Article citation info:
CZAPP S, SZULTKA S, RATKOWSKI F, TOMASZEWSKI A. Risk of power cables insulation failure due to the thermal effect of solar radiation. Eksploatacja i Niezawodnosc – Maintenance and Reliability 2020; 22 (2): 232–240, http://dx.doi.org/10.17531/ein.2020.2.6.

Stanisław CZAPP
Seweryn SZULTKA
Filip RATKOWSKI
Adam TOMASZEWSKI

RISK OF POWER CABLES INSULATION FAILURE DUE TO THE THERMAL EFFECT OF SOLAR RADIATION

RYZYKO USZKODZENIA CIEPLNEGO IZOLACJI KABLI ELEKTROENERGETYCZNYCH Z POWODU ODDZIAŁYWANIA PROMIENIOWANIA SŁONECZNEGO

Low-voltage, as well as high-voltage power cable lines, are usually buried in the ground. The ampacity of the power cables in the ground mainly depends on the thermal resistivity of the soil, which may vary in a wide range. A common practice in power cable systems performance is to supply them from a pole of an overhead line. If so, a section of the line is located in free air and can be directly exposed to solar radiation. In some cases, the ampacity of power cables placed in free air is lower than in the ground. Differences in ampacities can be very high if thermal resistivity of the soil is very low, and simultaneously solar irradiation of cables in air occurs. This paper presents the risk of power cables overheating and in consequence the risk of their failure, when part of the underground power cable line is placed in free air. Temperature distribution of cables in the air (with and without solar radiation) for various load currents is presented. Thermal endurance of power cables insulation, operating with the overheating, is estimated.

Keywords: *failure risk, heat transfer, numerical modelling, power cables, solar radiation.*

Linie kablowe zarówno niskiego, jak i wysokiego napięcia zwykle buduje się jako podziemne. Obciążalność kabli układanych w ziemi w znacznym stopniu zależy od rezystywności cieplej gruntu, a może się ona zmieniać w bardzo szerokim zakresie. Obecnie powszechną praktyką jest zasilanie linii kablowych z linii napowietrznych, co sprawia, że pewien odcinek linii kablowej znajduje się w powietrzu i może być poddany bezpośredniemu oddziaływaniu promieniowania słonecznego. W pewnych przypadkach obciążalność prądowa długotrwała kabli w powietrzu jest niższa niż w ziemi – różnice w tej obciążalności mogą być bardzo duże, jeżeli grunt ma niską rezystywność cieplną, a na odcinek linii w powietrzu oddziałuje promieniowanie słoneczne. W artykule przedstawiono problem przegrzania kabli elektroenergetycznych, gdy przyjęta obciążalność linii kablowej wynika z warunków dla ułożenia w ziemi, a na pewnym odcinku linia jest umieszczona w powietrzu. Przedstawiono rozkłady temperatury kabli w powietrzu (z uwzględnieniem i bez uwzględnienia promieniowania słonecznego) dla różnych prądów obciążenia kabli. Oszacowano trwałość termiczną izolacji kabli, mających przez znaczny przedział czasu temperaturę wyższą niż dopuszczalna długotrwale.

Słowa kluczowe: *ryzyko uszkodzenia, wymiana ciepła, modelowanie numeryczne, kable elektroenergetyczne, promieniowanie słoneczne.*

1. Introduction

Distribution of power in power networks is performed with the use of overhead power lines as well as underground power cables. The investment cost of the underground power cable distribution systems is higher compared to the use of overhead lines but gives higher reliability of supply, especially reflected in improved SAIDI and SAIFI indicators [1, 19, 24].

Power cables are usually buried in the ground, but in many cases, their ending sections are placed in air, to be connected with conductors of overhead lines, as it is presented in Fig. 1. Depending on the height of the pole, length of the power cables in air can be from a few to several meters. Given that the cable section in the air is connected in series with a section buried in the ground, the ampacity of the whole power cable line depends on the section for which thermal condition for heat transfer from the cables is the worst. The worst thermal condition is expected for the section in air, during sunny weather and without any wind.

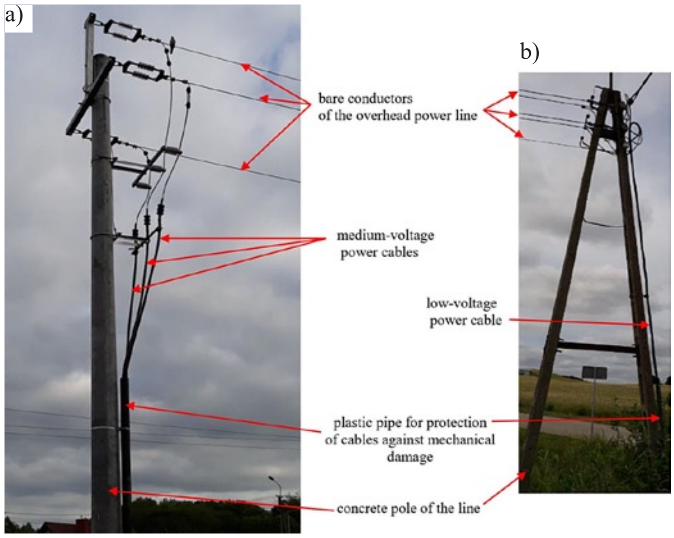


Fig. 1. Poles for: a) medium-voltage overhead power line, b) low-voltage overhead power line; and their connections with power cable lines

The problem of power cables heating and calculation of their ampacity are the subject of many papers and standards, especially [12-

16]. Knowledge of the actual operating conditions of power cables helps to avoid design errors and, as a result, it may increase the reliability and safety of power installations [2, 17, 26].

The effect of sunlight on the heating of power cables is not fully studied, and the provisions of the standards do not fully describe this effect [4, 6-8, 18, 25-26]. Paper [26] clearly indicates that cables exposed to solar radiation may be damaged very fast. In the described installation (Fig. 2), power cables were put into operation during autumn. In spite of a very low value of the load current, their first damage occurred during the nearest summer. After this summer, power cables operated without problems, but their thermal damage returned during the next summer.

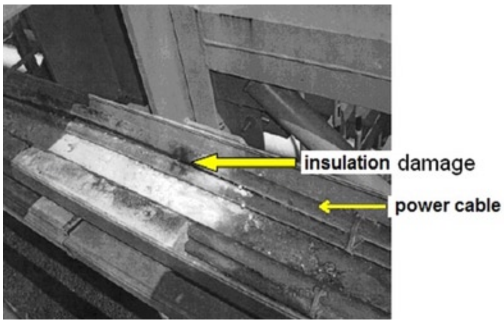


Fig. 2. Thermal damage of the power cables exposed to solar radiation [26]

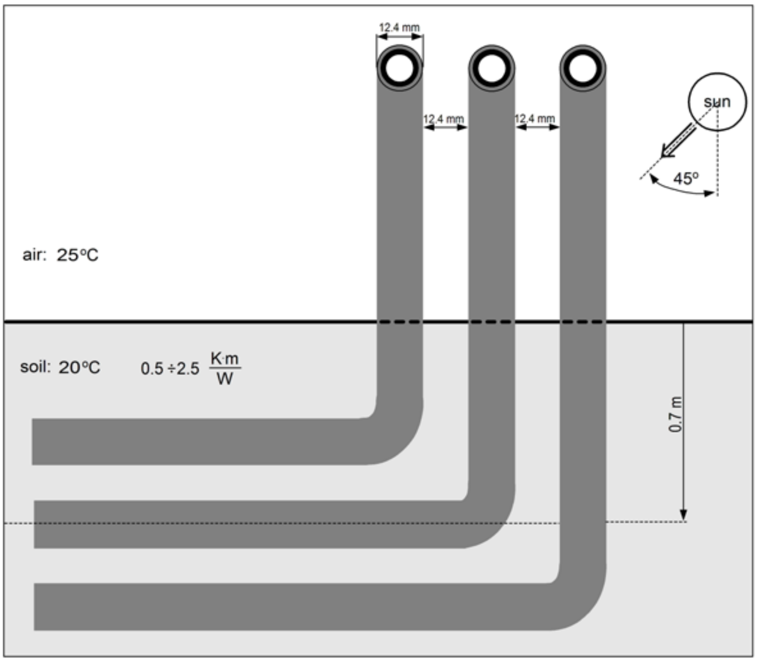


Fig. 3. Analyzed arrangement of the power cable system composed of three single-core cables

Accurate calculation of power cables ampacity and temperature of the insulation for various ambient conditions are possible only with the use of the numerical approach [8-10, 13, 27]. This paper presents the problem of evaluation of the power cables ampacity and their insulation temperature when cables are placed in changing ambient condition “ground-air”, and especially solar radiation may occur. The common practice is to calculate the ampacity taking into account thermal conditions occurring in the ground. Unfortunately, such an assumption may be dangerous for the part of the cable line in free air. In this paper, the authors prove that thermal condition in the air can give a negative effect on ampacity and endurance of the whole power cable line, in particular when solar radiation occurs. It is very important in terms of the reliability of power supply, because, due to significant overheating of cables in air, fast destruction of their insulation may appear. For calculation of the ampacity and insulation temperature, advanced computer modelling is employed.

A power cable line presented in Fig. 3 is considered in this paper. This cable line is placed partially in the ground and partially in free air (section in the air goes from the ground to a pole of the overhead line, as it is presented in Fig. 1). The power cable line is composed of three single-core PVC-insulated cables (maximum permissible continuous operating temperature is equal to 70°C). The power cables nominal cross-sectional area of the copper conductor is equal to 35 mm^2. They are laid in flat formation (0.7 m from the ground surface), the spacing between cables is equal to their external diameter. Ambient air temperature is 25°C and soil temperature is 20°C (reference ambient conditions for Poland according to IEC 60287-3-1 [16]). Thermal resistivity of the soil is considered to be within the range ρ_s = (0.5–2.5) (K·m)/W.

The main purpose of the investigation is to calculate ampacity of power cable line for various thermal resistivities of the soil, and after assuming the calculated ampacity as a power cable load, temperature of the cable’s insulation in free air is evaluated – with and without solar radiation. On the base of the calculated temperature of the cables in air, a decrease in their thermal endurance is evaluated.

2. Calculation of power cables ampacity

For a given value of current flowing in a core of a power cable, heat balance in a steady-state can be described by the following equation:

$$q_c + q_r = q_s + q_J \quad (1)$$

where:

- q_c – heat flux density dissipated to the surroundings of power cables; by convection (cables in the air) or by conduction (cables in the ground), W/m^2,
- q_r – heat flux density dissipated to the surroundings of power cables by radiation, W/m^2,
- q_s – heat flux density delivered to the power cables by solar radiation, W/m^2,
- q_J – heat flux density generated in the conductor due to the flow of electric current (Joule’s heat), W/m^2.

In the case of cables laid in the ground, heat flux density q_c mainly depends on the value of thermal resistivity of the soil. The lower value of thermal resistivity of the soil, the higher value of the ampacity of power cables [5]. In the case of cables laid in free air, heat flux density q_c mainly depends on the value of convective heat transfer coefficient α. This coefficient is directly related to the speed and direction of the wind flowing around the cables as well as the temperature difference between the cable and air. Therefore, in the case of sunny, windless weather, convective heat transfer coefficient reaches small values. Additional heat flux may occur for cables in free air – heat flux density q_s generated by solar radiation. It all makes that in the case of a cable line placed in series in the ground of high thermal conductivity (low thermal resistivity) and in air, where there is slight heat exchange by convection and there is sunlight, risk of overheating of the power cables may occur.

For the purpose of power cable systems projects, calculation of power cables ampacity is usually performed with the use of IEC 60287 [14, 15] provisions. These IEC standards allow to evaluate ampacity of power cables placed in various configurations as well as ambient conditions, especially placed in the ground and in air.

The ampacity of an underground power cable, when drying out of the soil is excluded, can be calculated as follows [14, 15]:

$$I_{\max} = \sqrt{\frac{\Delta\theta - W_{\mathrm{d}} \cdot \left[0.5 \cdot T_1 + n_{\mathrm{c}} \cdot (T_2 + T_3 + T_4)\right] - \Delta\theta_{\mathrm{add}}}{R \cdot T_1 + n_{\mathrm{c}} \cdot R \cdot (1+\lambda_1) \cdot T_2 + n_{\mathrm{c}} \cdot R \cdot (1+\lambda_1+\lambda_2) \cdot (T_3 + T_4)}} \quad (2)$$

where:

- $I_{\max}$ – ampacity of a power cable, A,
- $\Delta\theta$ – maximum permissible temperature rise of the conductor above ambient temperature, K,
- R – AC current resistance of a conductor at its maximum permissible temperature, Ω/m,
- W_{d} – dielectric losses per phase, W/m,
- T_1 – thermal resistance (per core/phase) between the conductor and sheath/insulation, (K·m)/W,
- T_2 – thermal resistance between the sheath/insulation and armour, (K·m)/W,
- T_3 – thermal resistance of external serving of the cable, (K·m)/W,
- T_4 – external thermal resistance of surrounding medium (soil/backfill), (K·m)/W,
- n_{c} – number of conductors in a multicore power cable, -,
- λ_1 – ratio of the total losses in metallic sheaths (if any) to the total conductor losses, -,
- λ_2 – ratio of the total losses in metallic armour (if any) to the total conductor losses, -.
- $\Delta\theta_{\mathrm{add}}$ – additional reducing factor of the maximum permissible temperature rise of the conductor above ambient temperature, K, (for a cable directly buried in the ground $\Delta\theta_{\mathrm{add}} = 0$).

Calculation of ampacity of power cables according to IEC 60287 [14, 15] provisions can be performed with the use of CYMCAP software [3]. Table 1 presents the result of this calculation, and Fig. 4 depicts the distribution of the temperature in the ground for three selected thermal resistivities of the soil ρ_s: 0.5, 1.0 and 2.5 (K·m)/W.

One can see that the ampacity of the analyzed power cable line (part in the ground) strictly depends on the thermal resistivity of the soil. It may vary almost twice if this resistivity changes from 2.5 (K·m)/W to 0.5 (K·m)/W, and it is very high for the latter value. Thus, for the safe operation of the underground power cable line with a section placed in air, it is important to evaluate the temperature of the power cable in this section, especially if direct solar radiation may occur. If the temperature exceeds permissible 70°C, it is necessary to reduce permissible load of the part of the cable line in the ground.

Including solar radiation in the calculation of power cables temperature and ampacity is not easy. Methods of power cables ampacity calculation, included in standards IEC 60287 [14, 15], utilize Neher-McGrath assumptions but are characterized by simplifications. For more complicated cases of cables arrangement, e.g. in case of strong solar radiation, and especially in case of the mixed effect of solar radiation and wind, it is no possible to calculate the ampacity with sufficient accuracy. Therefore, the ampacity and temperature of the

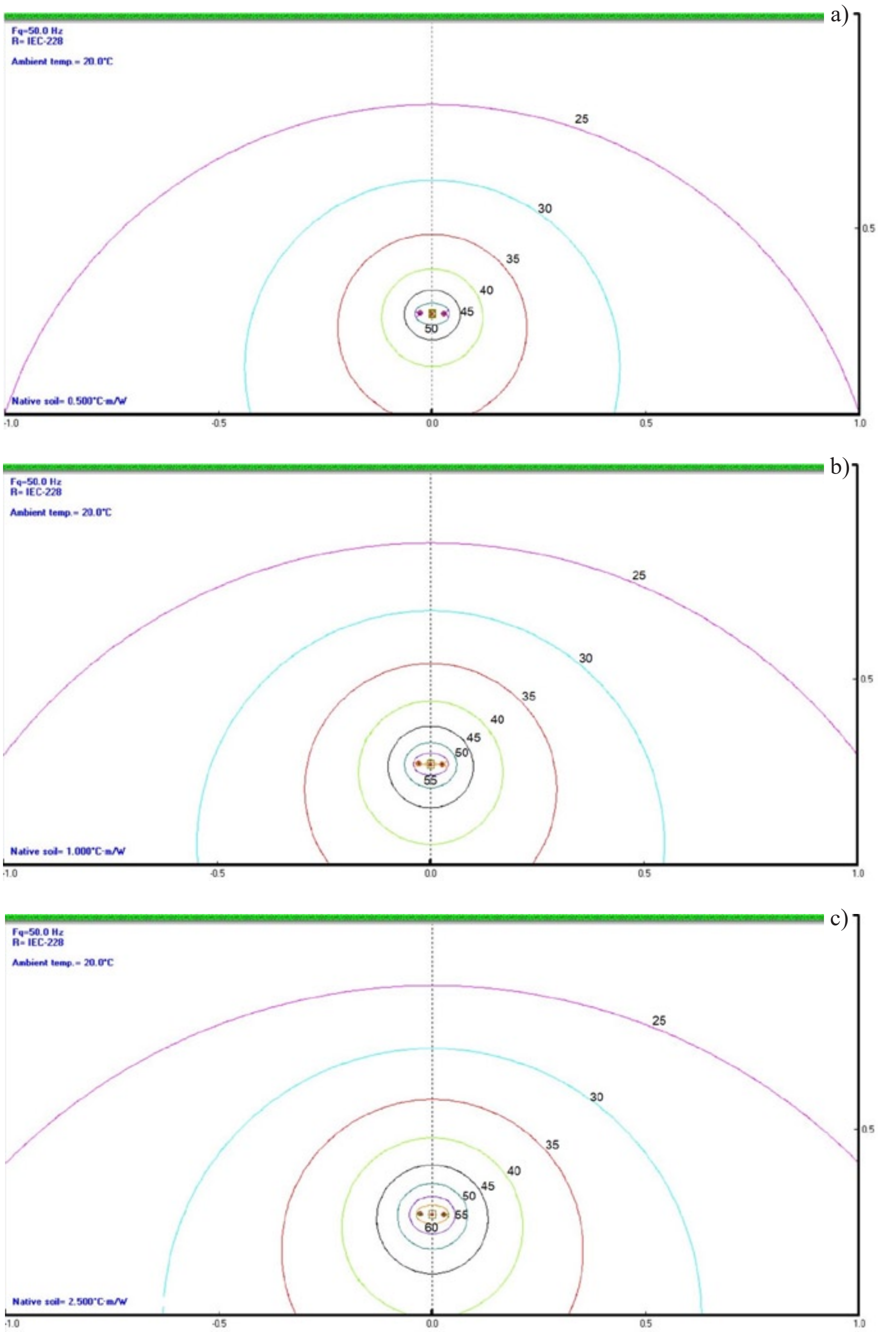


Fig. 4. Temperature distribution (°C) around the analyzed three power cables in flat formation, directly buried in the ground at the depth 0.7 m, for the following load current I_{load} and thermal resistivity of the soil ρ_s:
a) I_{load} = 230 A, ρ_s = 0.5 (K·m)/W, b) I_{load} = 176 A, ρ_s = 1.0 (K·m)/W, c) I_{load} = 118 A, ρ_s = 2.5 (K·m)/W

Table 1. Ampacity of the analyzed power cable line calculated with the use of CYMCAP software

soil, (K·m)/W	0.5	1.0	1.5	2.0	2.5
ampacity, A	230	176	148	130	118

analyzed power cable line are evaluated with the use of the advanced numerical modelling, what is presented in the next section.

3. Modelling of the thermal condition of power cables in free air

In order to investigate the thermal processes in the cable line placed in free air, a computational fluid dynamics implemented in Ansys software has been used. Steady-state fluid flow has been modelled and then heat exchange calculations have been performed. The 3D computational domain is presented in Fig. 5. It consists of three power cables surrounded by air. The total number of the finite elements in the numerical grid exceeds 16×10^6.

a) b)

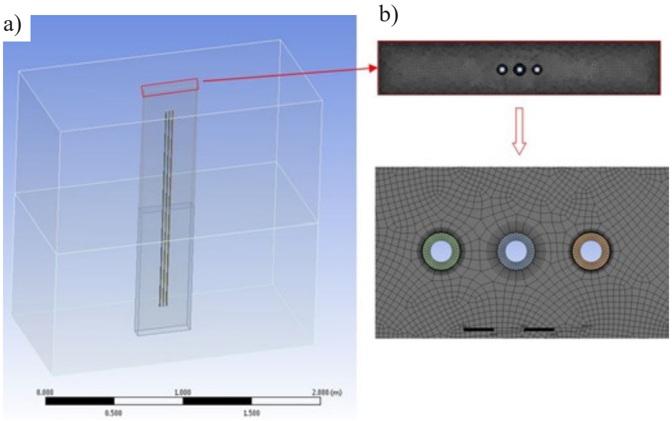
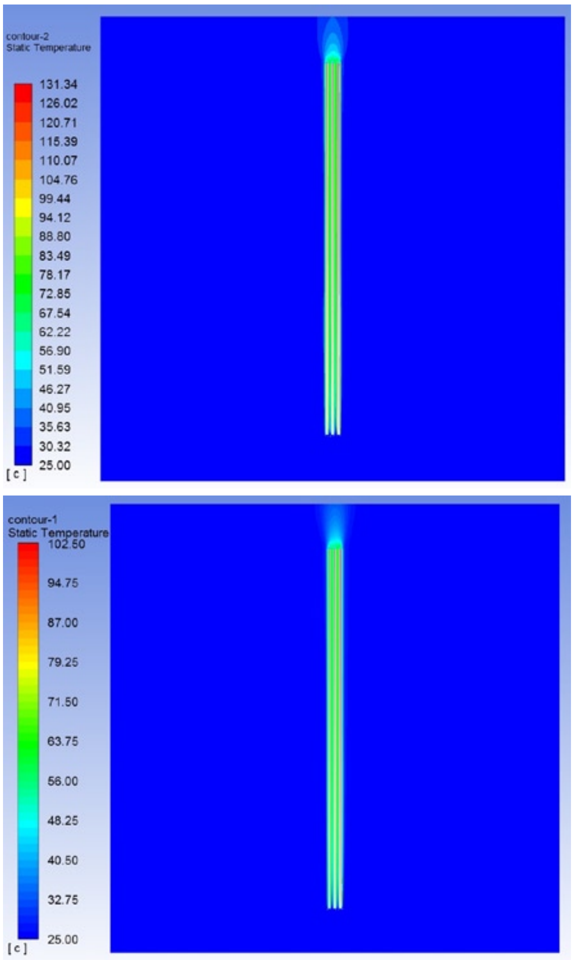


Fig. 5. Computational domain of the analyzed cable system (a) and density of the numerical grid (b)

a) b)



Heat is introduced to the cables from two different sources: from the electric current to internal surface of the cable insulation and also from solar radiation to half of the external surface of the cable (at the right side – see Fig. 3). The lack of accurate measurement data regarding solar radiation incident on the surface of the earth [23] caused that the heat flux density supplied from sun radiation is calculated for the sun's altitude of 45°, which is consistent with conditions in the

c) d) e)

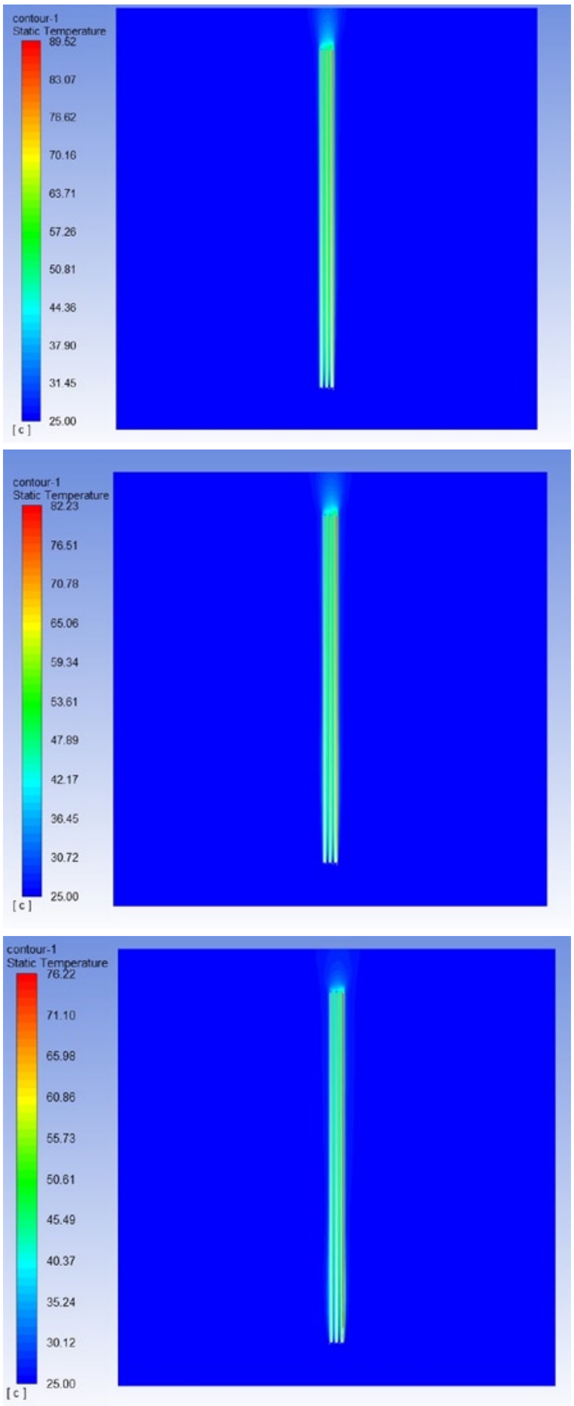
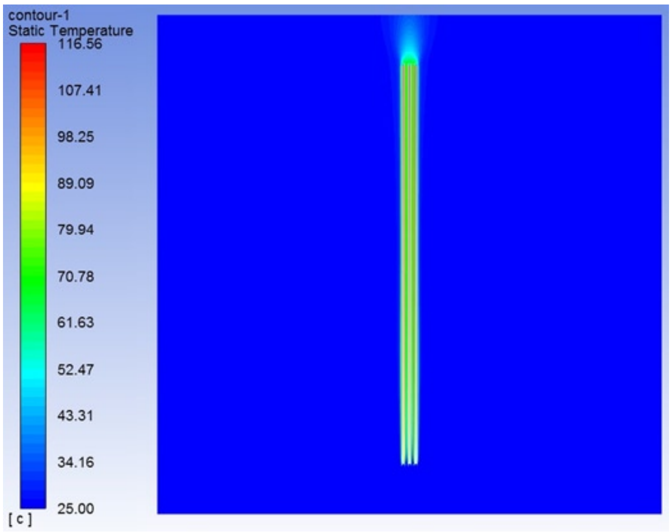
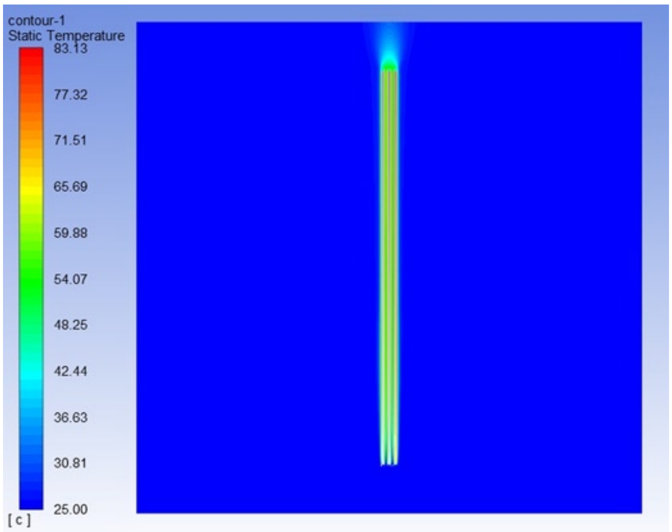


Fig. 6. Temperature distribution around the analyzed three power cables (with solar radiation) for the following load current I_{load}:
a) I_{load} = 230 A, max insulation temp. 131.34 °C,
b) I_{load} = 176 A, max insulation temp. 102.50 °C,
c) I_{load} = 148 A, max insulation temp. 89.52 °C,
d) I_{load} = 130 A, max insulation temp. 82.23 °C,
e) I_{load} = 118 A, max insulation temp. 76.22 °C

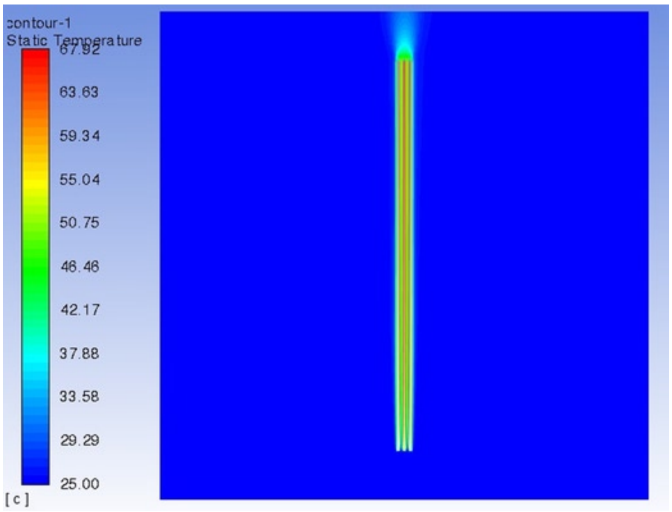
a)



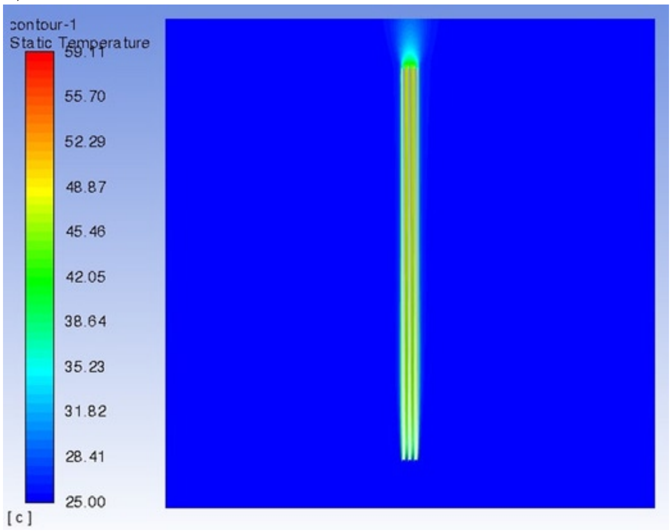
b)



c)



d)



e)

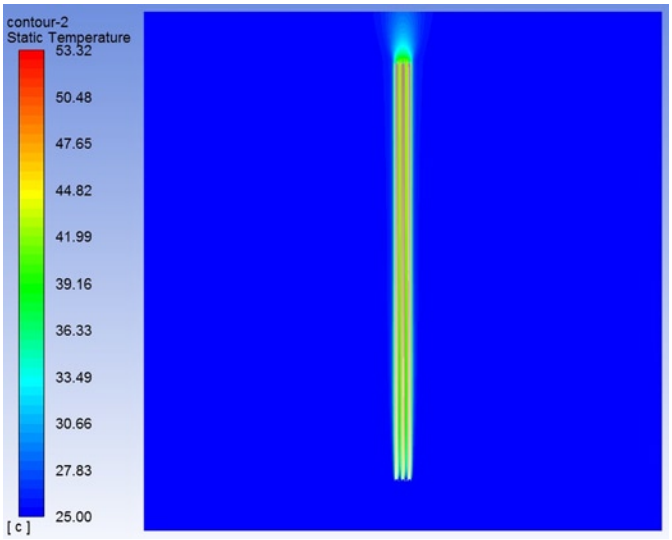


Fig. 7. Temperature distribution around the analyzed three power cables (without solar radiation) for the following load current I_{load}:
- *a) I_{load} = 230 A, max insulation temp. 116.56°C*
- *b) I_{load} = 176 A, max insulation temp. 83.13°C*
- *c) I_{load} = 148 A, max insulation temp. 67.92°C*
- *d) I_{load} = 130 A, max insulation temp. 59.11°C*
- *e) I_{load} = 118 A, max insulation temp. 53.32°C*

European region during summer period. The external (ambient) air temperature is 25°C. In this case, heat exchanges between power cables and air by natural convection and by thermal radiation. In calculations, the case with no wind is analyzed, in order to show the worst thermal conditions, which may appear during the year. Therefore, the presence of gravity force has to be included, and air density is described by ideal gas law. The turbulence model chosen in calculations is *k-epsilon* standard with the option of full buoyancy effects enabled. The thermal radiation of cables external surface was modelled by Discrete Ordinates (DO) model.

Figures 6 and 7 summarizes the temperature distributions for power cables placed in air (with solar radiation – Fig. 6; without solar radiation – Fig. 7). For these cables, the current in the conductor was assumed as resulting from the ampacity of the cables placed in the ground (see Tab. 1). In the upper left corner of each subfigure in Figs 6 and 7, the maximum temperature of the cable insulation is displayed.

When solar radiation is taken into account, the maximum temperature of the insulation varies from 76.22°C (Fig. 6e) to 131.34°C (Fig. 6a), for cables load from 118 A to 230 A respectively. One can see that in each case the temperature exceeds the permissible level of 70°C. For cases without solar radiation and the mentioned range of the cables load, the maximum temperature of the insulation varies from 53.32°C (Fig. 7e) to 116.56°C (Fig. 7a).

Figure 8 contains examples of air velocity distributions around the power cables. The whole velocity field is the effect of natural convec-

Table 2. Overheating of the section of the power cable line placed in the air, for load current equal to the ampacity of the power cables buried in the ground

Cables							Air/ground percentage	
in the ground			in air					
Thermal resistivity of the soil	Ampacity	Max cables temp.	Load current	Solar radiation	Max cables temp.	Load current giving max temp. 70 °C	temp.	ampacity
(K·m)/W	A	°C	A	-	°C	A	%	%
0.5	230	70	230	no	117	152	167	66
				yes	131	96	187	42
1.0	176	70	176	no	83	152	118	86
				yes	102	96	145	54
1.5	148	70	148	no	68	152	97	103
				yes	90	96	129	65
2.0	130	70	130	no	59	152	84	117
				yes	83	96	119	74
2.5	118	70	118	no	53	152	76	129
				yes	76	96	108	81

tion. When the load is 230 A and solar radiation is taken into account, the maximum air velocity around the cables is 0.98 m/s. For the load equal to 118 A and when solar radiation is not taken into account, the maximum air velocity around the cables is only 0.60 m/s. Thus, it is very important to leave the free air movement along the cables. Otherwise, the temperature of the cable's insulation, especially in the presence of solar radiation, could rise even more.

When comparing load current giving max temp. 70°C of power cables in free air with ampacities of power cables in the ground, it may conclude that the latter is higher – in some cases significantly higher (Tab. 2). Aggregated results included in Tab. 2 show that for thermal resistivities of the soil ρ_s = 0.5 and 1.0 (K·m)/W the ampacity of the power cables in the ground (230 A and 176 A respectively) exceeds the ampacity of the power cables in free air even if no solar radiation occurs (152 A without solar radiation and 96 A with solar radiation).

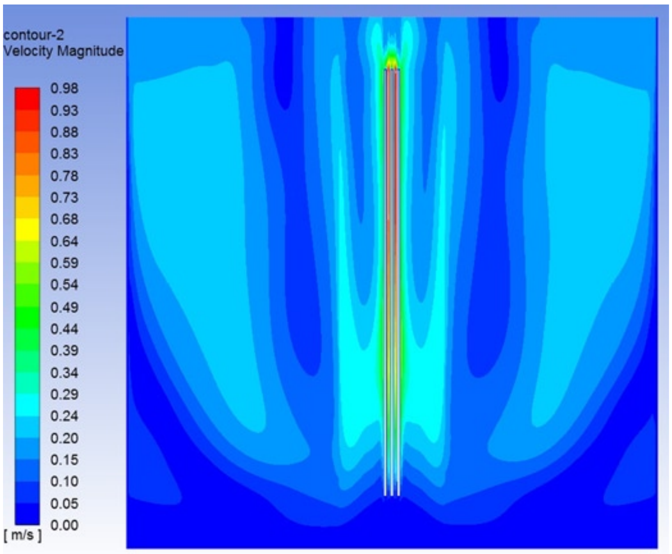
The worst case is for thermal resistivity of the soil equal to 0.5 (K·m)/W. In the case of load current equal to 230 A (ampacity in the ground) temperature of the cables insulation in the air is 117 °C without solar radiation and 131°C with solar radiation, what exceeds the permissible level (70°C) by 67% and by 87% respectively. When solar radiation occurs, PVC insulation of power cables in free air may be overheated (76°C) even if thermal resistivity of the soil is relatively high (e.g. 2.5 (K·m)/W). While the ampacity in the ground is equal to 118 A, the ampacity in the air is equal to the aforementioned only 96 A.

High cables ampacity in the ground (due to the low resistivity of the soil) may lead to strong overheating of power cable line situated in free air (during insolation), and this may lead to noticeable decrease its thermal endurance.

4. Thermal endurance of the power cables insulation

Exceeding the permissible temperature specified for a particular type of a power cable insulation for a long time causes a decrease in its designed endurance, according to the exponential relationship described by the Arrhenius curve [11, 22, 28].

a)



b)

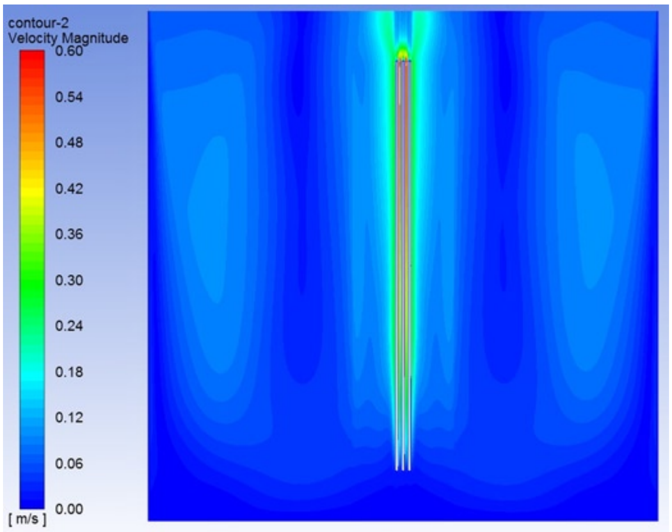


Fig. 8. Air velocity distribution around the analyzed three power cables for the following load current I_{load}: a) I_{load} = 230 A, with sun, max velocity 0.98 m/s, b) I_{load} = 118 A, without sun, max velocity 0.60 m/s

Table 3. Thermal endurance (at given overload and resultant endurance) of the power cables of PVC insulation placed in free air

Cables							
in the ground		in air					
Thermal resistivity of the soil	Ampacity	Solar radiation	Load current giving max temp. 70°C	Ground/air percentage ampacity	Cable overload	Thermal endurance	
						at given overload*	resultant
(K.m)/W	A	-	A	%	%	years	
0.5	230	no	152	151	51	0.24	2.09
		yes	96	240	140	0.00011	0.00061
1.0	176	no	152	116	16	5.3	15.5
		yes	96	183	83	0.02	0.08
1.5	148	no	152	97	0	20	20
		yes	96	154	54	0.19	0.99
2.0	130	no	152	86	0	20	20
		yes	96	135	35	0.96	4.34
2.5	118	no	152	78	0	20	20
		yes	96	123	23	2.86	9.54

** "at given overload" – it is assumed that cables insulation temperature results (all the year) from the ampacity given for the cables buried in the ground*

Usually, the continuous operating temperature of the power cables is selected so that the rated thermal endurance of the insulation is around 20–30 years. In this paper, it is assumed that this endurance is E_{rat} = 20 years (PVC insulation, maximum permissible continuous operating temperature 70°C). For cables with PVC insulation it was estimated that 1 hour of the operation at the 20% overload ($1.2I_{max}$) corresponds to 5 hours of the operation at maximum permissible continuous operating temperature, and 1 hour of the operation at the 45% overload ($1.45I_{max}$) reflects 50 hours of the operation at the aforementioned temperature [22].

Taking the above into account, thermal endurance of the cable insulation for the overloaded cable can be determined by the relationship:

$$E_{ins} = 20.976 \cdot \exp(-0.087 \cdot ol) \qquad (3)$$

where:
E_{ins} – thermal endurance of the cable insulation, years,
ol – power cable overload, %.

Figure 9 presents a variation of the function E_{ins} described in (3) for cable overload within the range (0–45)%. One can see that thermal endurance of the cable insulation decreases five times (from 20 to 4 years) when the cable overload in equal to 20%. When the overload is equal to 45% or more, the thermal endurance is below 1 year.

Aggregated results of the thermal endurance calculation according to (3) are presented in Tab. 3. Consecutive calculations of the endurance named "at given overload" are performed with the assumption that power cables (their insulation) are operating all year with insulation temperature resulting from the load current being equal to the ampacity of cables buried in the ground. For example, thermal resistivity of the soil 0.5 (K·m)/W gives ampacity in the ground 230 A. Such a current gives (in the air of ambient temperature 25°C and presence of solar radiation) an overload equal to 140% (insulation temperature 131°C). In effect, thermal endurance of the power cables operating all the time in this temperature is equal to 0.24 years (around 3 months).

However, it is obvious that ambient temperature varies within the day and within the year seasons. It is important especially for cables placed in the air. In Polish climate conditions, the average sunshine

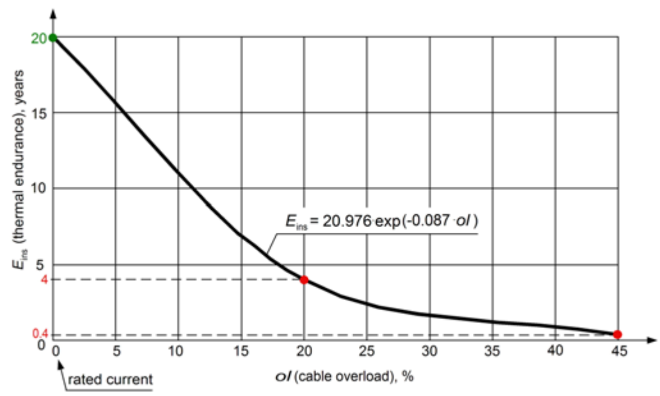


Fig. 9. Variation of the thermal endurance E_{ins} of the PVC insulation as a function of the cable overload

duration is assumed to be 1600 hours a year [21]. During this time, the direct influence of solar radiation is considered. The average number of days per year with a temperature above 25°C (without direct effect of solar radiation) in Polish conditions is 38 [20]. The information provided above was used to calculate the resultant thermal endurance of the power cables insulation (last column in Tab. 3), taking into account variation of ambient conditions within the year. Figure 10 presents graphical comparison of the resultant thermal endurance for all analyzed cases.

Example calculations are provided below for the case when thermal resistivity of the soil for cables buried in the ground is equal to 0.5 (K·m)/W (Tab. 3). It was assumed the insulation degradation proceeds linearly during the time for a constant overload. The resultant thermal endurance $E_{ins\text{-}res}$ is then as follows:

• without solar radiation:

$$E_{ins\text{-}res} = \frac{1}{\frac{t_a}{E_{rat}} + \frac{t_b}{E_{ins\text{-}b}}} = \frac{1}{\frac{\frac{365-38}{365}}{20} + \frac{1-\frac{365-38}{365}}{0.24}} = 2.09 \text{ years} \qquad (4)$$

where:
t_a – period of the year for which there is no overload,
t_b – period of the year for which the overload occurs (1- t_a),
E_{rat} – rated thermal endurance (20 years for insulation temp. 70°C),
E_{ins-b} – thermal endurance (years) at given overload (see Tab. 3),
365 – total days per year,
38 – days per year with temperature above 25°C [20],
0.24 – thermal endurance (years) for cable load 230 A and without solar radiation (see Tab. 3),

• with solar radiation:

$$E_{ins-res} = \frac{1}{\frac{t_a}{E_{rat}} + \frac{t_b}{E_{ins-b}}} = \frac{1}{\frac{\frac{8760-1600}{8760}}{20} + \frac{1-\frac{8760-1600}{8760}}{0.00011}} = 0.00061 \text{ years} \quad (5)$$

where:
8760 – total hours per year,
1600 – hours per year with solar radiation at least 1000 W/m^2 [21],
0.00011 – thermal endurance (years) for cable load 230 A and solar radiation (see Tab. 3).

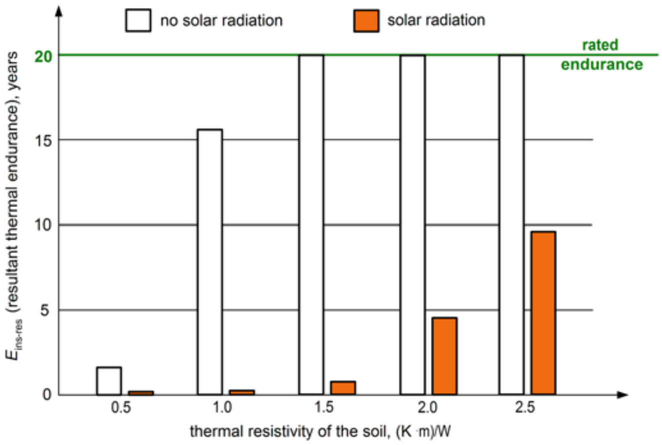


Fig. 10. Resultant thermal endurance of the insulation of power cables partially installed in the air (for detailed values see last column in Tab. 3)

The above-presented examples of calculation reflect the most unfavourable case of the line "ground-air". For this case, power cables are allowed to be loaded relatively high (230 A), due to good parameters of soil for heat dissipation from cables to the ground. Overheating and risk of thermal failure of the section in air occur because this section is allowed to be loaded significantly lower (152 A without solar radiation and 96 A with solar radiation – see Tab. 3). In consequence, resultant thermal endurance of the power cables insulation can be even around 90% lower than the rated thermal endurance (around 2 years instead of 20).

If ampacity of the power cable line located in the arrangement "ground-air" is adopted on the base of the thermal condition in the ground, for the cases with thermal resistivity of the soil equal to 0.5 and 1.0 (K·m)/W decrease in the thermal endurance and thermal failure of the power cables in air may occur even without solar radiation. For cases with thermal resistivity of the soil equal to 1.5, 2.0 and 2.5 (K·m)/W resultant thermal endurance is approx. equal to the rated endurance (20 years), but only when no solar radiation occurs. When solar radiation affects the cables, the endurance decrease is at least 50%. It gives a negative impact on power network maintenance costs as well as the reliability of supply.

During the design process of the power cable lines placed partially in the ground and in air, the ampacity of the cables in the ground should be evaluated taking into account ambient conditions in air, including solar radiation, especially when the ampacity is obtained for the soil of very low thermal resistivity.

5. Conclusions

Power cable lines are usually directly buried in the ground, which gives relatively favourable thermal conditions for heat transfer from the cables to the surrounding environment. However, in practice, these lines are very often supplied from poles of overhead lines and part of the cable line in free air cannot be loaded at the same level as the part in the ground. The real risk of the cables overheating in air occurs, especially in the presence of direct solar radiation. Results of the investigation conducted in this paper have shown that in case of the most unfavourable conditions (low thermal resistivity of the soil and strong solar radiation occur) power cables insulation in air may have temperature almost two times higher than the permissible value (131°C instead of 70°C). Overheating of the insulation leads to a decrease of its thermal endurance, which in real operating conditions may be over 10 times lower than the rated value, assumed during the project stage. All these aspects may lead to worsened reliability of supply and higher cost of the power network maintenance. Thus, in such cases, advanced modelling of the power cables thermal condition in the air is strongly recommended to be applied, in addition to the typical simple calculation according to the commonly used IEC standards.

References

1. Benato R, Paolucci A. EHV AC Undergrounding Electrical Power: Performance and Planning. Springer, 2010, https://doi.org/10.1007/978-1-84882-867-4.
2. Brender D, Lindsey T L. Effect of rooftop exposure in direct sunlight on conduit ambient temperatures. IEEE Transactions on Industry Applications 2008; 44 (6): 1872-1878, https://doi.org/10.1109/TIA.2008.2006301.
3. CYMCAP - software for power cable ampacity rating.
4. Czapp S, Czapp M, Szultka S, Tomaszewski A. Ampacity of power cables exposed to solar radiation - recommendations of standards vs. CFD simulations. 17th International Conference Heat Transfer and Renewable Sources of Energy (HTRSE-2018), Międzyzdroje, Poland, 02-05.09.2018, E3S Web of Conferences 2018; 70 (03004): 1-5, https://doi.org/10.1051/e3sconf/20187003004.
5. Czapp S, Ratkowski F. Effect of soil moisture on current-carrying capacity of low-voltage power cables. Przeglad Elektrotechniczny 2019; 95 (6): 154-159, https://doi.org/10.15199/48.2019.06.29.
6. Czapp S, Ratkowski F, Szultka S, Tomaszewski A. Overheating of underground power cable line due to its partial exposition to solar radiation. 24th International Conference on Methods and Models in Automation and Robotics (MMAR) 2019, Międzyzdroje, Poland, 26-29.08.2019: 396-400, https://doi.org/10.1109/MMAR.2019.8864691.

7. Czapp S, Szultka S, Tomaszewski A. CFD-based evaluation of current-carrying capacity of power cables installed in free air. 18th International Scientific Conference on Electric Power Engineering (EPE) 2017, Kouty nad Desnou, Czech Republic, 17-19.05.2017: 692-697, https://doi.org/10.1109/EPE.2017.7967271.
8. Czapp S, Szultka S, Tomaszewski A, Szultka A. Effect of solar radiation on current-carrying capacity of PVC-insulated power cables - the numerical point of view. Tehnicki Vjesnik 2019; 26 (6): 1821-1826, https://doi.org/10.17559/TV-20181029214825.
9. De Leon F. Calculation of underground cable ampacity. CYME Int. TD 2005: 1-6.
10. De Leon F. Major factors affecting cable ampacity. IEEE Power Engineering Society General Meeting 2006: 1-6, https://doi.org/10.1109/PES.2006.1708875.
11. Gebura A, Kowalska D, Tokarski T. Badania przyśpieszonego starzenia przewodów elektrycznych. Research Works of Air Force Institute of Technology, 2003.
12. HD 60364-5-52: Low-voltage electrical installations - Part 5-52: Selection and erection of electrical equipment - Wiring systems, 2011.
13. Holyk C, Anders G J. Power cable rating calculations-A historical perspective. IEEE Industry Applications Magazine 2015; 21 (4): 6-64, https://doi.org/10.1109/MIAS.2015.2417094.
14. 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, 2006.
15. IEC 60287-2-1: Electric cables - Calculation of the current rating - Part 2-1: Thermal resistance - Calculation of the thermal resistance, 2015.
16. IEC 60287-3-1: Electric cables - Calculation of the current rating - Part 3-1: Sections on operating conditions - Reference operating conditions and selection of cable type, 1999.
17. Kacejko P, Kmak J, Nowak W, Pijarski P, Szpyra W, Tarko R, Wydra M. Dynamic management of transmission capacity in power systems. Zeszyty Naukowe Wydziału Elektrotechniki i Automatyki Politechniki Gdańskiej 2017; 53: 107-110.
18. Klimenta D, Perović B, Klimenta J, Jevtić M, Milovanović M, Krstić I. Modelling the thermal effect of solar radiation on the ampacity of a low voltage underground cable. International Journal of Thermal Sciences 2018; 134: 507-516, https://doi.org/10.1016/j.ijthermalsci.2018.08.012.
19. Kornatka M. Analysis of the exploitation failure rate in Polish MV networks. Eksploatacja i Niezawodnosc - Maintenance and Reliability 2018; 20 (3): 413-419, https://doi.org/10.17531/ein.2018.3.9.
20. Kossowska-Cezak U. Zmiany wieloletnie liczby termicznych dni charakterystycznych w Warszawie (1951 - 2010). Prace Geograficzne 2014; 136: 9-30.
21. Kuczmarski M. Usłonecznienie Polski i jego przydatność dla helioterapii, Dokumentacja Geograficzna 1990; 4.
22. Instalacje elektryczne i teletechniczne. Poradnik montera i inżyniera elektryka (red. J. Strzałka). Rozdział: Zabezpieczenia w instalacjach elektrycznych. VERLAG DASHÖFER, Warszawa 2001-2019, ISBN 978-83-88285-11-0.
23. Notton G, Voyant C, Fouilloy A, Duchaud J L, Nivet M L. Some applications of ANN to solar radiation estimation and forecasting for energy applications. Applied Sciences 2019; 209 (9): 1-20, https://doi.org/10.3390/app9010209.
24. Olejnik B, Łowczowski K. Techniczne metody poprawy współczynników SAIDI oraz SAIFI stosowane w sieci dystrybucyjnej, Computer Applications in Electrical Engineering 2016, Poznan, Poland, 18-19.04.2016.
25. Shabani H, Vahidi B. A probabilistic approach for optimal power cable ampacity computation by considering uncertainty of parameters and economic constraints, International Journal of Electrical Power and Energy Systems 2019; 106: 432-443, https://doi.org/10.1016/j.ijepes.2018.10.030.
26. Spyra F. Wpływ czynników zewnętrznych na obciążalność prądową kabli w elektroenergetycznej linii kablowej. Energetyka 2007; 6-7: 451-454.
27. Yang L, Qiu W, Huang J, Hao Y, Fu M, Hou S, Li L. Comparison of conductor-temperature calculations based on different radial-position-temperature detections for high-voltage power cable. Energies 2018; 11 (1): 1-17, https://doi.org/10.3390/en11010117.
28. Zawodniak J. Ageing processes in insulation of cable line and overhead cover conductor line. Automatyka, Elektryka, Zakłócenia 2018; 31 (1): 34-40, https://doi.org/10.17274/AEZ.2018.31.03.

Stanisław CZAPP
Seweryn SZULTKA
Filip RATKOWSKI
Gdańsk University of Technology
Faculty of Electrical and Control Engineering
Narutowicza 11/12 str., 80-233 Gdańsk, Poland

Adam TOMASZEWSKI
Polish Academy of Sciences
Institute of Fluid Flow Machinery
Fiszera 14 str., 80-231 Gdansk, Poland

E-mails: stanislaw.czapp@pg.edu.pl, seweryn.szultka@pg.edu.pl, filip.ratkowski@pg.edu.pl, atomaszewski@imp.gda.pl