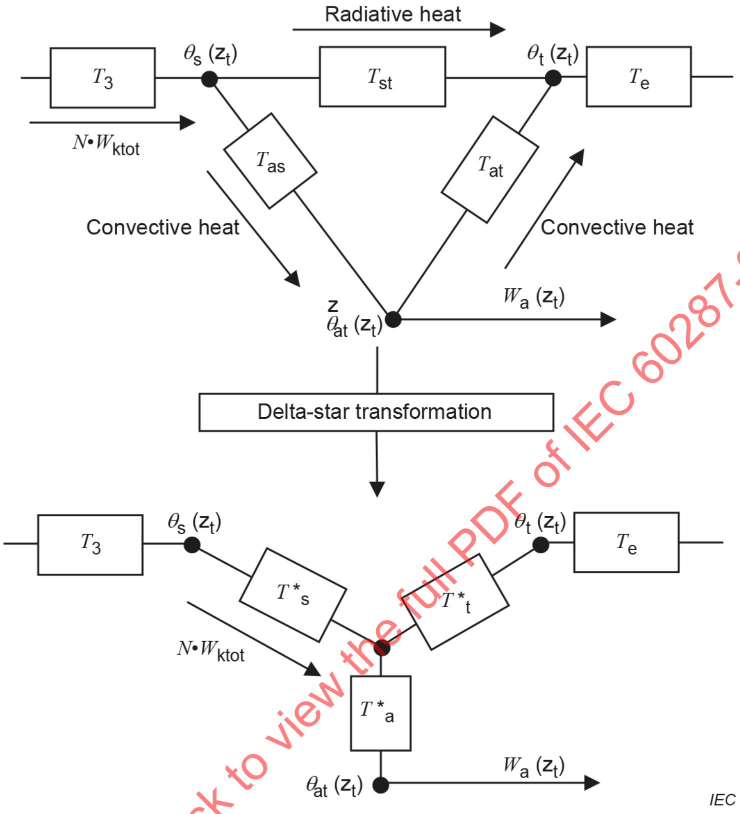


**Figure B.1 – Delta-star transformation**