

Thermal analysis of electrical cables buried in the ground

Analiza termică a cablurilor electrice îngropate în sol

Sorin DIMITRIU¹, Dragoș PAVEL²

¹National University of Science and Technology „Politehnica” Bucharest, Faculty of Mechanical Engineering and Mecatronics
Splaiul Independenței 313, sector 6, Bucharest, Romania
E-mail: dimitriu47@yahoo.com

²Police Academy „Alexandru Ioan Cuza”, Bucharest, Faculty of Firefighters
Șoseaua Morarilor 3, sector 2, Bucharest, Romania
E-mail: pavel_dragos@yahoo.co.uk

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Abstract. *The paper proposes a calculation model for the temperature of electrical cables buried in the ground, in protective tubes. The heat transfer between the cable and the ground is analysed similarly to the heat propagation mode through cooling fins. The cable insulation and the protective tube are unrolled in the form of flat blades and the temperature distribution in the tube, the temperature of the contact area and the temperature of the electrical conductor are determined. For a given cable, the coincidence of the results with those in the manufacturer's catalogue confirms the validity of the model.*

Key words: *buried cables, heating of electrical conductors, fire risk in buried cables*

Rezumat. *Lucrarea propune un model de calcul pentru temperatura cablurilor electrice îngropate în pământ, în tuburi de protecție. Transferul de căldură dintre cablu și pământ este analizat similar modului de propagare a căldurii prin aripioarele de răcire. Izolația cablului și tubul de protecție sunt derulate sub formă de lamele plate și se stabilește distribuția temperaturii în tub, temperatura zonei de contact și temperatura conductorului electric. Pentru un anumit cablu, coincidența rezultatelor cu cele din catalogul producătorului confirmă validitatea modelului.*

Cuvinte cheie: *cabluri îngropate, încălzire conductori electrice, risc de incendiu la cabluri îngropate*

1. Introduction.

In modern urban infrastructures, the electric power distribution cables suspended on poles have disappeared, the entire distribution network being made by buried cables, both directly in the ground and in cable ducts. Given the constantly increasing energy density and the increasingly limited laying space, fires that can occur in this underground network pose a major technical risk. Unlike fires that start on the surface,

underground fires evolve in a closed environment, with non-existent or very low ventilation, producing an accumulation of heat, gases and pressure that can lead to tragic events. The initiation of such events is determined by excessive heating of the cables, the occurrence of short circuits generated by insulation defects, overload, high thermal resistivity of the soil and unfavourable heat dissipation conditions. The main element that determines the risk of fire and the lifespan in these conditions is the temperature that the electric cable reaches during operation [1], [2].

A number of factors can be distinguished that determine the operating temperature of a buried electrical cable and the temperature field that forms around it.

Thermal overload, generated by exceeding the current value above the nominal capacity of the cable (ampacity), is a first critical mechanism. Heat generation, produced by the dissipation of electrical energy in the cable through the Joule-Lenz effect, is proportional to the square of the operating current, which means that a relatively small increase in its current produces a significant increase in the temperature of the conductor. The insulation of modern electrical cables buried in the ground is mainly made of polymeric materials, chosen for their resistance to humidity, temperature, chemicals and mechanical stress. Exceeding the maximum permissible temperature accelerates the degradation of the polymeric insulation, reducing its dielectric strength and increasing the probability of an electric arc [3].

The thermal resistivity of the soil, which can vary depending on humidity, composition and compaction, can amplify the thermal degradation process of the insulation. Dry or sandy soils have a low thermal conductivity, which reduces their ability to absorb the heat generated by the cable [4].

Insulation failure is another important factor, which can occur through thermal aging, mechanical damage or water infiltration. Aged and weakened insulation can lead to the appearance of an electric arc, a phenomenon characterized by local temperatures of over 3000°C, sufficient condition to ignite combustible materials around the cable. In underground spaces, where cables are often grouped and placed next to each other, an electric arc can trigger a chain fire, simultaneously affecting several circuits. According to analyses carried out by IEEE and CIGRÉ, electric arcs are one of the main causes of fires in underground distribution networks [5].

Insufficient ventilation is another critical element. Cables laid in cable ducts, galleries or ducts are in a closed environment, where air cannot efficiently evacuate heat. In this way, the ambient temperature gradually increases, reducing the temperature difference required for heat transfer and leading to a dangerous accumulation of heat in the mass of the cable and insulation. In addition, insulating materials such as PVC, XLPE or synthetic rubber are combustible and, once ignited, can sustain combustion and produce dense smoke and toxic gases, including hydrogen chloride (HCl) which in humid conditions forms hydrochloric acid, carbon monoxide (CO) and aromatic hydrocarbons [6].

Accumulation of flammable gases in underground spaces. Pyrolysis of the plastic materials from which cable insulation is made produces combustible gases which, in the absence of ventilation, can form explosive mixtures. In such conditions, a spark or an

electric arc can trigger a deflagration. Numerous technical reports on fires in underground urban networks show that explosions in electrical conduits are frequently associated with the accumulation of gases resulting from the thermal degradation of cables [7]. In addition, due to the thermal regime determined by the accumulation of heat, polyethylene (PE) natural gas distribution pipes laid in proximity can also be affected, a situation in which their accumulation through infiltration can lead to disasters.

The prevention of underground fires caused by buried electrical cables requires an integrated approach, including both design measures and appropriate operation and maintenance. In the design phase, it is essential to correctly dimension the cables according to the IEC 60287 and IEC 60853 standards, which provide calculation methods for the allowable current depending on the thermal conditions of the soil. The use of filling materials with high thermal conductivity (thermal backfill) can significantly reduce the cable temperature, as shown in studies in the specialized literature [8]. Also, avoiding excessive grouping of cables, protecting them and ensuring routes with adequate thermal dissipation are fundamental measures. In operation, monitoring the temperature of cables through distributed sensors (DTS – Distributed Temperature Sensing) allows early detection of areas with high thermal risk. As maintenance, periodic inspections, including thermal imaging at the cable ends and checking connections, can prevent contact defects that generate hot spots. In addition, the use of cables with flame retardant insulation and LSZH (Low Smoke Zero Halogen) sheaths reduces the risk of fire propagation and smoke toxicity.

Underground fires due to heating of electrical cables are the result of a complex combination of thermal, electrical and infrastructure factors. They can be prevented by rigorous design, responsible operation and continuous maintenance. In the context of increasing energy demand and densification of urban networks, understanding the heating mechanisms of underground cables and associated risks, becomes essential for the protection of critical infrastructures and public safety. Consequently, the problem of studying the development of the phenomenon of heating of underground electrical cables, the accumulation of heat and its propagation in the environment surrounding buried cables, constitutes a topic of study that is not only interesting, but also very useful in preventing events with particularly serious consequences, both for the infrastructure and for its users [9, 10, 11, 12].

This paper proposes a calculation method by which the temperature of an electrical cable laid inside a protective tube buried in the ground can be determined, depending on the operating conditions.

2. Mathematic model.

The mathematical model assumes that the heat transfer in the cable insulation and in the wall of the protective tube is similar to the heat transfer through the rectangular cooling fins. For the construction of this model, it was considered that half of the circumference of the insulation and the protective tube, respectively, is deployed in the

form of rectangular cooling fins that receive heat from the conductor material and release it to the ground.

2.1. Physical model.

The physical model is presented in Figure 1. The electric cable having the section corresponding to the diameter d and the insulation thickness δ_{is} is considered to be inserted inside a protective tube with diameter D and wall thickness δ_t . The cable insulation and the wall of the protective tube are in direct contact over a length of the circumference corresponding to the contact angle θ . The tube is considered to be buried in the soil having a constant temperature t_s . The geometry of the system is considered to be symmetrical with respect to the vertical diameter $A-A$. During operation the cable heats up due to dissipation by the Joule-Lenz effect, generating a heat flux:

$$\dot{Q} = RI^2 \text{ [W/m]} \quad (1)$$

where R [Ω/m] is the specific resistance of the cable, and I [A] is the electric current flowing through the cable. The air in the space between the cable and the protective tube, having a very low thermal conductivity coefficient and being at the same time an unventilated environment, behaves as a thermal insulator, so that the heat transfer between the cable and the protective tube is carried out only through the contact spot whose width is determined by the contact angle θ [rad]. The heat then propagates by conduction through the wall of the protective tube to the soil with which it is in direct contact on its outer surface.

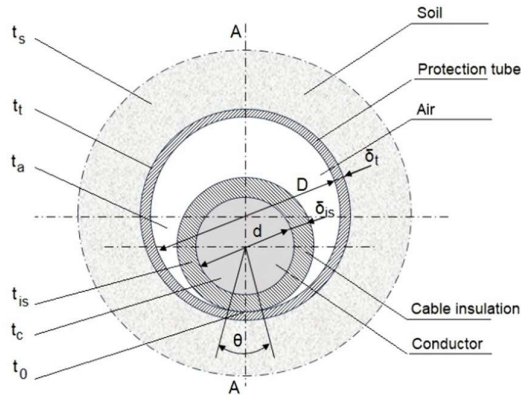


Fig. 1. Physical model

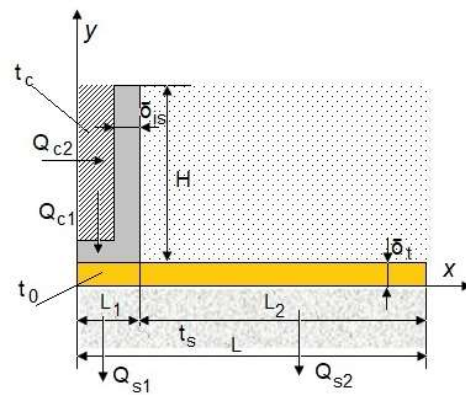


Fig. 2. The calculation model

To build the mathematical model, considering the symmetry with respect to the $A-A$ axis, only half of the system formed by the protective tube and the cable inside it was considered. The wall of the tube, corresponding to the length L of the semicircle $A-A$ was deployed horizontally (x -axis), and the arc of a circle with the length H , corresponding to the cable insulation starting from the contact spot boundary, was deployed vertically (y -axis). The direct contact was considered on the length L_1 , corresponding to the contact semi angle $\theta/2$. In this way, the system shown in Figure 2

was obtained, equivalent in terms of heat transfer to the real one and whose dimensions are:

$$L = \frac{\pi}{2} D; L_1 = \frac{\theta}{4} (d + 2\delta_{is}); L_2 = L - L_1; H = \frac{\pi}{2} (d + 2\delta_{is}) - L_1 \quad (1)$$

The heat flux produced in the electrical conductor is transmitted to the direct contact area, in the form of flux $\dot{Q}_{c1}$ and by conduction in the insulation in the form of flux $\dot{Q}_{c2}$. To the ground, the heat is transmitted in the area of the direct contact spot, in the form of flux $\dot{Q}_{s1}$ and by conduction along the wall of the protective tube in the form of flux $\dot{Q}_{s2}$, the energy balance having the form:

$$\dot{Q} = RI^2 = 2 (\dot{Q}_{c1} + \dot{Q}_{c2}) = 2 (\dot{Q}_{s1} + \dot{Q}_{s2}) \quad [\text{W/m}] \quad (3)$$

2.2. Heat transfer through the tube wall.

The heat exchange with the ground is carried out only on the outer surface of the tube, along the length L_2 , the other surface in contact with the air inside being considered thermally insulated. It is considered that from the contact spot area having temperature t_0 , the heat is transmitted by conduction through the tube wall and from there to the ground having temperature t_s , through a layer having thickness $\delta_s = D/2$. For an elementary section of thickness dx and width of 1m, in which the temperature is t (Figure 3), the energy balance has the expression:

$$\dot{Q}_s = \dot{Q}_{x+dx} - \dot{Q}_x \quad (4)$$

where:

$$\dot{Q}_x = -\lambda_t \frac{dt}{dx} \delta_t; \dot{Q}_{x+dx} = \dot{Q}_x + \lambda_t \frac{d^2t}{dx^2} \delta_t dx; \dot{Q}_s = k_s (t - t_s) dx \quad (5)$$

λ_t [W/mK] being the thermal conductivity coefficient of the protective tube material, and k_s the heat transfer coefficient in the soil:

$$k_s = \frac{1}{R_{ts}} = \frac{\lambda_s}{\delta_s} \quad [\text{W/m}^2\text{K}] \quad (6)$$

In relation (6) λ_s [W/mK] is the thermal conductivity coefficient of the soil, and δ_s [m] is the thickness of the layer through which heat propagates in the soil to the area with temperature t_s .

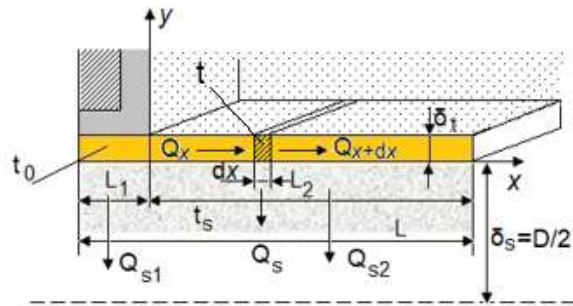


Fig. 3. Heat transfer model between the protection tube and the ground.

From relations (4) and (5) we obtain the differential equation:

$$\frac{d^2 \theta_t}{dx_2^2} = m_t^2 \theta_t; m_t = \sqrt{\frac{k_s}{\lambda_t \delta_t}}; \theta_t = t - t_s \quad (7)$$

The solution to equation (7) has the form:

$$\theta_t(x) = C_1 e^{m_t x} + C_2 e^{-m_t x} \quad (8)$$

with boundary conditions:

$$x = 0 \rightarrow \theta_t = \theta_{t0} = t_0 - t_s; x = L_2 \rightarrow \frac{dt}{dx} = 0 \text{ (zero heat flux)} \quad (9)$$

The expression for the temperature field in the tube wall results in the form:

$$t(x) = t_s + (t_0 - t_s) \frac{\cosh m_t (L_2 - x)}{\cosh m_t L_2} \text{ [}^\circ\text{C]} \quad (10)$$

To determine the temperature in the contact spot area, it is considered that the unfolded tube portion behaves like a flat fin. As a result, the heat flux given off to the ground through the portion of length L_2 has the expression:

$$\dot{Q}_{s2} = k_s \eta_t L_2 (t_0 - t_s) \text{ [W/m]} \quad (11)$$

where η_t is the efficiency of the fin equivalent to the arc of the tube wall:

$$\eta_t = \frac{\tanh m_t L_2}{m_t L_2} \quad (12)$$

The heat flux transmitted to the ground by the contact area with temperature t_0 has the expression:

$$\dot{Q}_{s1} = k_s L_1 (t_0 - t_s) \text{ [W/m]} \quad (13)$$

and as a result, the total heat flux given off to the ground on the perimeter of the protective tube can be written:

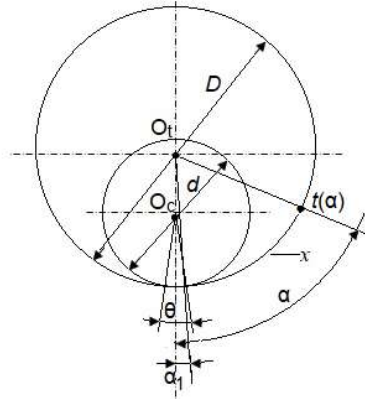


Fig.4. Positioning the point with temperature $t(\alpha)$ on the tube circumference.

$$\dot{Q}_s = 2(\dot{Q}_{s1} + \dot{Q}_{s2}) = 2k_s(L_1 + \eta_t L_2)(t_0 - t_s) = RI^2 \quad [W/m] \quad (14)$$

where the temperature of the contact area results from:

$$t_0 = t_s + \frac{RI^2}{2k_s(L_1 + \eta_t L_2)} \quad [^\circ\text{C}] \quad (15)$$

The temperature at any point on the circumference of the protective tube, given by relation (11), can be expressed as a function of the angle α [rad] at the centre O_t of the tube (Figure 4):

$$t(\alpha) = t_0 \quad [^\circ\text{C}] \quad \left(\alpha \leq \theta \frac{d}{2D} \right)$$

$$t(\alpha) = t_s + (t_0 - t_s) \frac{\cosh m_t \frac{D}{2} (\pi - \alpha)}{\cosh m_t L_2} \quad [^\circ\text{C}] \quad \left(\alpha > \theta \frac{d}{2D} \right) \quad (16)$$

2.3. Heat transfer in cable insulation.

The heat exchange between the conductor and the insulation is carried out on the inner face, along the length H , the other face in contact with the air inside being considered thermally insulated. It is considered that the heat transfer takes place through the insulation, up to the contact surface area, having the temperature t_0 from where it continues to the wall of the protective tube and then into the ground. For an elementary section of thickness dy and width of 1m, in which the temperature is t (Figure 5), the energy balance has the expression:

$$\dot{Q}_c = \dot{Q}_{y+dy} - \dot{Q}_y \quad (17)$$

where:

$$\dot{Q}_y = -\lambda_{is} \frac{dt}{dy} \delta_{is}; \quad \dot{Q}_{y+dy} = \dot{Q}_y - \lambda_{is} \frac{d^2 t}{dy^2} \delta_{is} dy; \quad \dot{Q}_c = k_c(t_c - t)dy \quad (18)$$

λ_{is} [W/mK] being the thermal conductivity coefficient of the insulation material, and k_c the thermal transfer coefficient in the conductor:

$$k_c = \frac{I}{R_{tc}} = \frac{2\lambda_c}{d} \quad [W/m^2K] \quad (19)$$

In relation (19) λ_c [W/mK] is the thermal conductivity coefficient of the conductor material, and d [m] is the diameter of the conductor cross-section.

From relations (17) and (18) the differential equation is obtained:

$$\frac{d^2 \theta_c}{dy^2} = m_c^2 \theta_c; \quad m_c = \sqrt{\frac{k_c}{\lambda_{is} \delta_{is}}}; \quad \theta_c = t_c - t \quad (20)$$

The solution to equation (20) has the form:

$$\theta_c(y) = C_1 e^{m_c y} + C_2 e^{-m_c y} \quad (21)$$

with the boundary conditions:

$$y=0 \rightarrow \theta_c = \theta_{c0} = t_c - t_0; \quad x=H \rightarrow \frac{dt}{dy} = 0 \text{ (zero heat flux)} \quad (22)$$

The expression of the temperature field in the tube wall results in the form:

$$t(y) = t_c + (t_c - t_0) \frac{\cosh m_c(H - y)}{\cosh m_c H} \text{ [}^\circ\text{C]} \quad (23)$$

To determine the temperature in the conductor, it is considered that the unfolded insulation portion behaves like a flat fin. As a result, the heat flux transferred by the conductor through the portion of length H has the expression:

$$\dot{Q}_{s2} = k_c \eta_c H (t_c - t_0) \text{ [W/m]} \quad (24)$$

where η_c is the efficiency of the fin equivalent to the arc of the insulation:

$$\eta_c = \frac{\tanh m_c H}{m_c H} \quad (25)$$

The heat flux transmitted to the protection tube through the contact area with temperature t_0 has the expression:

$$\dot{Q}_{cl} = k_c L_1 (t_c - t_0) \text{ [W/m]} \quad (26)$$

and as a result, the total heat flux given off by the conductor through the insulation on its perimeter can be written in the form:

$$\dot{Q}_c = 2(\dot{Q}_{cl} + \dot{Q}_{c2}) = 2k_c(L_1 + \eta_c L_H)(t_c - t_0) = RI^2 \text{ [W/m]} \quad (27)$$

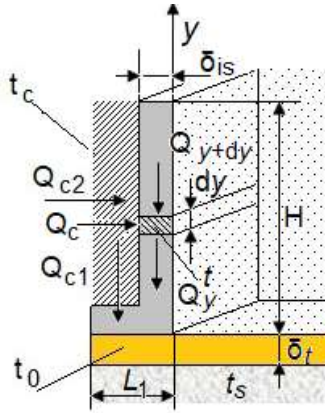


Fig.5. Heat transfer model between conductor and insulation.

where does the conductor temperature come from:

$$t_c = t_0 + \frac{RI^2}{2k_c(L_1 + \eta_c H)} \text{ [}^\circ\text{C]} \quad (28)$$

Relations (15) and (28) can be combined in the form:

$$t_c = t_s + \frac{RI^2}{2} \left[\frac{1}{k_s(L_l + \eta_l L_2)} + \frac{1}{k_c(L_l + \eta_c H)} \right] \text{ [}^\circ\text{C]} \quad (29)$$

from which the expression for the thermal resistance between the conductor and the ground results:

$$R_{tcs} = \frac{1}{2} \left[\frac{1}{k_s(L_l + \eta_l L_2)} + \frac{1}{k_c(L_l + \eta_c H)} \right] \text{ [mK/W]} \quad (30)$$

3. Results and discussions

For testing the model, a medium voltage cable with cross-linked polyethylene (XLPE) insulation and PVC sheath was considered, for the nominal voltage of 12/20 kV, type NA2XSY, from the production of IPROEB Bistrița [13]. The cable is intended for the distribution of electrical energy in fixed installations, indoors, outdoors and buried. The cable consists of a compacted aluminium multi-wire conductor, insulated with XLPE, with a copper wire and tape screen and an outer PVC sheath. The cable structure is shown in Figure 6.

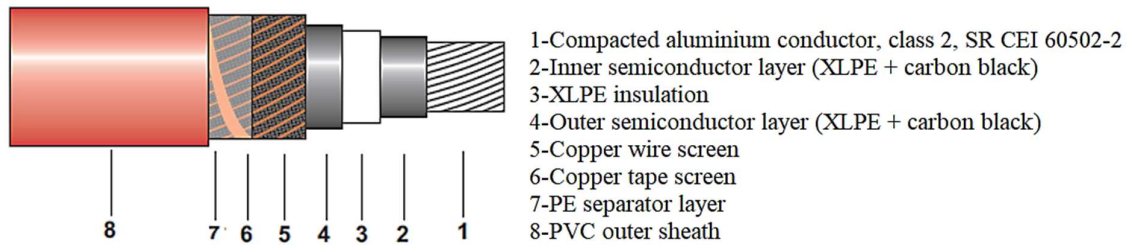


Fig. 6. The structural elements of the MT NA2XSY 12/20kV cable [13].

The cable is manufactured in nine sizes, differentiated by the cross-sectional area of the multi-wire aluminium conductor. Table 1 presents the construction dimensions for the nine cable sizes.

Table 1

Dimensions of MV NA2XSY 12/20 kV cables [13].

Conduct. / Screen section [mm ²]	Conduct. outer diameter [mm]	Semicond. inn. layer thickness [mm]	XLPE insulation thickness [mm]	Semicond. out. layer thickness [mm]	Copper screen thickness [mm]	Separator layer thickness [mm]	Outer sheath thickness [mm]	Cable outer diameter [mm]	Specific electrical resistance [Ω/km]
1x35/16	6,86	0,5	5,5	0,5	0,25	1,5	2,5	28,37	0,806
1x50/16	8,20	0,5	5,5	0,5	0,24	1,5	2,5	29,67	0,564
1x70/16	9,70	0,5	5,5	0,5	0,22	1,5	2,5	31,14	0,403
1x95/16	11,30	0,5	5,5	0,5	0,21	1,5	2,5	32,72	0,297
1x120/16	12,70	0,5	5,5	0,5	0,20	1,5	2,5	34,09	0,235
1x150/16	14,20	0,5	5,5	0,5	0,19	1,5	2,5	35,68	0,188
1x150/25	14,20	0,5	5,5	0,5	0,29	1,5	2,5	35,78	0,188
1x185/25	15,77	0,5	5,5	0,5	0,27	1,5	2,5	37,32	0,152
1x240/25	17,96	0,5	5,5	0,5	0,25	1,5	2,5	39,47	0,118
1x300/25	20,08	0,5	5,5	0,5	0,24	1,5	2,5	41,56	0,094

In order to apply the mathematical model, the cable insulation was considered homogeneous, having the real thickness and an equivalent thermal conductivity coefficient, according to the structure and materials of the n layers that make up the insulation (Table 2):

$$\lambda_{ec} = \frac{\ln \frac{d_{n+1}}{d_1}}{\sum_{i=1}^n \left(\frac{1}{\lambda_i} \ln \frac{d_{i+1}}{d_i} \right)} \quad [\text{W/mK}] \quad (31)$$

Table 2

Thermal characteristics of cables.

Cable Type	1x35/16	1x50/16	1x70/16	1x95/16	1x120/16	1x150/25	1x185/25	1x240/25	1x300/25
R_t [mK/W]	0,714	0,654	0,599	0,551	0,516	0,481	0,451	0,416	0,387
λ_{ec} [W/mK]	0,316	0,313	0,310	0,307	0,305	0,306	0,304	0,301	0,299
δ_{is} [mm]	10,75	10,74	10,72	10,71	10,70	10,79	10,77	10,75	10,74

Since the space between the conductor and the protective tube is not ventilated, the air in this space behaves as a thermal insulator and as a result the heat transfer between the conductor and the protective tube is carried out only on the direct contact area. Due to the low conductivity coefficient of the protective tube material ($\lambda_{PVC} = 0.17 \text{ W/mK}$), the heat transfer to the ground through the protective tube wall is noticeable only on an arc of a circle of $20^\circ \dots 30^\circ$ on both sides, around the contact area. Figure 7 shows the temperature distribution in the protective tube wall, according to relations (16), (17) and (18), for the cable with a cross section of 150 mm^2 for different values of the working current.

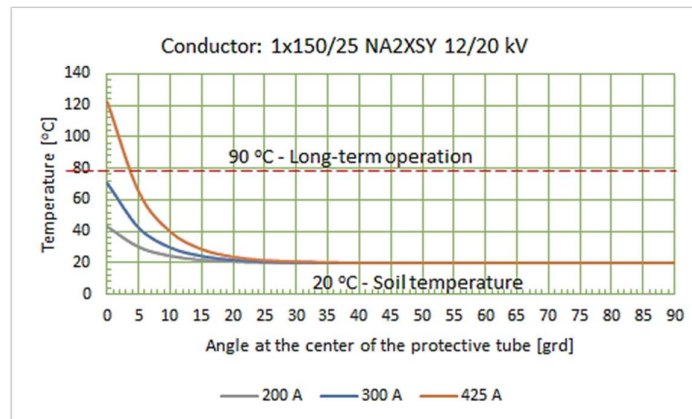


Fig. 7. Temperature variation in the wall of the PVC protective tube

According to the manufacturer's catalogue data [13], the maximum current for this cable, in long-term operation, is about 350 A, a value at which the cable reaches the maximum operating temperature of 90°C , up to which insulation damage does not occur. It can be seen that the dangerous zone where insulation damage and its penetration can occur is in the contact zone. As long as the current is below the limit

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value, the temperature in this zone does not affect the insulation, exceeding it leading to the local formation of a high-temperature zone that can melt the insulation.

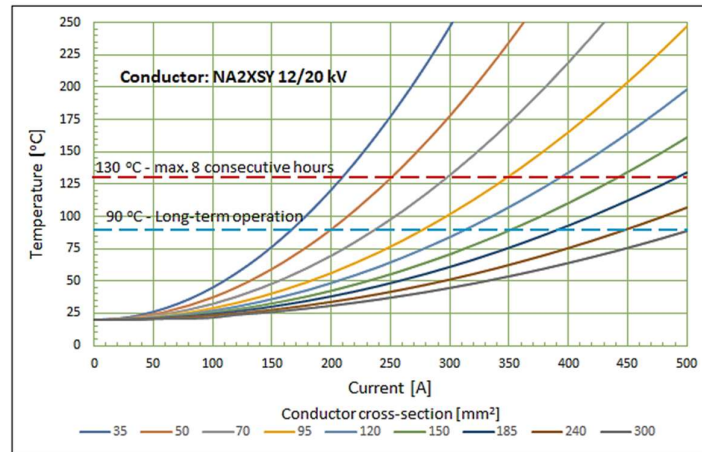


Fig. 8. Temperature variation depending on current and cross section.

The maximum current at which the limit temperature is reached in the conductor at which insulation damage begins depends on the conductor cross-section. Figure 8 shows the variation of the conductor temperature in relation to the value of the operating current, for the series of nine values of the cross-section of the MV conductor, NA2XSY 12/20kV calculated according to the model developed in the work.

The manufacturer guarantees safe operation at higher temperatures, up to 130 °C, provided that they are not exceeded for more than 8 consecutive hours and not more than 125 hours per year [13]. Figure 9 shows the maximum permissible current values for continuous load operation at a temperature of 90 °C for different installation situations for the NA2XSY 12/20 kV cable, according to the manufacturer's catalogue.

The calculation results are compared with these data.

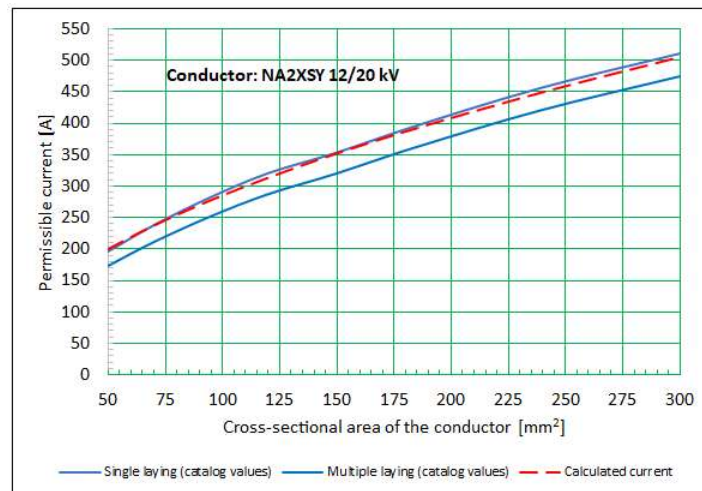


Fig.9. The allowable current at the temperature of 90°C.

4. Conclusions.

The work aims to develop a mathematical method that allows determining the temperature of an electrical cable buried in the ground, inserted inside a protective tube, depending on the value of the working current.

It was intended to highlight the way in which heat transfer occurs, determine the conductor temperature and the temperature distribution in the wall of the protective tube in contact with the ground.

Starting from the analogy with heat transfer through extended surfaces (flat fins), easy-to-use calculation relationships were obtained, which take into account the properties and dimensions of the conductor, insulation, protective tube and ground.

The model was used to study a medium voltage (MV) cable, with a single multi-wire aluminium conductor, type NA2XSY 12/20 kV, from the current production of the Romanian company IPROEB – Bistrița. The coincidence of the results with the manufacturer's specifications shows that the model is correct and can be used for the study of the thermal regime of conductors buried in the ground.

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