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FEM-Based Thermal Analysis of Underground Power Cables Located in Backfills Made of Different Materials

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Конечноэлементный расчет температурного поля в подземных высоковольтных линиях электропередач с заполнителями из различных материалов

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Выполнен предварительный расчет температурного поля в подземных высоковольтных линиях электропередач, которые планируется использовать в электростанции мощностью 600 МВт. Исследуется система из трех силовых кабелей, размещенных в трубах из полиэтилена низкого давления, с многослойной засыпкой (грунт и термоизолирующие материалы). Рассматриваются различные конфигурации размещения слоев засыпки. Глубина размещения силовых кабелей, измеряемая от реперной точки (0,5 м ниже уровня грунта), варьируется от 2 до 6 м, что оказывает влияние на температурное распределение в грунте, изоляционном и проводящем слоях кабелей. С использованием метода конечных элементов выполнен численный расчет установившихся температурных полей. Для дополнительного учета влияния сформированной так называемой “сухой зоны” на распределение температуры постулируется зависимость теплопроводности грунта от температуры.

Ключевые слова: подземные высоковольтные линии электропередач, метод конечных элементов, теплопроводность, теплоизоляторы жидкостного типа.

Introduction. Since underground power cables operate at the maximum possible conductor current, heat dissipation from the conductor to the surrounding soil plays a crucial role in evaluating the performance of buried cable systems. The current-carrying capacity mostly depends on the conductor temperature: when it is too high, the cable can overheat.

The traditional method (IEC and IEEE Standards [1, 2]) used for calculating of the thermal resistance between the cable system and the external environment assumes that the soil is homogeneous with constant thermal conductivity. In fact, the soil is multilayered and consists of organic matter, sand, clay, gravel and other materials. Heat conduction from the hot cable to the external environment depends on the thermal conductivity of each layer, which, in turn, depends on the porosity, liquid-vapor transport, and temperature [3]. When the porosity is considerable and pores are saturated with water, the thermal conductivity of the soil increases [4, 5]. The thermal conductivity of the soil layers decreases with temperature [6]. Moreover, the shape of the trench, cable location, and configuration of the soil layers influence the temperature distribution in the soil and cable.

In recent years, many numerical and experimental studies have been performed to assess the thermal behavior of underground cable systems [7–13]. The literature survey concludes that different methods are applied, and the associated physics is complex involving the thermal, electrical and humidity migration phenomena. Therefore, the development of alternative methods, which allow cable engineers to determine the maximum temperature of the underground power cables is necessary.

This paper presents the thermal analysis of the transmission line, which will be installed in the Polish power plant that delivers 600 MW of power. We consider the in-line arrangement of the cables buried in the multilayered soil (the native soil and the thermal backfill). The shape of the backfill bedding, presented in this study, differs from those analyzed in the literature. The burial depth of the cables measured from the reference level (0.5 m below the ground) varies from 2 to 6 m.

The numerical simulations performed in this paper consider three different conditions of cable placement:

1). The cables are located in the HDPE casing pipes, filled with sand-bentonite mixture (SBM), and located in the fluidized thermal backfill (FTB) bedding, buried in the native soil.

2). The power cable installation in the HDPE casing pipes (filled with SBM) buried in the native soil.

3). The last, economically less expensive solution considers the cable laying in HDPE casing pipes filled with dry sand. The HDPE casing pipes are buried in the native soil.

Based on the performed thermal analysis, the best cable placement configuration will be selected. The criterion here is the lowest conductor temperature determined using the finite element method (FEM) [14].

1. Solutions for Underground Cable Installation. The power cables in a 3-phase circuit are installed in different formations. Typical formations include trefoil (triangular) and flat (in-line) arrangement (Fig. 1). The choices between these two types of power cable placement depend on several factors like screen bonding method, conductor cross-sectional area and available space for installation.

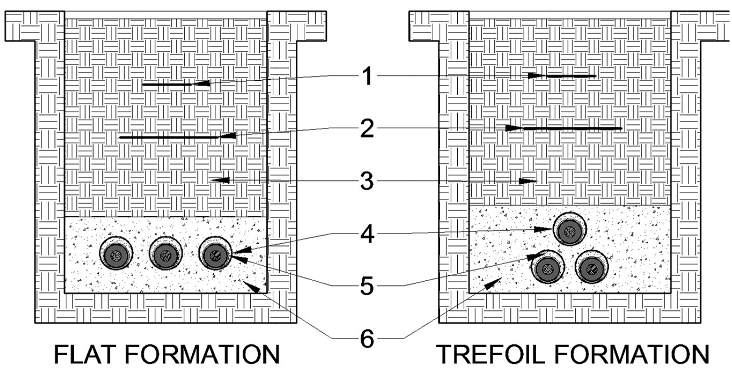


Fig. 1. Installation types for buried cables in ducts: (*1*) warning tape, (*2*) warning grid, (*3*) native soil, (*4*) PVC or PE pipe filled with bentonite (*5*), and (*6*) thermal backfill.

One method of increasing the maximum allowable electrical load is to increase the amount of heat dissipated from the cables. It can be achieved, e.g., by replacing the native soil around the cable with a thermal backfill material, which has a higher thermal conductivity. It is noteworthy that the gain is larger for a dry thermal backfill, e.g., FTB has up to two times higher thermal conductivity than the dry soil. For safety reasons, the backfill material is usually covered with a protective layer consisting of different materials, e.g., concrete that is covered with the native soil [15].

FTB is an engineered slurry backfill mixture which, when solidified, turns into an efficient heat-conducting medium with the following specific thermal and mechanical properties [16]. FTB consists of [17]:

(i) natural mineral aggregates or mixtures of aggregates to make up the bulk of the volume;

(ii) cementitious material to ensure the interparticle bond and strength;

(iii) fluidizer or flow modifier to impart a homogeneous fluid consistency for ease of placement;

(iv) additives to improve the thermal properties.

The cables are placed in trefoil or flat formation inside concrete encased PVC or PE ducts, where the ground is subject to unusually heavy loads and where vibration is considerable (e.g., under level crossings, Fig. 1).

In both cases, PVC or PE casing pipes are filled with SBM, which improves the thermal conditions of the cable line. Its application allows the increase of the current-carrying capacity without exceeding the allowable cable temperature [18]. Furthermore, bentonite, which is commercially available in a powder form, is a swelling montmorillonite clay, and when mixed with water, expands and forms a gel, acting as a lubricant or a fluidizer for the mix [17]. Trefoil formation is used for low loads, and flat structure is applied to particular cases (protected cables: 225 and 400 kV auxiliaries, and road crossings) [19].

2. **Work Procedure**.

2.1. ***Material Properties and Computational Cases***. This study implies the thermal analysis of three 220/400(420) kV, XLPE insulated, single core underground power cables with the flat formation layout. All parameters of the considered power cable are specified by the producer (Table 1).

T a b l e 1

400 kV High Voltage Power Cable Characteristics

Characteristic	Value	Unit
Cross-section area	1600	mm^2
Conductor diameter	49.6	mm
Total thickness of insulation	27	mm
Total diameter	127.9	mm
DC resistance at 20℃	0.0113	Ω/km
AC resistance at 90℃/50 Hz	0.0157	Ω/km
Current loading at 65℃/90℃	1267/1145	A

The material, thermal conductivity, and thickness of the individual cable layers are given in Table 2.

Figure 3 represents the computational conditions of underground power cable placement in the soil as considered during the computations. Three power cables are laying in-line at a depth of 2 to 6 m below the brick road in the trench of 140 cm width. The spacing between the subsequent cables is equal to 40 cm. The power cables are located in the HDPE casing pipes, with an external diameter of 25 cm and 1.4 cm wall thickness, filled with the SBM. Furthermore, the pipes are placed in the FTB layer, which is buried in the native soil.

T a b l e 2

Thermal Properties and Thicknesses of 400 kV Power Cable Layout Materials*

Layer No.	Cable layout	Material	Thickness (mm)	Thermal conductivity W/(m·K)
1	Conductor	Copper	∅49.6	400
2	Inner semi-conductive layer		2.0	0.2875
3	Insulation	XLPE	27.0	0.2875
4	Outer semi-conductive layer		1.5	0.2875
5	Semi-conductive swelling tape as longitudinal water barrier		0.7	0.2875
6	Wire screen	Copper	4.8	400
7	Semi-conductive swelling tape as longitudinal water barrier		0.7	0.2875
8	Aluminum laminated sheath	Aluminum	0.2	0.2875
9	HDPE oversheath	HDPE	5.1	0.2875

* In reference to Fig. 2.

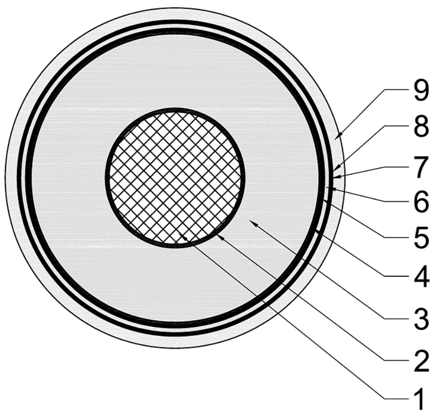


Fig. 2. 400 kV high voltage power cable cross section: (*1*) conductor, (*2*, *4*) semi-conductive layer, (*3*) insulation, (*5*, *7*) semi-conductive swelling tape, (*6*) wire screen, (*8*) aluminum laminated sheath, and (*9*) HDPE oversheath.

In the second considered case of cable placement, the HDPE casing pipes are located in the native soil (Fig. 3b). A comparison between the first and the second types of cable installation predicts further maximum cable temperature drop when replacing the native soil with FTB backfill. The third computational case considers the HDPE casing pipes filled with dry sand (Fig. 3c), but not with the SBM, as in previous cases. Additionally, the pipes are located in native soil as in the second considered case of cable placement. The costs associated with this type of cable location are the lowest, but the cable temperature can increase significantly as compared to other analyzed cases.

IEC standards [1] for Poland region assumes the constant thermal conductivity of a native soil (k_{IEC}) equals 1.0 W/(m·K). In fact, the soil should be considered as a porous material with temperature-dependent thermal properties.

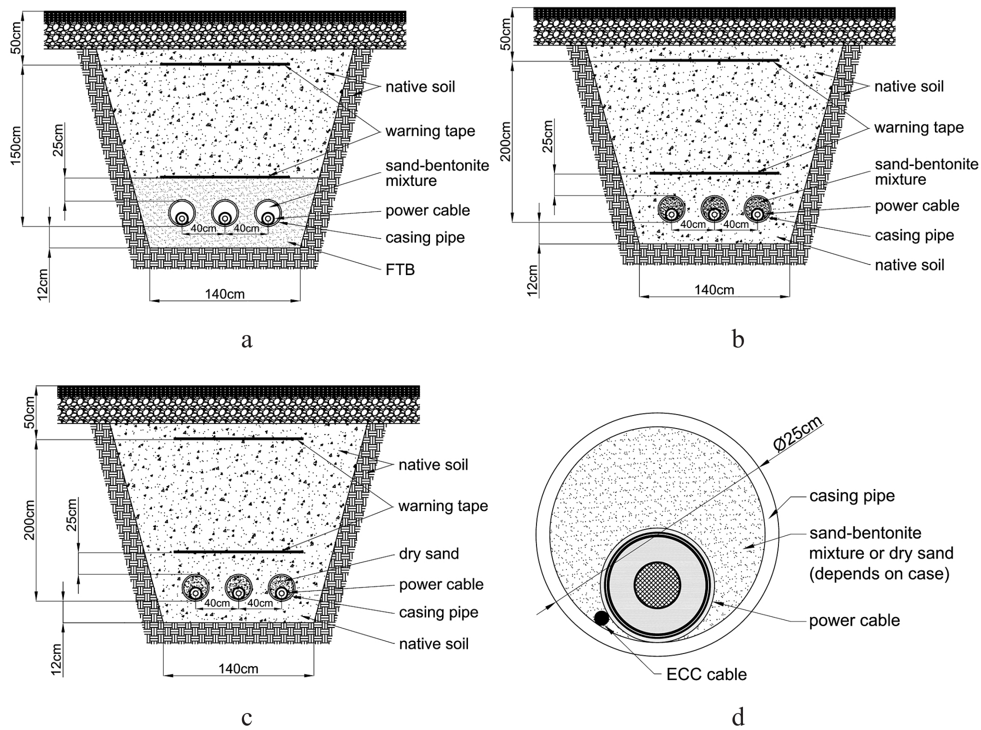


Fig. 3. The power cables laying conditions: (a) case 1; (b) case 2; (c) case 3; (d) cross section of 400 kV power cable in casing tube filled with compacted bentonite.

The water existing in the pores may locally evaporate near the cable when the thermal loading of the conductor is large. The thermal conductivity of the vapor phase is about 20-times lower than of the liquid. Hence, the heat transfer conditions worsen significantly with an increase in vapor phase content in the soil. Kroener et al. [3] presented the extensive numerical approach for thermal performance assessment of underground power cables, including liquid-vapor transport, in the soil. However, due to the vast complexity of the extensive numerical approach, other simplified models can be used. This paper considers the case when the dry zones [6] can form if the temperature of the native soil approaches the maximum allowable cable temperature $T_{\max,p}$, given by the producer. The rapid decrease in soil thermal conductivity $k_{soil}(T)$, while the cable temperature approaches $T_{\max,p}$, can be achieved by utilizing the following relationship:

$$k_{soil}(T) = k_{\min} + (k_{IEC} - k_{\min}) e^{-a_1((T - T_{ref})/(a_2 T_{\max,p}))^2}, \tag{1}$$

where $k_{\min}$ is the thermal conductivity of dry sand (assumed as 0.3 W/(m·K)), $T_{ref} = 30$°C is the temperature at a known depth below ground level (in this paper considered as 0.5 m), and $T_{\max,p} = 90$°C is the maximum allowable temperature of the cable operation, as specified by the producer. The a_1 and a_2 coefficients are defined as

$$a_1 = T_{\max,p} / T_{ref}, \tag{2}$$

$$a_2 = 1 - 1/a_1. \tag{3}$$

For this thermal conductivity model, if $T = T_{ref}$ then $k_{soil}(T) = k_{IEC}$, and if $T > T_{\max, p}$ then $k_{soil}(T)$ approaches $k_{\min}$. Since the proposed formula for thermal conductivity includes only T_{ref} and $T_{\max, p}$ as input parameters, its implementation in the FEM code is straightforward. In general, the temperature values derived via Eq. (1) are larger than those corresponding to $k_{soil}(T) = k_{IEC} = 1\,\text{W/(m}\cdot\text{K)}$. This results in a safety margin, especially when the properties of the soil are not sufficiently recognized and, locally, the mean thermal conductivity of the soil can be significantly lower than $k_{IEC} = 1\,\text{W/(m}\cdot\text{K)}$. This simplified approach in determining the thermal conductivity of the soil also helps to avoid the difficulties associated with the modeling of the humidity transport in the soil and can be directly implemented in the FEM procedures for heat transfer.

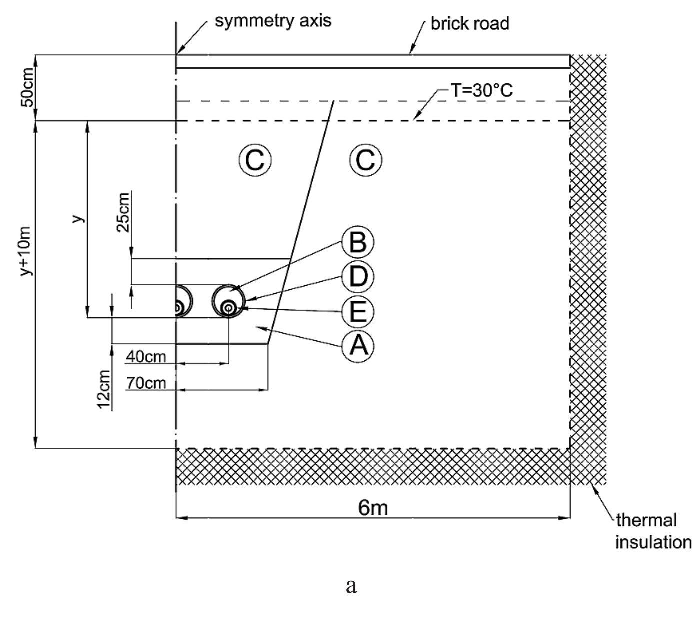
In this studies, homogeneous conditions with thermal conductivities given in Table 3 are considered. Since the most unfavorable conditions of cable operation are simulated, the dry conditions are thus assumed.

T a b l e 3

Thermal Conductivity of Applied Materials

Material	Thermal conductivity W/(m·K)
FTB	1.54 (dry conditions)
SBM	0.95 (dry conditions)
Dry sand	0.30 (dry conditions)
HDPE pipe	0.48

For the first considered type of cable installation underground (Fig. 4a), the cables are arranged at the bottom of the trench and placed in the FTB layer. In this case, the use of SGFC (sand, gravel, fly ash, and cement-mix) is proposed. SGFC is one of the FTB types and consists: 41% of fine aggregate, 49% of coarse aggregate, 2.5% of cement, and 7.5% of fly ash used as fluidizer. This mixture type is characterized by dry density of 2187 kg/m^3 and thermal conductivity of 1.54 W/(m·K) [17] in dry conditions.



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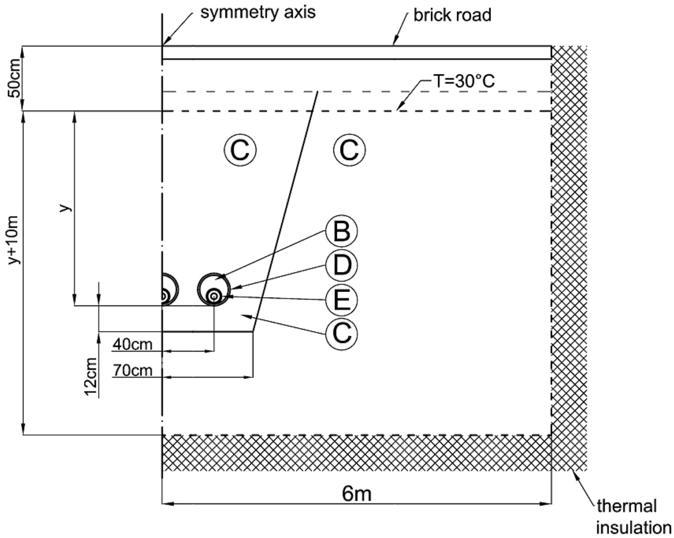

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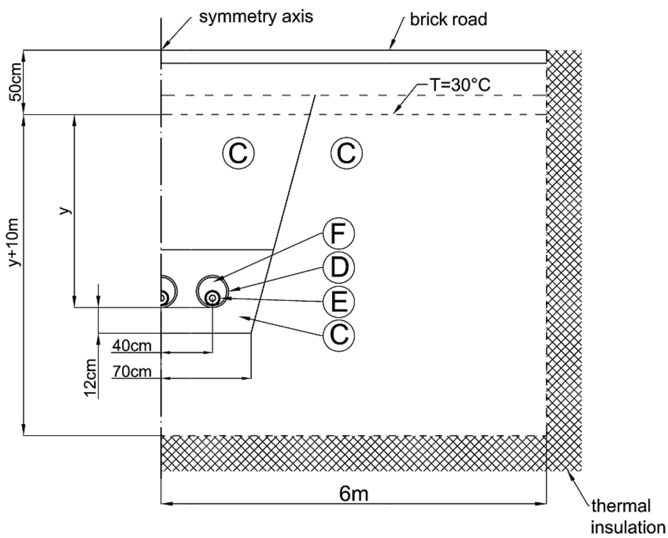

c

Fig. 4. Boundary conditions for presented cases: (a) cables placed in FTB – tubes filled with SBM; (b) cables placed in native soil, tubes filled with SBM; (c) cables placed in native soil, tubes filled with dry sand; *A* – FTB, *B* – SBM, *C* – native soil, *D* – casing tube, *E* – power cable, and *F* – dry sand.

The casing tube is filled with sand-bentonite-based buffer material of 1700 kg/m^3 dry unit weight and thermal conductivity of 0.95 W/(m$\cdot$K) [20]. A mixture proposed in [20] is used in this study, which consists of MX-80 (Na-bentonite) and sand (obtained from crushed granite). It is considered to be composed of 37.5% sand mass fraction and 8.17% water content.

2.2. ***Numerical Determination of Underground Power Cables' Temperature***. The numerical computations are performed to determine the maximum temperature of the conductor for the cable installation types shown in Fig. 3. The computations are carried out using the FEM code developed in MATLAB [21].

The two-dimensional steady-state heat conduction equation:

$$\frac{\partial}{\partial x}\left[k(T)\frac{\partial T}{\partial x}\right]+\frac{\partial}{\partial y}\left[k(T)\frac{\partial T}{\partial y}\right]=-q_v \tag{4}$$

is solved to determine the temperature distribution in the analyzed thermal system. In Eq. (4), T denotes the temperature at any point in the $x-y$ plane around the underground cable, $k(T)$ is the temperature-dependent thermal conductivity, and q_v is the volumetric heat source per unit volume. Its value is calculated using the procedure presented below.

The Joule–Lenz law [22] determines the heat , ΔQ, generated by the power line cable buried in the ground:

$$\Delta Q = I^2 R_{AC}, \qquad \text{W/km}, \tag{5}$$

where I denote an electrical current and R_{AC} is the AC electrical resistance of the wire conductor at the maximum operating temperature. DC resistance of the cable conductor is given by [22]:

$$R_{DC} = R_0[1+\alpha_0(T-20^\circ\,\text{C})], \qquad \Omega\text{/km}, \tag{6}$$

where R_0 (in Ω/km) and α_0 are reference conductor resistance and the temperature coefficient of the conductor material (both given at the reference temperature of 20°C), and T (in °C) is the conductor temperature. For the described computational cases (braided copper conductor), the following values are used: R_0 = 0.0113 Ω/km, α_0 = 0.00393, and $T = T_{\max,p}$ = 90°C. In this case, the DC cable resistance is R_{DC} = 0.0144 Ω/km.

Equation (7) gives the cable AC resistance, where both skin and proximity effects are denoted as ζ_s and ζ_p, respectively [22]:

$$R_{AC} = R_{DC}(1+\zeta_s+\zeta_p). \tag{7}$$

Both proximity and skin effect can increase the cable resistance to R_{AC} = 0.0157 Ω/km.

The generated heat value calculated from Eq. (5) for electrical current $I = 1145$ A and for cable unit length is assessed by the following formula:

$$\Delta Q = I^2 R_{AC} = 1145^2 \cdot 0.0157 \cdot 0.001 = 20.58 \text{ W}.$$

The volumetric heat source q_v per unit volume used in the calculation of the temperature field in the FEM model is defined as

$$q_v = \frac{\Delta Q}{A_c \cdot [1 \text{ m}]} = \frac{20.58}{1600 \cdot 10^{-6}} = 12864 \text{ W/m}^3, \tag{8}$$

where A_c denotes the cross-sectional area of the conductor.

2.3. ***Boundary Conditions***. The appropriate boundary conditions must be specified to solve the steady-state heat conduction equation [Eq. (4)]. The soil temperature at the depth of 0.5 m below the ground level was assumed to be higher by 5°C than in [23] T_g = 30°C.

Symbol y denotes the burial depths which vary from 2 to 6 m. At the right and bottom boundary, and symmetry plane the thermal insulation boundary condition is applied. The right boundary of the computational domain is located at a distance of 6 m from the plane of symmetry (the distance is measured in the normal direction to the symmetry plane). The distance from the ground level to the bottom boundary of the computational

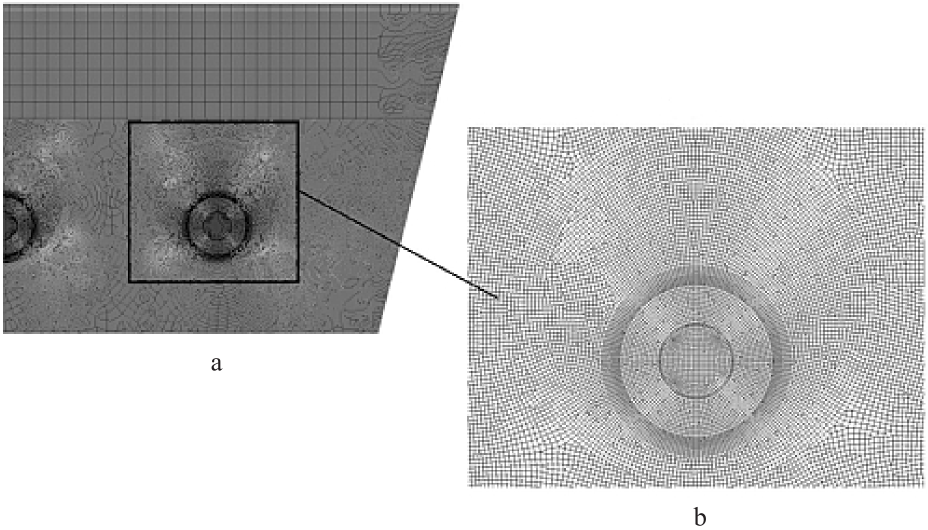

Fig. 5. Numerical grid used in the computation: (a) FTB backfill; (b) cable.

domain is $y+10$ m. Any further increase in this distance will have no influence on the temperature distribution in the analyzed domain. Similarly, increasing the distance from the right boundary to the symmetry plane does not change the obtained temperature distribution.

Figure 5 presents the numerical grid used in the computations. The mesh consists of quadrilateral and triangular finite elements. Since the computational domain is large, only the backfill part is presented, as shown in Fig. 5a with a close-up on the cable location in Fig. 5b.

For the cable burial depth of $y = 2$ m, the discrete model consists of 209,854 nodes and 210,018 elements. The grid independence tests were performed for two times larger number of nodes, and the obtained maximum temperature of the wire conductor does not change by more than 0.001°C. In the case where the FTB backfill is replaced with the native soil (Fig. 4b, c), the numerical grid does not change; only the treatment of the thermal conductivity is different (constant value for FTB backfill, temperature dependent value for native soil).

3. **Results and Discussion**. Figure 6 presents the temperature distributions obtained for cable burial depth of $y = 2$ m. The lowest value of the maximum cable temperature $T_{max} = 77.3$°C is obtained in the case when the cables are installed in HDPE casing pipes filled with SBM and then these pipes are covered with the FTB backfill (Fig. 6a). On the other hand, when filled with dry sand HDPE casing pipes are covered with the native soil. Then, the largest temperature of the conductor $T_{max} = 91.9$°C is obtained (Fig. 6c). It should be noted that the maximum allowable temperature $T_{max,\,p} = 90$°C is exceeded in this case. When the HDPE casing pipes are filled with SBM and then covered by the native soil, the maximum temperature of the cable core is $T_{max} = 86.4$°C.

Figure 7 reveals that with the increase in burial depth of the cable, the maximum temperature of the conductor T_{max} increases significantly. For the cable installation in HDPE pipes filled with a sand-bentonite mixture and buried in FTB layer placed in native soil, the temperature is 77.3°C for the burial depth of 2 m and 143.6°C for the burial depth of 6 m.

The proposed computational approach includes the effect of temperature-dependent thermal conductivity [Eq. (1)] and predicts a larger maximum temperature of the conductor

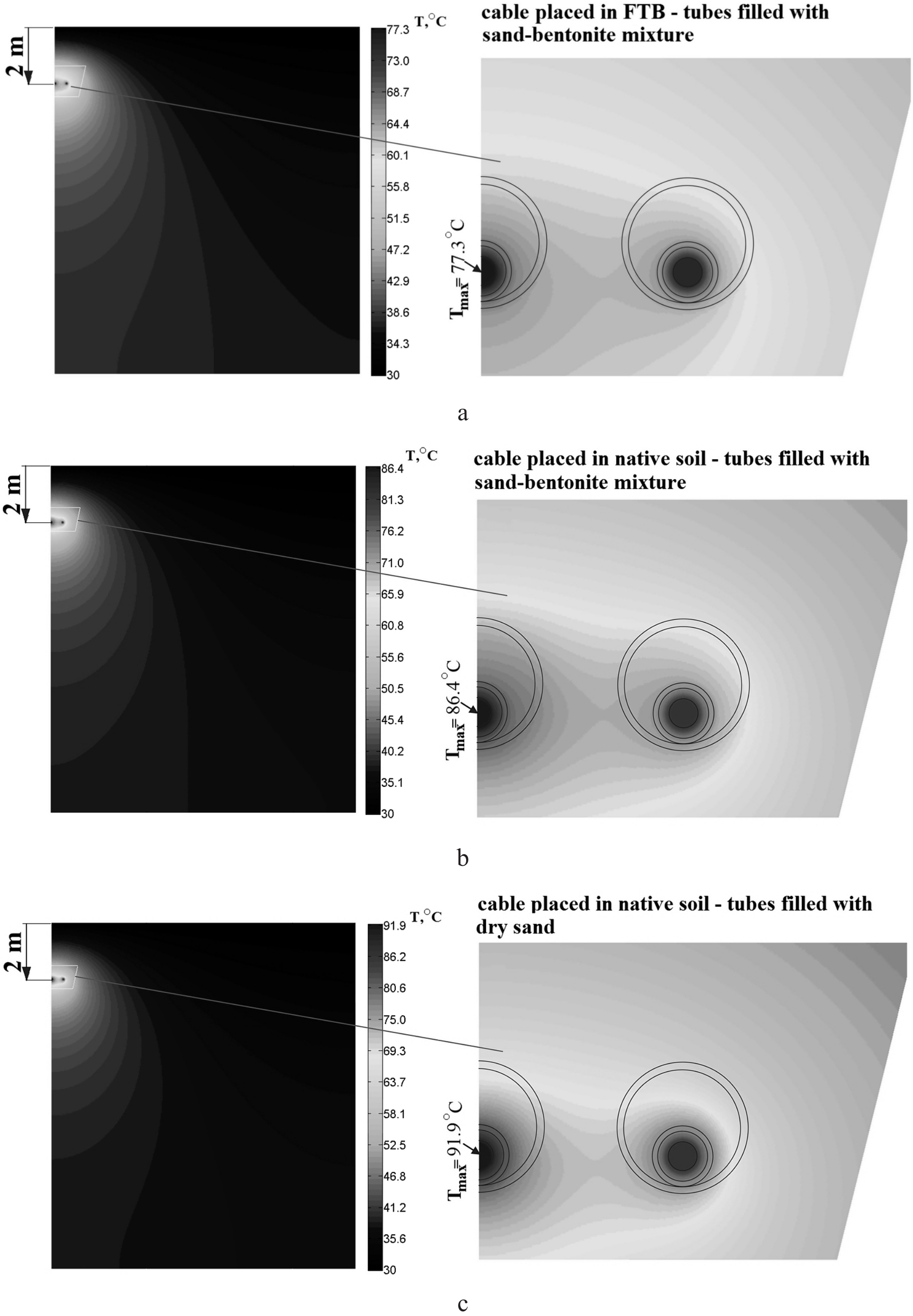

Fig. 6. Temperature distributions obtained for the layout conditions of the power cable shown in Fig. 3 and burial depth of 2 m.

than the standards [1]. The differences in the conductor maximum temperatures $\Delta T = T_{\max,\,pm} - T_{\max,\,IEC}$ were obtained using the proposed method. IEC standards are lower for burial depth of 2 m than for burial depth of 6 m. If the FTB/SBM configuration is

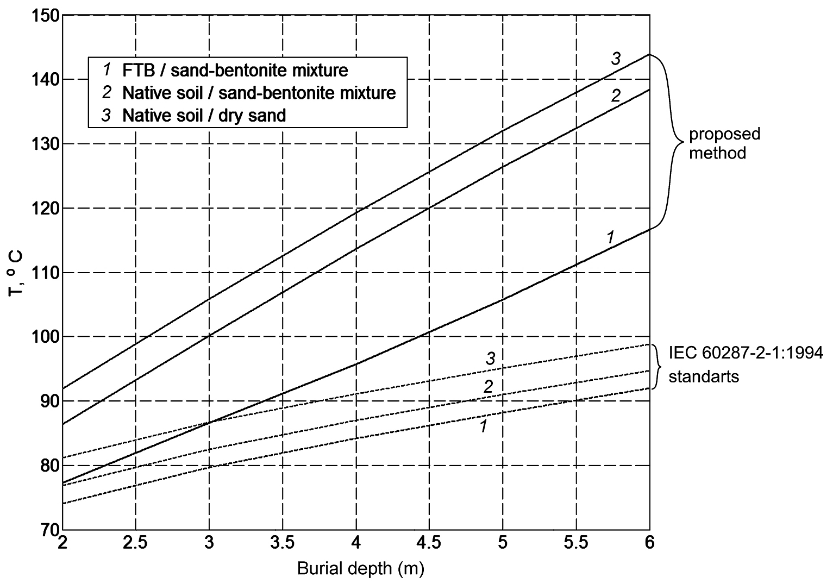

Fig. 7. The calculated maximum temperature of the conductors located at different burial depths for the layout conditions of the power cable shown in Fig. 4, according to the proposed computational approach and standards [2].

applied (Fig. 3a), then, for the burial depth of 2 m: $\Delta T = 2.5$°C and the burial depth of 6 m: $\Delta T = 24$°C. These differences are larger when HDPE pipes are covered only with the native soil than when the FTB layer is used. The maximum relative temperature difference $\Delta T_{rel} = (\Delta T / T_{\max, IEC}) \cdot 100\% = 45\%$ is observed for burial depth of 6 m, in the case when the HDPE casing pipes are filled with dry sand. For the burial depth of 2 m, the ΔT_{rel} does not exceed 12% for the analyzed computational cases.

Conclusions. This paper presents a thermal analysis of underground 400 kV high-voltage power cable system. An in-line arrangement of cables is considered. The burial depths varied from 2 to 6 m. The computations were performed using the FEM code developed in MATLAB. Three different types of cable installation in the soil were studied:

(i) cables located in HDPE casing pipes, filled with the SBM, and buried in FTB layer placed in the native soil;

(ii) cables located in HDPE casing pipes, filled with the SBM, and buried in the native soil;

(iii) cables located in the HDPE casing pipes, filled with the dry sand, and buried in the native soil.

Standards [1] for Poland, which assume a constant thermal conductivity of the soil equal 1.0 W/(m·K), were used at first. Next, an approach that considers the temperature-dependent thermal conductivity was applied. The obtained results were compared. The performed case studies produced the following conclusions:

1. The maximum temperature of the cable conductor increases with the burial depth.

2. When the cables are located in HDPE casing pipes filled with the SBM and these pipes are covered with the FTB layer, the maximum cable temperature is the lowest.

3. The computations that consider the proposed approach of temperature dependent thermal conductivity of the native soil gives similar results to standards [1] (the relative temperature difference up to 12%) when the burial depth is low (e.g., 2 m). Significant differences are obtained (the relative temperature difference up to 45%) when the burial depth is high (e.g., 6 m). The proposed computational approach with temperature-dependent

thermal conductivity predicts larger values of the maximum conductor temperature than the standards [1].

The proposed computational approach, which considers the temperature-dependent soil thermal conductivity, will be validated in future.

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Р е з ю м е

Виконано попередній розрахунок температурного поля в підземних високовольтних лініях електропередач, які планується використовувати в електростанції потужністю 600 МВт. Досліджується система з трьох силових кабелів, що розміщені в трубах із поліетилену низького тиску, з багатошаровою засипкою (ґрунт і термоізольовані матеріали). Розглядаються різні конфігурації розміщення шарів засипки. Глибина розміщення силових кабелів, що вимірюється від реперної точки (0,5 м нижче рівня ґрунту), варіюється від 2 до 6 м, що впливає на температурний розподіл у грунті, ізоляційному і провідному кабелях. Із використанням методу скінченних елементів виконано числовий розрахунок усталених температурних полів. Для додаткового врахування впливу сформованої так званої “сухої зони” на розподіл температури постулюється залежність теплопровідності грунту від температури.

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