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A method for determining the current-carrying capacity and durability of power cables based on variable ambient temperature and solar radiation

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Abstract

Modern power networks contain a large number of distributed energy sources, particularly photovoltaics. In the case of photovoltaic sources, the associated electrical installation components, including cables installed in free air, are exposed to solar radiation and significant ambient temperature variability. In the classical approach to calculating the current-carrying capacity of power cables in free air, a constant ambient temperature is assumed and the direct influence of solar radiation is usually not considered. Such an approach, under certain conditions for a given country, may lead to an underestimation of this capacity (a cold region of the country) or an overestimation (an exceptionally warm region of the country). This paper proposes an alternative approach for determining the current-carrying capacity of power cables. The concept takes into account daily and annual fluctuations in ambient temperature. This is based on actual data obtained from measurements with a measurement step of one hour. As a case study, the results of calculations for sample weather scenarios for northern Poland are shown. The analysis indicates that under certain real-world conditions, cables may be overheated, which reduces the durability of their insulation. For the case of non-rated ageing of cable insulation due to high temperature, a current-carrying capacity correction factor was determined. This approach, different from the normative scheme, allows for determining the thermal exposure of cables that is close to the real one. The analysis results can be useful in designing electrical installations, particularly when components are located on the building facade or roof.

Keywords: Electrical installations; Heat transfer; Power cables; Solar radiation

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1. Introduction

Determining the thermal parameters of electrical installations, including cable ratings, aroused the interest of researchers already at the end of the 19th century [1]. Currently, the main attention is paid to the continuous current-carrying capacity of power cables/wires, which depends on many factors, as stated in [2]. A general overview of the basic heat transfer concepts for cable systems and associated current-carrying capacity is given in [3]. There are different methods for determining this capacity. As presented by the authors of the paper [4], these include mainly the finite element method (FEM), which is extensively analysed in [5] with respect to buried power cables in contact with native soil or thermal backfill, as well as the IEC 60287 method [6,7], but the latter is usually used in practice. Standard IEC 60287-1-1 [6], along with the second part IEC 60287-2-1 [7], provides relationships that precisely indicate what the current-carrying capacity depends on. In the con-

Nomenclature

I_{dd} – current-carrying capacity of the cable, A
$I_{dd\text{-}cor}$ – current-carrying capacity of the cable with the effect of solar radiation, A
L_n – rated insulation durability at temperature τ_{dd}, year
L_x – insulation durability at temperature τ_x, year
L_{xi} – insulation durability corresponding to a given temperature in a time interval t_i, year
L_{tot} – resultant durability of insulation, year
R_e – electrical resistance of the core of a power cable, Ω
R_c – thermal resistance related to the heat emitted by the cable, K/W
t_i – relative partial interval of insulation operating time at a specific temperature

Greek symbols

$\Delta\Theta_{dd}$ – highest permissible temperature rise of the power cable, K
$\Delta\Theta_{dd\text{-}cor}$ – corrected permissible temperature rise of the power cable, K
$\Delta\Theta_s$ – temp. rise of the power cable caused by solar radiation, K
$\Delta\tau$ – change in temperature which causes a twofold change in the durability of the insulation, K
τ_{dd} – highest permissible long-term temperature of the power cable, °C
τ_o – ambient temperature, °C
τ_x – temperature other than the highest permissible long-term temperature, °C

Abbreviations and Acronyms

FEM – finite element method
IMGW-PIB – Institute of Meteorology and Water Management – National Research Institute
PV – photovoltaic
PVC – polyvinyl chloride

text of the relationships indicated there, many publications analyse the detailed impact of various factors on cables.

Paper [8] indicates that underground cables are affected by the temperature distribution around the cables, the burial depth of the cables, distances between the cables, the thermal resistivity of the soil, as well as the material for cable backfilling. The influence of soil parameters and soil structure on cable current-carrying capacity is also analysed in [9,10]. These papers emphasise the accuracy of the capacity calculations when cables are laid in multi-layered soils or within stabilised/thermal backfill. Good modelling results for such systems have been achieved in these papers. Paper [11] considers the temperature distribution of cables arranged in layers in cable channels. The layered arrangement affects the uneven temperature distribution of the cable layers, which can lead to local overheating of the cable's insulation. As shown in [12], for high-voltage cables, the bonding method of the metal sheaths is also crucial. Currents circulating in the metal sheaths may significantly heat the cables, reducing their current-carrying capacity. The authors of the paper [13] draw attention to the specific heat transfer characteristics when cables are placed in ducts. Previous standard-compliant approaches may lead to unacceptable inaccuracies, so their paper proposes a more precise approach that is simple enough to implement in computer calculations. The permissible load of underground cables is also associated with the phenomenon of local drying out of the soil (due to heat emission from the cables or the influence of local heat sources). This issue is discussed in detail in [14]. In [15], the phenomenon of drying out of the soil is also considered, but in a different scheme – it is assumed that the top layer of soil near the ground surface dries out, while the layer of soil under the cables does not dry out. This is related to some extent to the effect of solar radiation on the ground surface. An important factor determining the current-carrying capacity is the ambient temperature [16] – as the authors note, it has been changing around the world in recent years and even in one country it may result in different permissible loads for the same cable systems. Very high air temperatures in summer may affect the drying out of the soil around the cables and, consequently, the deterioration of the current-carrying capacity of the cables, as discussed in [17]. The authors point out that in some regions the temperatures may exceed 50°C. High summer temperatures and solar radiation may result (following strong heating of the ground surface) in a significant increase in the temperature of the soil surrounding the cable – it affects the permissible current of this cable, which is also raised in [18]. In some cases, a forced cooling system is used to improve the thermal conditions of buried power cables [19]. In advanced analysis using the FEM-based Arrhenius thermal aging model included in [20], the authors draw attention to the unfavourable thermal conditions of the cable environment as well. They point out possible solar irradiance and high ambient temperature levels, which should be taken into account when determining the current-carrying capacity of cables. In [21], the FEM-based Arrhenius approach is applied again; here, to assess the durability of cable lines exposed to thermal effects of a heating pipeline and several different types of pavements (for different levels of thermal conductivity, emissivity and solar absorptivity). Power cables may be laid in free air for some sections and exposed to direct solar radiation. This radiation is the source of the temperature increase of the cable insulation [22], even if cables are laid in protective pipes [23]. Particularly strong exposure of electrical installation elements, including cables, to high temperatures occurs in the case of photovoltaic (PV) systems, which are numerically demonstrated in [24] and measured in [25]. Paper [26] notes that PV cable systems are exposed to harsh operating conditions, among others, ultraviolet radiation and thermal stress. As a result, the cable insulation degrades, both in terms of electrical and mechanical properties. To decrease the temperature of the PV modules, cooling systems are applied [27,28] – this may beneficially reduce the temperature of the cable connectors in these modules.

A review of the literature and international standards allows us to draw the following conclusions:

- analyses of the current-carrying capacity of power cables usually concern the case when these cables are laid in the ground;
- previous studies have considered the direct impact of solar radiation on outdoor cables to a limited extent, but with the increasingly widespread use of PV systems, this issue has become highly relevant and large-scale;

- ambient temperature of cables (initial temperature before current loading) for a given region of the world is usually assumed to be constant throughout the year, as specified in the standard [29], however, in real conditions for electrical devices placed in the air, the ambient temperature can vary significantly throughout the day and throughout the year.

In the context of the above-mentioned observations, a research gap can be identified regarding a more detailed analysis of the thermal conditions of cables laid in the air – it is mainly about the direct impact of solar radiation and the daily-annual variability of ambient temperature. The exposure of cables to direct solar radiation, as well as the actual ambient temperature, is strongly related to the durability of cable insulation. It should be remembered that unexpected rapid ageing of this insulation reduces its insulating properties and may be the cause of fire and electric shock.

Therefore, this paper, being a modified and extended version of the conference paper [30], presents the results of measurements of daily-annual variability of ambient temperature for a selected region of Poland and the results of numerical calculations of the solar radiation effect. Based on this, sample scenarios of cable temperature changes throughout the day for different seasons are presented, enabling the assessment of the actual thermal exposure of cables in sunny locations. Having the expected temperatures of cable insulation throughout the year, their thermal durability is calculated. A correction factor for the current-carrying capacity of power cables is also determined to achieve insulation ageing at the rated level.

The concept proposed by the authors, based on numerical modelling of solar radiation and taking into account daily and annual ambient temperature variations, is an alternative approach to the design of cable systems. This concept can be used when designing power systems located outdoors and exposed to solar radiation.

2. Current-carrying capacity of cables and numerical calculations of the solar radiation effect

2.1. Current-carrying capacity of power cables according to the standards

The current-carrying capacity I_{dd} of power cables/wires for low-voltage systems can be determined based on the standards [6,7] and presented in the following simplified form [30]:

$$I_{dd} = \sqrt{\frac{\Delta\Theta_{dd}}{R_e R_c}} = \sqrt{\frac{\tau_{dd}-\tau_o}{R_e R_c}}, \tag{1}$$

where: $\Delta\Theta_{dd}$ – the highest permissible temperature rise of the power cable, τ_{dd} – the highest permissible long-term temperature of the power cable, τ_o – ambient temperature, R_e – electrical resistance of the core of a power cable, R_c – thermal resistance related to the heat emitted by the cable to the environment.

For further considerations, the key parameters in Eq. (1) are temperatures τ_{dd} and τ_o. The temperature τ_{dd} is related to the insulation material, and for polyvinyl chloride (PVC) insulated cables commonly used in electrical installations, it is τ_{dd} = 70°C. For design purposes, the ambient temperature in Poland is assumed to be τ_o = 25°C [29], and it is stated that the analysed element of the electrical installation is not exposed to solar radiation. Under such conditions, the maximum permissible temperature rise is $\Delta\Theta_{dd}$ = 45 K (70°C – 25°C). In the case of solar radiation, the current-carrying capacity I_{dd} should be corrected, taking into account the temperature rise of the conductor caused by this radiation. This is presented in the following relation:

$$I_{dd\text{-}cor} = \sqrt{\frac{\Delta\Theta_{dd\text{-}cor}}{R_e R_c}} = \sqrt{\frac{(\tau_{dd}-\tau_o)-\Delta\Theta_s}{R_e R_c}}, \tag{2}$$

where: $I_{dd\text{-}cor}$ – current-carrying capacity of the cable with the effect of solar radiation, $\Delta\Theta_{dd\text{-}cor}$ – corrected permissible temperature rise of the power cable, $\Delta\Theta_s$ – temperature rise of the power cable caused by solar radiation.

The main difficulty in determining the current-carrying capacity according to Eq. (2) is calculating the temperature rise caused by solar radiation. This rise depends, among other things, on solar irradiance, which in turn depends on latitude, season and time of the day. The temperature rise of the conductors caused by solar radiation has been estimated based on the developed numerical model.

2.2. Numerical calculations of the effect of solar radiation on cables

Numerical calculations were performed for a sample single-core low-voltage cable having a cross-sectional area of the core equal to 35 mm^2 (a cable with copper conductors, insulation and a PVC sheath, 2 m long), which is buried for half its length and arranged in free air for the remaining half (Fig. 1).

Since the ground surface is not perfectly smooth, a small obstacle (0.1 m high) is modelled in front of the cable. Computer simulations are intended to show, among other things, the cable's most vulnerable areas to overheating. The calculations

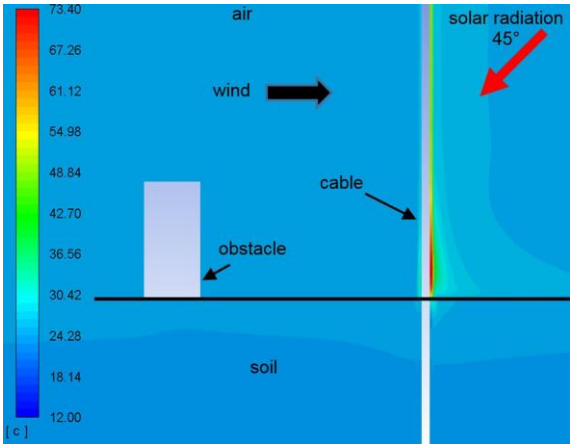


Fig. 1. Temperature distribution around a vertically placed cable exposed to solar radiation. The cable is not loaded with current. Maximum temperature: 73.40°C [30].

were performed for atmospheric conditions that often occur during summer in Poland or at similar latitudes. The air temperature was assumed to be 25°C, and the soil temperature at a depth of 1.2 m was taken as 12°C (consistent with geological data [31]). The calculations were performed for a wind speed of 1 m/s. The thermal conductivity of the soil was assumed to be 0.4 W/(m·K), which corresponds to a thermal resistivity of 2.5 (m·K)/W. It is considered to be quite unfavourable from the point of view of determining the continuous current-carrying capacity of power cables/wires [32,33]. The numerical model assumed solar radiation with an intensity of 1000 W/m^2 incident at an angle of 45° on the vertical cable – this angle reflects average summer conditions. The absorption coefficient of solar radiation for the cable insulation surface was set at 0.9. It was also assumed that the cable is not loaded with current. In this way, the effect of solar radiation alone on the cable temperature rise can be determined.

Stationary calculations were performed in Ansys Fluent, taking into account the effect of gravity. The *k-ε* standard turbulence model was used with the 'enhanced wall treatment' function activated, and 'full buoyancy effects' were enabled in the additional options to correctly model the effect of buoyancy during free convection modelling. The energy equation was activated to model thermal phenomena and obtain the temperature distribution in the computational domain. Air density varied with temperature according to the ideal gas equation of state. The airflow velocity was specified at the inlet, and the 'pressure outlet' boundary condition was applied at the outlet.

The temperature of the warmest points of the cable is as high as 73.40°C (Fig. 1), even though the cable is not loaded with current. The highest temperature area occurs just above the ground (the area above the ground is shielded from the wind by the aforementioned 0.1 m obstacle) on the side facing the incident sun.

Analysing the cable cross-section and the surrounding area at a height of 0.5 m above the ground, the simulation data shows that it is slightly over 51°C, which is significantly lower than for the section just above the ground, because air movement caused by the wind (cable cooling) is important. The exact temperature distribution in the cross-section at a height of 0.5 m is shown in Fig. 2.

Numerical analyses indicate that solar radiation can cause a cable temperature rise of:

- almost 50 K (73.40°C – 25°C) under very unfavourable conditions (intense sunlight, cable surrounded by still air, e.g. in a roof recess),
- 26 K (51°C – 25°C) under more favourable conditions (intense sunlight, but cable is cooled by wind).

The results of numerical analyses of the temperature increase of cable insulation caused by solar radiation were used to calculate the expected temperatures of this insulation for a selected region of Poland and assumed weather scenarios. The expected temperatures of the cables at specific times of day and year were used to determine the expected durability of the insulation.

3. Annual ambient temperature variation and cable thermal rating

Design calculations for cable current-carrying capacity and insulation durability usually refer to standard temperature conditions, which are generally considered to be the highest possible (most unfavourable) during the considered period of operation of the electrical installation. Design assumptions are generally known and available, but actual temperature conditions can vary significantly depending on the time of day and season. To provide a realistic estimate of the assumed ambient temperature variability for power cables installed outdoors, the authors of the study compiled daily temperatures for 2024, considering three weather scenarios:

- Scenario 1 (the most restrictive) – the highest temperature was assumed for each day considered;
- Scenario 2 – the average temperature was assumed for each day considered;
- Scenario 3 – the lowest temperature was assumed for each day considered.

The data regarding ambient temperature comes from the Gdańsk Świbno weather station, in northern Poland, and was provided by the Institute of Meteorology and Water Management – National Research Institute (Instytut Meteorologii i Gospodarki Wodnej – Państwowy Instytut Badawczy, IMGW-PIB).

As a result of the analysis of the distribution of the highest temperatures throughout the year (Scenario 1 – the most restrictive of those considered, Fig. 3), one warmest day was identified in each quarter of the year. The selected days and their temperature distributions are presented in Fig. 4 (bars 'A'). It was then assumed that electric current flowing through the power cables is equal to the current-carrying capacity, resulting in a 45 K increase in the cable insulation temperature (bars 'B' in Fig. 4).

Furthermore, it was assumed that for half of each quarter, solar radiation affects the power cables and causes a specific increase in insulation temperature – elevated 'C' columns relative to 'B' columns at selected times of the day. Table 1 provides, for example, a detailed summary of temperatures on a given/selected warmest day in the third quarter of 2024 – this is a numerical representation of the data from Fig. 4c. Column 2 in Table 1 contains a summary of the maximum hourly ambient temperatures based on meteorological data. Column 3 contains the cable insulation temperatures, assuming that the current flowing through the cable is equal to the current-carrying capacity – then the cable insulation

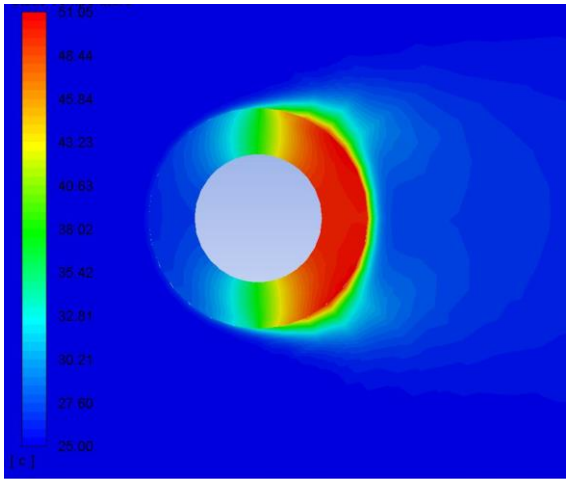


Fig. 2. Temperature fields in the cable cross-section at a height of 0.5 m above the ground. The arrangement is as in Fig. 1. The cable is not subjected to any current. The maximum temperature in the analysed cross-section is 51.05°C.

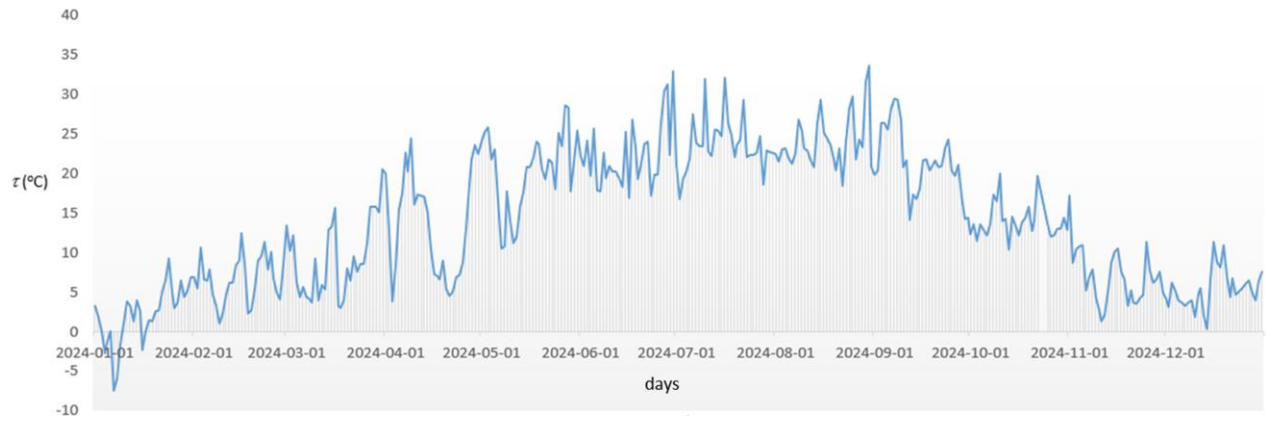


Fig. 3. The highest temperature for each day in 2024. Data from the IMGW-PIB Gdańsk Świbno station.
Own elaboration based on data from IMGW-PIB [30].

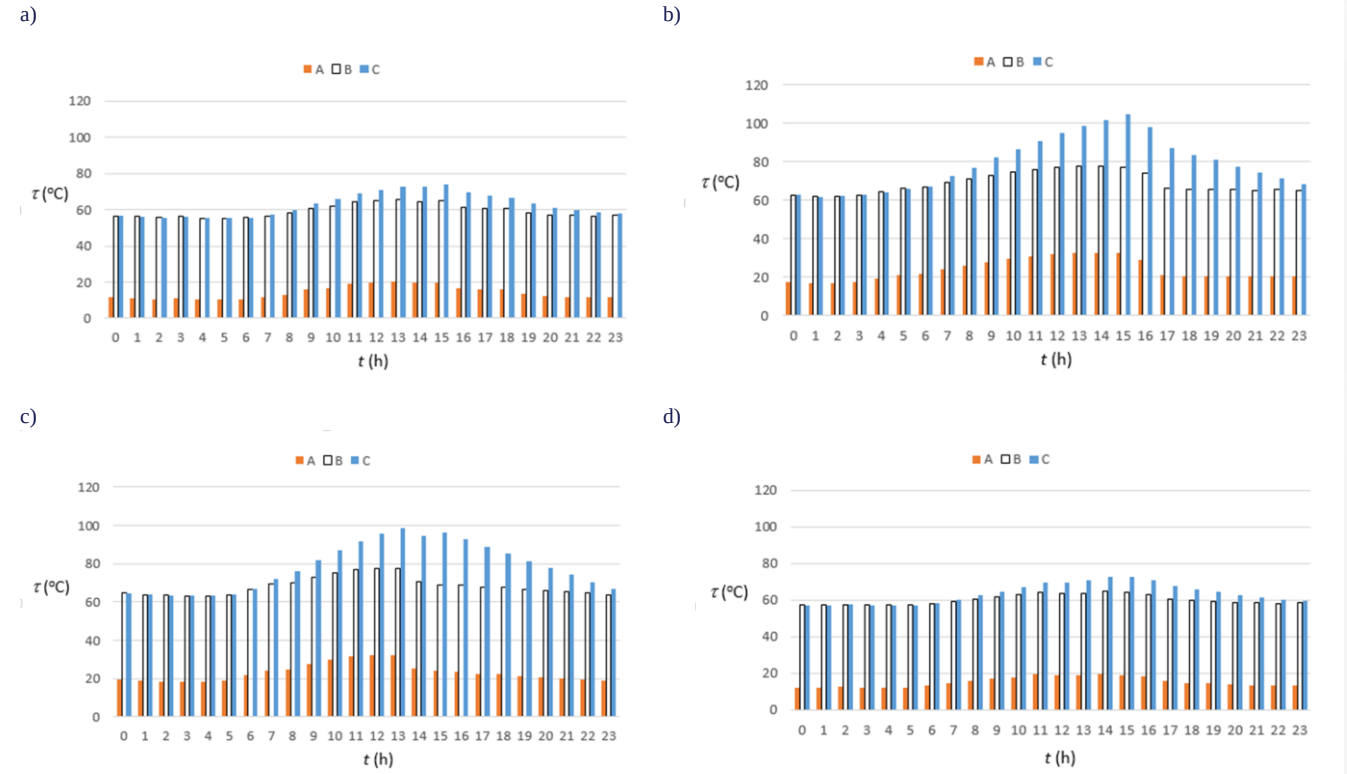


Fig. 4. Daily variation of air and cable insulation temperatures for selected days of 2024 in each quarter (Scenario 1): a) March 31 b) June 30, c) August 30, d) October 10. Bars: A – air temperature (IMGW-PIB data from the Gdańsk Świbno measuring station); B – calculated temperature of cable insulation in places shielded from direct solar radiation, cable loaded with current (I_{dd}); C – calculated temperature of cable insulation in places exposed to direct solar radiation, cable loaded with current (I_{dd}) [30].

temperature increase is 45 K. This corresponds to conditions without solar radiation lasting half of the quarter (assumed to be 45 days). In the case of solar radiation (the remainder of the quarter – also assumed to be 45 days), a further increase in insulation temperature is assumed at individual hours (column 4 in Table 1; Note: there is no column 4 for days without solar radiation). The resulting temperature values are shown in column 5. Similar calculations as in Table 1 were made for the remaining quarters of 2024.

The rated durability of the insulation (L_n) is assumed to be 25 years. The long-term permissible temperature τ_{dd} for PVC insulation is 70°C. The temperature τ_x was determined for each hour of the day (Fig. 4 and sample detailed data in Table 1), with 45 days without solar radiation and 45 days with radiation at specific times assumed for each quarter.

Based on the assumptions made above, the durability of the insulation at temperature τ_x was calculated according to the following relationship:

$$L_x = L_n 2^{\frac{\tau_{dd}-\tau_x}{\Delta\tau}}, \quad (3)$$

where L_n is the rated insulation durability at temperature τ_{dd}, τ_{dd} – the highest permissible long-term temperature of the power cable, τ_x – temperature other than the highest permissible long-

Table 1. Hourly temperature distribution (°C) for the warmest day in the third quarter of 2024 (Scenario 1) – representative day 2024-08-30 (data from IMGW-PIB). Bars 'A', 'B', and 'C' from Fig. 4.

Time of the day, h	Ambient temp. (bars 'A'), °C	Temperature of the cable loaded with current (I_{dd}), in places not exposed to solar radiation (bars 'B'), °C	Assumed increase in cable temperature due to solar radiation, °C	Temperature of the cable loaded with current (I_{dd}), in places exposed to solar radiation (bars 'C'), °C
0:00	19.5	64.5	0	64.5
1:00	18.9	63.9	0	63.9
2:00	18.4	63.4	0	63.4
3:00	18.3	63.3	0	63.3
4:00	18.2	63.2	0	63.2
5:00	18.8	63.8	0	63.8
6:00	21.7	66.7	0	66.7
7:00	24.1	69.1	3	72.1
8:00	25.0	70.0	6	76.0
9:00	27.7	72.7	9	81.7
10:00	29.9	74.9	12	86.9
11:00	31.8	76.8	15	91.8
12:00	32.5	77.5	18	95.5
13:00	32.2	77.2	21	98.2
14:00	25.3	70.3	24	94.3
15:00	24.0	69.0	27	96.0
16:00	23.8	68.8	24	92.8
17:00	22.7	67.7	21	88.7
18:00	22.4	67.4	18	85.4
19:00	21.4	66.4	15	81.4
20:00	20.7	65.7	12	77.7
21:00	20.2	65.2	9	74.2
22:00	19.5	64.5	6	70.5
23:00	18.9	63.9	3	66.9

term temperature, $\Delta\tau$ – a change in temperature which causes a twofold change in the durability of the insulation (assumed 8 K). Sample calculation results based on Eq. (3) are included in Table 2.

Due to the estimated variation of the cable insulation temperature over time, it is necessary to use the relationship for the resultant insulation durability:

$$L_{tot} = \frac{1}{\sum_{i=1}^{N}\left(\frac{t_i}{L_{xi}}\right)}, \tag{4}$$

where L_{xi} – insulation durability corresponding to a given temperature in the considered partial time interval t_i, t_i – relative partial interval of insulation operating time at a specific temperature.

Table 2. Example calculation results based on Eq. (3); Scenario 1.

Parameter	Value	L_x, year	Comments
τ_o, °C	29.9	–	–
τ_{dd}, °C	70	–	–
$\Delta\tau$, K	8	–	–
$\Delta\tau_{dd}$, K	45	–	–
τ_{x1},°C	74.9	16.35	places not exposed to solar radiation
$\Delta\Theta_s$, K	12	–	–
τ_{x2}, °C	86.9	5.78	places exposed to solar radiation

By applying Eq. (4), using the data presented in Fig. 4 and other assumptions, it was calculated that the insulation durability for the analysed conditions is 17.1 years. The calculations show that the expected actual insulation durability is significantly lower than the rated durability (25 years). Therefore, to maintain the rated insulation durability, the load should be reduced by 5.3% compared to the standard current-carrying capacity of power cables in the analysed case. Table 3 presents the results of the current-carrying capacity correction, for example, PVC-insulated cables with data included in the standard [33]. This correction allows for reducing the temperature rise of the cables caused by the flowing current from 45 K to approximately 40 K, which is sufficient to achieve an insulation durability of 25 years.

Table 3. Correction of the current-carrying capacity of PVC-insulated cables to achieve the rated insulation durability (25 years). Cables installed in locations exposed to solar radiation. Scenario 1.

Cross-section of conductor, mm²	2.5	2.5	4	4	6	6
Number of loaded conductors	2	3	2	3	2	3
Current-carrying capacity without correction, A (according to [33])	23	19.5	31	26	39	33
Correction factor	1×0.947					
Current-carrying capacity after correction, A	21.8	18.5	29.4	24.6	36.9	31.3

For a different weather scenario, the correction factor will have a different value and can be estimated based on temperature data for the analysed region of the country/world using the methodology presented in this study.

In order to better illustrate the usefulness of the indicated calculation method for determining the correction factor, two further scenarios were used, based on the actual average temperatures (Scenario 2) and lowest temperatures (Scenario 3) from the Gdańsk Świbno station, and based on operating time at a specific temperature in the year 2024.

Scenario 2 focuses on the use of average temperatures throughout each analysed day. The annual distribution of average (median) temperatures throughout the year is shown in Fig. 5. Similarly to Scenario 1, in Scenario 2, each representative day in each quarter was selected. The selection was based on the temperature in each quarter, as shown in Fig. 6.

Bars 'A', 'B' and 'C' presented in Fig. 6 were determined similarly to Scenario 1. Based on the assumptions made in Scenario 1, the insulation durability at a given temperature was calculated. Example results are provided in Table 4. By applying Eq. (4) and the assumptions previously described, the resulting insulation durability is 35.31 years. The calculated durability is therefore significantly higher than the assumed rated durability of 25 years of the insulation.

To fully utilise the technically assumed durability of cables, it is possible to increase the current-carrying capacity of power cables. For the assumed weather Scenario 2, the current-carrying

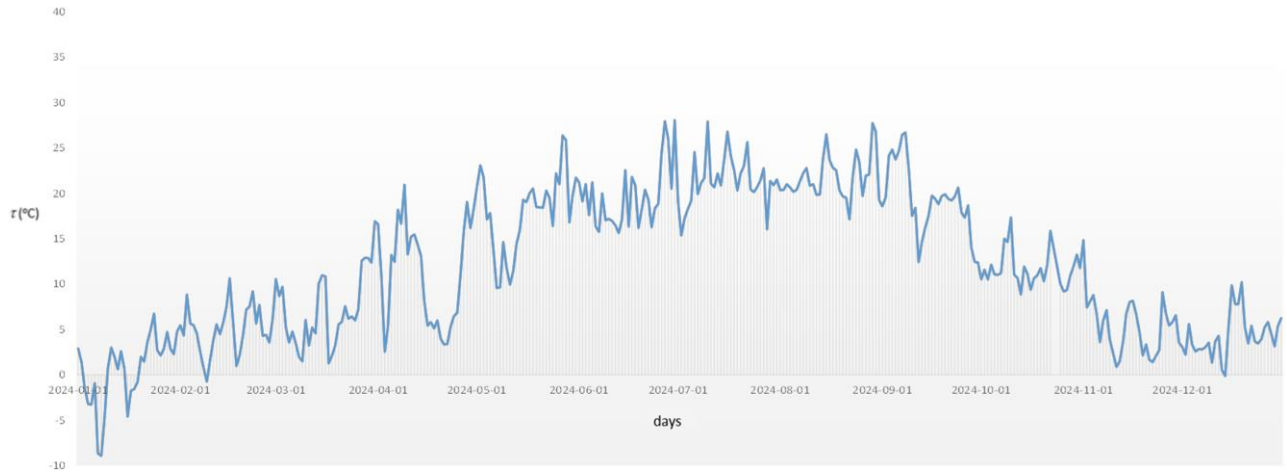


Fig. 5. The average temperature for each day in 2024. Data from the IMGW-PIB Gdańsk Świbno station. Own elaboration based on data from IMGW-PIB.

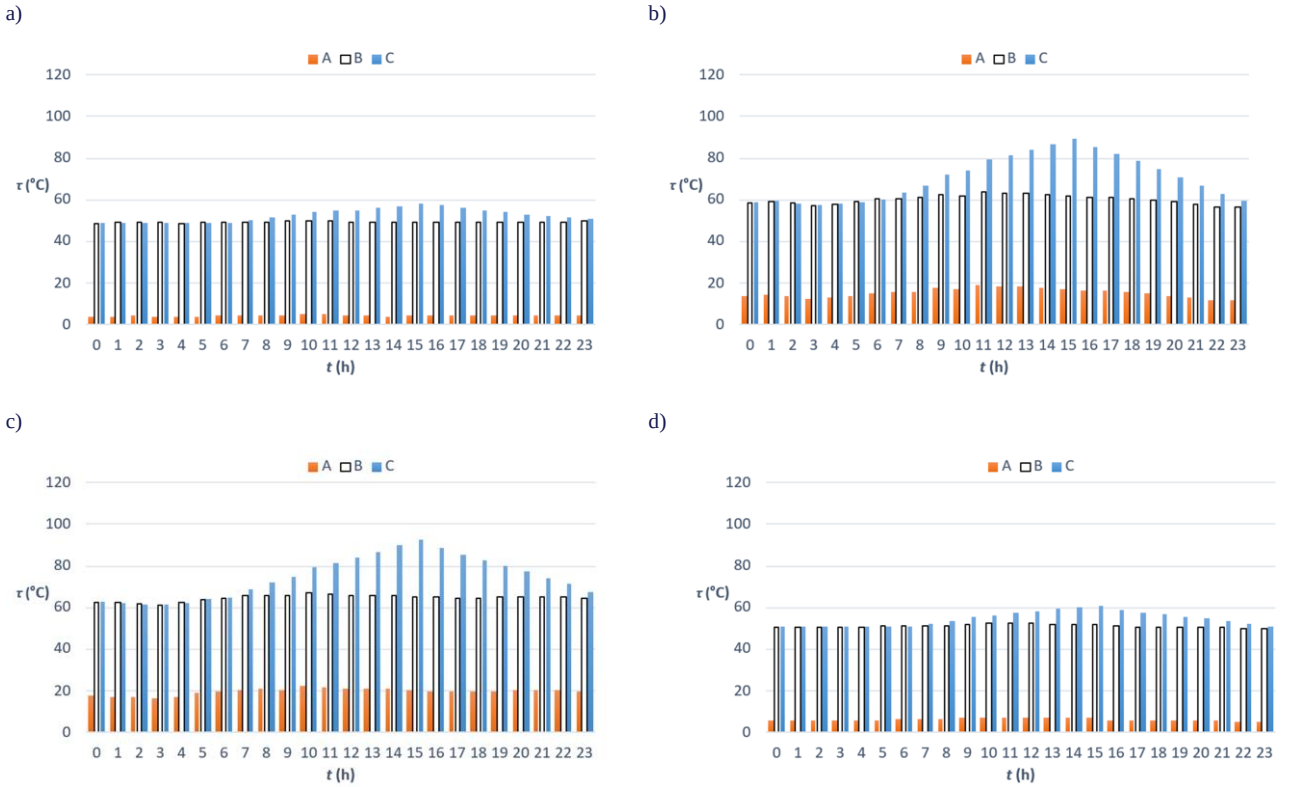


Fig. 6. Daily variation of air and cable insulation temperatures for selected days of 2024 in each quarter (Scenario 2): a) February 20, b) June 9, c) July 12, d) November 17. Bars: A – air temperature (IMGW-PIB data from the Gdańsk Świbno measuring station); B – calculated temperature of cable insulation in places shielded from direct solar radiation, cable loaded with current I_{dd}; C – calculated temperature of cable insulation in places exposed to direct solar radiation, cable loaded with current I_{dd}.

Table 4. Example calculation results based on Eq. (3); Scenario 2.

Parameter	Value	L_x (y)	Comments
τ_o, °C	22.1	–	–
τ_{dd}, °C	70	–	–
$\Delta\tau$, K	8	–	–
$\Delta\Theta_{dd}$, K	45	–	–
τ_{x1}, °C	67.1	32.14	places not exposed to solar radiation
$\Delta\Theta_s$, K	12	–	–
τ_{x2}, °C	79.1	11.36	places exposed to solar radiation

capacity of power cables can be adjusted/increased by 4.1%. Example values of the current-carrying capacity of power cables before and after applying the correction factor are given in Table 5.

The next scenario, i.e. Scenario 3, is based on the use of the lowest temperatures throughout each considered day. It is the most optimistic and somewhat risky scenario. The annual distribution of the lowest temperatures throughout the year is shown in Fig. 7. Similar to the previous two scenarios, each representative day in each quarter was selected.

Table 5. Correction of the current-carrying capacity of PVC-insulated cables to achieve the rated insulation durability (25 years). Cables installed in locations exposed to solar radiation. Scenario 2.

Cross-section of conductor, mm²	2.5	2.5	4	4	6	6
Number of loaded conductors	2	3	2	3	2	3
Current-carrying capacity without correction, A (according to [33])	23	19.5	31	26	39	33
Correction factor	1×1.041					
Current-carrying capacity after correction, A	23.9	20.3	32.3	27.1	40.6	34.4

The selection was based on the coldest day in each quarter, as shown in Fig. 8. Bars 'A', 'B' and 'C' presented in Fig. 8 were determined similarly to Scenario 1 and Scenario 2. Based on the assumptions made in the example presented, the insulation durability at a given temperature was calculated. The results of a sample calculation are provided in Table 6. The resultant durability of insulation was obtained as 81.23 years. Similarly to Scenario 2, the resulting durability of insulation is higher than the rated durability of 25 years. Hence, it is possible to increase the current-carrying capacity of power cables by as much as 12.4%. Further, theoretically, it is possible to introduce a correction (in this case a significant increase) of the current-carrying capacity (Table 7).

It is obvious that for scenarios 2 and 3 there is no need to correct/increase the current-carrying capacity – it can remain at the normative level (to maintain a high margin of safety).

The presented results should be interpreted with consideration of the uncertainty associated with the adopted input data and modelling assumptions. First, the numerical analysis was performed for a selected set of environmental conditions, including air temperature of 25°C, soil temperature of 12°C, wind speed of 1 m/s, solar irradiance of 1000 W/m^2, solar incidence angle of 45°, soil thermal conductivity of 0.4 W/(m·K), and solar absorptivity of the cable surface equal to 0.9. Therefore, the obtained temperature rises should be treated as representative for the assumed scenario and may vary under different local operating conditions.

Table 6. Example calculation results based on Eq. (3); Scenario 3.

Parameter	Value	L_x, year	Comments
τ_o, °C	9.9	–	–
τ_{dd}, °C	70	–	–
$\Delta\tau$, K	8	–	–
$\Delta\Theta_{dd}$, K	45	–	–
τ_{x1}, °C	54.9	16.35	places not exposed to solar radiation
$\Delta\Theta_s$, K	6	–	–
τ_{x2}, °C	60.9	54.99	places exposed to solar radiation

An additional source of uncertainty results from the simplifications adopted in the numerical model. The calculations were carried out as steady-state simulations using the standard k-ε turbulence model with enhanced wall treatment and full buoyancy effects. In real outdoor conditions, however, airflow and solar exposure reveal transient behaviour and may change over short periods. Consequently, the model should be regarded as an engineering approximation of the thermal effect rather than reproducing every instantaneous operating condition exactly. The uncertainty of the cable's durability calculations is also related to the adopted

Table 7. Correction of the current-carrying capacity of PVC-insulated cables to achieve the rated insulation durability (25 years). Cables installed in locations exposed to solar radiation. Scenario 3.

Cross section of conductor, mm²	2.5	2.5	4	4	6	6
Number of loaded conductors	2	3	2	3	2	3
Current-carrying capacity without correction, A (according to [33])	23	19.5	31	26	39	33
Correction factor	1×1.124					
Current-carrying capacity after correction, A	25.9	21.9	34.8	29.2	43.8	37.1

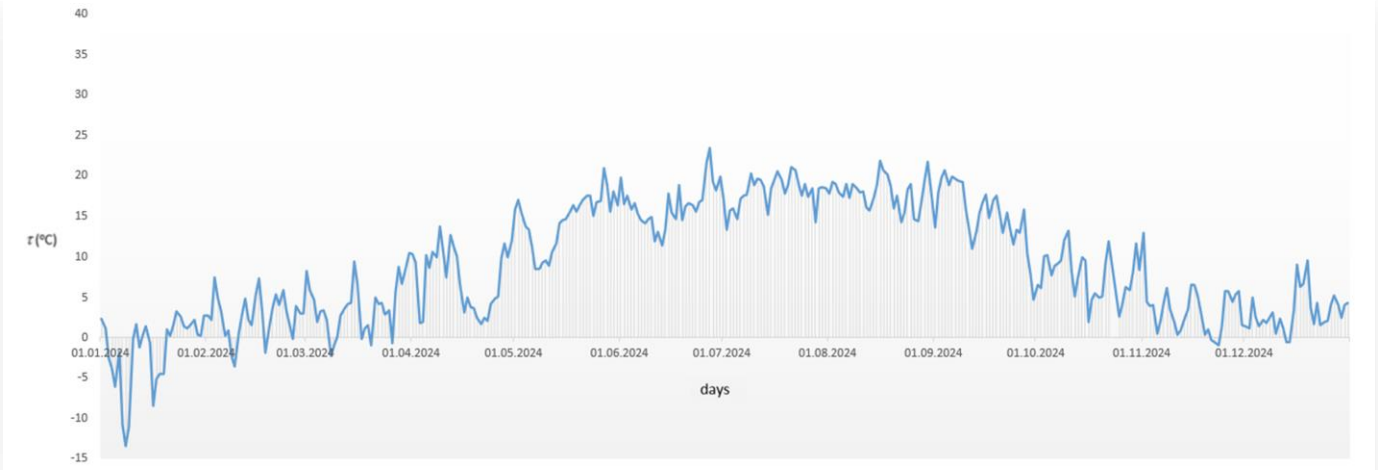


Fig. 7. The lowest temperature for each day in 2024. Data from the IMGW-PIB Gdańsk Świbno station. Own elaboration based on data from IMGW-PIB.

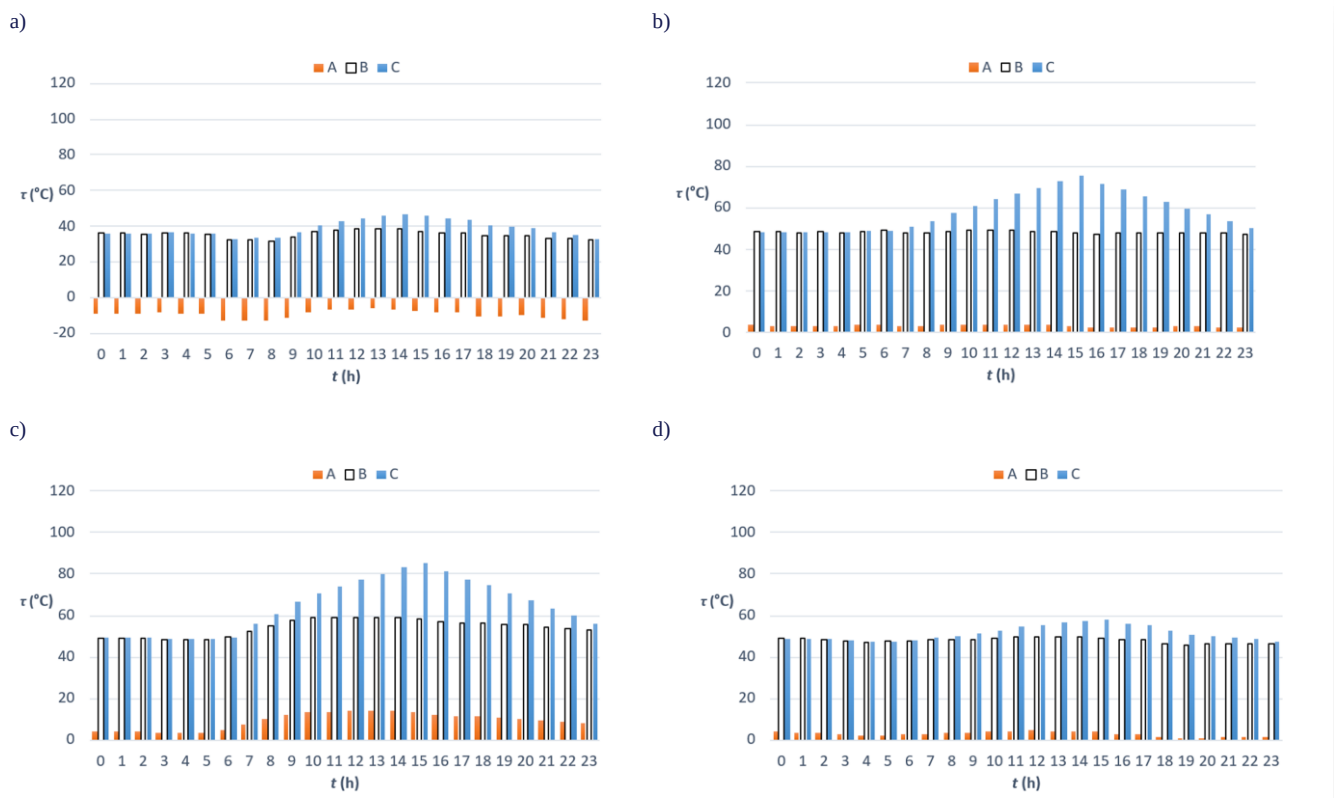


Fig. 8. Daily variation of air and cable insulation temperatures for selected days of 2024 in each quarter (Scenario 3): a) January 8, b) April 21, c) September 30, d) November 23. Bars: A – air temperature (IMGW-PIB data from the Gdańsk Świbno measuring station); B – calculated temperature of cable insulation in places shielded from direct solar radiation, cable loaded with current I_{dd}; C – calculated temperature of cable insulation in places exposed to direct solar radiation, cable loaded with current I_{dd}.

thermal-ageing model. In particular, the insulation lifetime was estimated using the assumed temperature interval causing a two-fold change in durability, equal to 8 K, and by applying representative daily temperature profiles for selected quarters of the year. Thus, the calculated insulation lifetime/durability should be interpreted as an estimate of expected long-term thermal exposure under the assumed scenarios, rather than as an exact prediction for every installation site. Despite these limitations, the proposed methodology remains useful for engineering analysis because it captures the dominant factors affecting free-air cable thermal loading, namely solar radiation and time-varying ambient temperature. The results are therefore suitable for comparative assessments, conservative design studies, and the determination of practical correction factors for cable current-carrying capacity.

4. Conclusions

The standard and practical determination of the current-carrying capacity of power cables assumes a constant design ambient temperature throughout the year. The authors of this paper, however, have proposed an alternative approach based on daily-annual variability of ambient temperature with a step of one hour, and accounting for the direct solar radiation.

The presented method for determining the expected cable temperature and associated insulation durability can be applied to electrical installations located in selected regions of the country or world, knowing, among other things, the local daily and annual ambient temperature variability. Taking into account local weather conditions, including expected solar radiation, allows for an estimate of cable insulation durability that is close to this realistic one. The approach proposed is particularly suitable for electrical installations placed on the facade or roof of a building.

The results obtained clearly demonstrate that solar radiation may significantly affect the thermal conditions of power cables installed in free air, which is consistent with previous findings reported in the literature. According to the obtained numerical modelling results, the authors' study indicates that under unfavourable local conditions (e.g. limited airflow), the temperature rise may reach values of up to 50 K above the ambient, which is comparable to or even exceeds typical design assumptions used in standard approaches.

In comparison with studies focusing on underground cables, where the thermal behaviour is strongly governed by soil properties and relatively stable boundary conditions, cables installed in free air are subject to much higher variability of environmental parameters. This variability is particularly related to insolation level, as well as daily and seasonal changes in ambient temperature, which are usually not taken into account in standard-based calculations (e.g., IEC 60287), where constant ambient temperature is assumed.

The results obtained in this paper are also consistent with other studies analysing the effect of ambient temperature profiles on cable current-carrying capacity, which indicate that the

use of constant design temperature may lead to inaccurate estimation of permissible current. However, the present study extends this approach by combining real hourly temperature data with the effect of solar radiation and linking these thermal conditions directly with insulation ageing.

The contribution of this work is the analytical evaluation of insulation durability under realistic operating conditions. While previous studies have mainly focused on temperature distribution or current-carrying capacity calculations, the present approach demonstrates that neglecting natural environmental variability may lead to a substantial reduction of insulation lifetime/durability (e.g. from 25 years to 17.1 years in the most restrictive scenario). This finding highlights the importance of considering both solar radiation and time-dependent ambient temperature in the design of outdoor electrical installations.

Furthermore, the proposed methodology allows for the determination of current-carrying capacity correction factor levels based on actual climatic data. This represents an advancement over standard approaches, which typically do not provide tools for such adjustments under variable environmental conditions. The obtained correction values (from approximately −5.3% to +12.4%, depending on the scenario) indicate that both conservative and optimised design strategies can be developed using the presented method.

Among the presented scenarios/assumptions for calculating the resultant durability of insulation of power cables, the measurement data leading to the determination of the lowest durability should be selected. Regarding the data analysed by the authors, it is suggested to adopt Scenario 1 (the most restrictive, but the safest) as a representative scenario for determining the current-carrying capacity of cables. If the cable system is critical, one may consider analysing historical temperature data from the last few years and taking the least favourable year.

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