UDC 621.319 **doi: 10.20998/2074-272X.2019.3.07**

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TECHNOLOGICAL PARAMETERS OF THE COOLING MODE OF POLYMER INSULATION OF POWER CABLES

Introduction. ***The cooling mode of polymer insulation after application to the extruder is one of the main factors determining cable performance. Theoretically, it is ideal to cool the insulation when the temperature of the cooling medium is equal to the melting point of the insulation material: in this case, the probability of formation of voids in the insulation is less. The cooling process is usually not subject to stringent requirements, since most insulating materials allow for quite sharp cooling. The exception is polyethylene, which requires gradual cooling. When the insulation is cooled in a cooling bath, the temperature decrease starts from the surface. In this regard, the cooling of the insulation of polyethylene is carried out in steps to a temperature at which the cooled extruded insulation will not be deformed or damaged on the receiving drum. Polyethylene is characterized by a large value of thermal expansion coefficient, the maximum value of which is in the temperature range (90-125) °C. As a result, there is an uneven reduction in the volume of the upper and inner insulation layers, especially for cables with a considerable insulation thickness. The rapid cooling of polyethylene leads to the formation of cracks, air inclusions both between the insulation and the conductive core, and in the layers located near the core. Purpose. The substantiation of the technological parameters of the cooling mode of power cables based on the calculation of the thermal equivalent circuit of a conductive core insulated with polyethylene in transient thermal mode. Methodology. The calculation of the temperature distribution in the thickness of extruded polyethylene insulation at different points in time, depending on the temperature of the cooling water, is made by the method of electrothermal analogies. There is a transition from the thermal equivalent circuit of power cables to the equivalent circuit of the discrete resistive equivalent circuit method, which is calculated using the nodal potential method. As a result of solving a three-diagonal system of linear algebraic equations by sweeping and finding at each discretization step (time step) thermal power fluxes in the branches of the thermal equivalent circuit, the temperature in the thermal capacitances determines the temperature in each insulation layer. Practical value. The duration of the transition process, corresponding to the achievement of the same temperature throughout the thickness of the insulation, can be considered as a criterion in determining the length of the cooling bath sections depending on the extrusion (reception) rate.*** References 12, figures 6.

Key words: **cooling mode, polyethylene insulation, thermal equivalent circuit, discrete resistive equivalent circuit method, transient mode, nodal potentials method, system of linear algebraic equations, cooling bath length.**

Обґрунтовано методику розрахунку режиму охолодження силових кабелів в перехідному тепловому режимі. Представлено теплову схему заміщення ізольованої струмопровідної жили. За допомогою методів дискретних резистивних схем заміщення і вузлових потенціалів отримано розподіл температури в товщі поліетиленової ізоляції в різні моменти часу в залежності від температури води, що охолоджує. Показано, що тривалість перехідного процесу, що відповідає досягненню однакової температури по всій товщині ізоляції, можна розглядати в якості критерію при визначенні технологічних параметрів охолодження. Бібл. 12, рис. 7.

Ключові слова: **режим охолодження, поліетиленова ізоляція, теплова схема заміщення, метод дискретних резистивних схем заміщення, несталий режим, метод вузлових потенціалів, система лінійних алгебраїчних рівнянь, довжина ванни охолодження.**

Обоснована методика расчета режима охлаждения силовых кабелей в переходном тепловом режиме. Представлена тепловая схема замещения изолированной токопроводящей жилы. С помощью методов дискретных резистивных схем замещения и узловых потенциалов получено распределение температуры в толще экструдированной полиэтиленовой изоляции в разные моменты времени в зависимости от температуры охлаждающей воды. Показано, что длительность переходного процесса, соответствующая достижению одинаковой температуры по всей толщине изоляции, можно рассматривать в качестве критерия при определении технологических параметров охлаждения. Библ. 12, рис. 7.

Ключевые слова: **режим охлаждения, полиэтиленовая изоляция, тепловая схема замещения, метод дискретных резистивных схем замещения, неустановившийся режим, метод узловых потенциалов, система линейных алгебраических уравнений, длина ванны охлаждения.**

Introduction. The cooling mode of polymer insulation after application in the extruder is one of the main factors determining cable performance. Theoretically, the cooling of the insulation is ideal at the temperature of the cooling medium equal to the melting point of the insulation material: in this case, the probability of formation of voids in the insulation is less [1-3]. In the process of cooling, heat from the surface of the insulation is removed with the help of air or water of lower temperature. The cooling process is mainly subject to the laws of convective heat transfer, and, here forced convection is usually observed due to the continuous axial movement of the workpiece during the technological process. The process of temperature change over the thickness of the insulation or shell, that is, inside a solid, occurs according to the laws of heat conduction.

The cooling process is usually not subject to stringent requirements, since most insulating materials allow for quite sharp cooling. The exception is polyethylene, which requires gradual cooling. When the insulation is cooled in a cooling bath, the temperature decrease starts from the surface. In this regard, the cooling of insulation of polyethylene is carried out stepwise to a temperature at which the cooled extruded insulation will not be deformed or damaged on the receiving drum [2, 3]. At cable companies, extruded coating is cooled to temperatures (40…50) °C to comply with safety requirements [4].

The length of the cooling bath depends on the speed of extrusion, the diameter of the core (or cable) and the thickness of the insulation (shell). The length of the bath for cooling insulation based on crystalline polymers is longer than for cooling insulation of amorphous polymers, since the crystallization process is exothermic [2, 3].

The rewinding speed depends on the diameter of the extruded cables. So, for telephone cables, the conductor diameter of which does not exceed 1 mm, the reception speed is one of the highest and reaches 1200 m/min. As the diameter of the core increases, the reception speed decreases and for power cables it is about (6-30) m/min. At cooling of polyethylene insulation, speed is limited by the length of the cooling bath.

Existing methods for calculation of the cooling modes of extruded insulation allow one to calculate the cable rewinding speed at a known cooling bath length or the bath length at a given rewinding speed [5, 6] without taking into account the temperature distribution over the entire insulation thickness in transient thermal mode.

Problem definition. Technological parameters of the cooling mode affect the internal structure of the polymer: the lower the cooling rate, the higher the content of the crystalline phase in the polymer insulation. At rapid cooling, relaxation processes do not have time to complete, a violation of the internal morphological structure occurs, leading to the formation of a non-equilibrium structure of polymer insulation with a predominance of the amorphous phase [1-3]. The quantitative ratio of the crystalline and amorphous phases ultimately determines the thermal, mechanical and electrical characteristics of extruded insulation.

At sharp cooling, it is also possible the formation of internal voids in the thickness of extruded insulation. This process is most likely to occur when cooling polyethylene, in which the volume of the melt at temperature of 200 °C is practically 25% higher than at 20 °C: a sharp change in volume occurs near its melting point [7]. Polyethylene is characterized by a large value of thermal expansion coefficient, the maximum value of which is in the temperature range (90-125) °C. As a result, there is an uneven reduction in the volume of the upper and inner insulation layers, especially for cables with a considerable insulation thickness. The sharp cooling of polyethylene leads to the formation of cracks, air inclusions both between the insulation and the conductive core, and in the layers located near the core.

Thus, in [5] the degree of cable cooling is determined at a given temperature at the inlet to the bath and the temperature of the cooling water during convective heat exchange between the surface of the insulation and cooling water [8].

For power cables, it is important to obtain the temperature field distribution over the thickness of extruded polyethylene insulation, which is determined by the thermal conductivity of polyethylene insulation, taking into account the temperature of heating of the conducing core and the temperature of the cooling water.

The goal of the paper is the justification of the technological parameters of the cooling mode of power cables based on the calculation of the thermal equivalent circuit of a conductive core insulated with polyethylene in transient thermal mode.

Thermal equivalent circuit of extruded insulated core in transient thermal mode. In the general case, the calculation of the temperature field over the thickness of the insulation when it is cooled is reduced to the specification of single-valued conditions: geometric conditions that characterize the shape and dimensions of the extruded conductive core; physical conditions characterizing thermal conductivity, heat capacity, density of the core, insulation and cooling medium, respectively; initial conditions characterizing the temperature distribution at the initial moment of time (at $t = 0$); boundary conditions characterizing the interaction of the extruded insulation under consideration with the environment [9].

To calculate the temperature distribution in the thickness of extruded polyethylene insulation at different times, depending on the cooling water temperature, we use the method of electrothermal analogies [9]. There is a complete analogy between the thermal and electrical equivalent circuits, which allows using the well-known methods of the theory of electrical circuits to calculate thermal circuits. The analogue of the potential in the thermal equivalent circuit is the temperature (T), and the analogue of the current is the heat flux (P) per unit length of insulation along its axis (per unit length of cable).

The thermal equivalent circuit of insulation of power cables (Fig. 1) is calculated using the method of discrete resistive equivalent circuits [9]. For this, thermal quantities will be replaced by their electrical counterparts. Then we calculate the thermal circuit and determine the desired temperature [9].

The thermal substitution circuit (Fig. 1) reflects: the heat capacity of the core C_g; the temperature-dependent (non-linear) thermal resistances R_t and thermal capacitances C_t of each insulation layer (from 1 to M), the thermal resistance of heat transfer R_{to} from the surface of the wire insulation, as well as the effect of the source of heating of the wire to the medium temperature T_w.

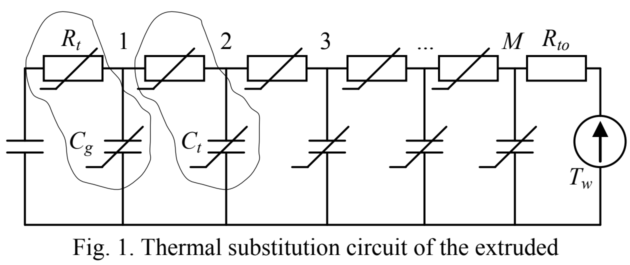


Fig. 1. Thermal substitution circuit of the extruded insulated core in transient thermal mode

To calculate the temperature field in the process of cooling of a moving insulated conductive core, we take the following assumptions:

1) an insulated core is considered symmetric about its axis;

2) the core moves at a constant speed;

3) the core material and insulation is isotropic;

4) changes in the size of the wire caused by shrinkage of the insulation are not take into account;

5) the heat transfer along the conductive core is neglected;

6) the internal sources of heat released during the phase transition of the polymer during cooling of the insulation are not take into account;

7) each element has constant electrical and physical characteristics in its volume.

Given the initial values of the temperature at the exit of extruded polyethylene insulation from the vulcanization chamber at time $t = 0$, namely: of a heated conductor, insulation (the temperature of which is the same throughout the thickness and on the surface), cooling water, it is possible to obtain the temperature distribution across the insulation thickness at different points in time.

The calculation technique. From the thermal equivalent circuit (Fig. 1), we turn to the equivalent circuit of the discrete resistive equivalent circuit (DREC) method (Fig. 2) [10], in accordance with which capacitances are represented by sources of EMF E_{cg}, E_{ct} and resistors R_{cg}, R_{ct}. The EMF sources «remember» the temperatures on the capacitances at the previous (k–1)th time («old» temperature). Finding a «new» temperature at the current k-th instant of time in time interval h is defined as

$$T_k \approx \frac{h}{C} \cdot P + T_{k-1}. \qquad (1)$$

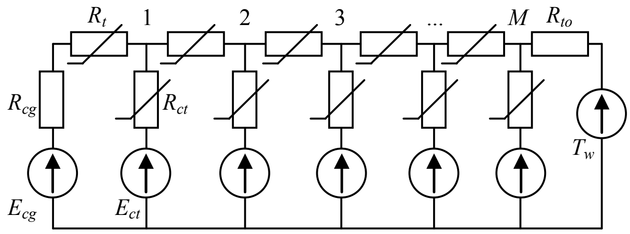


Fig. 2. Discrete resistive equivalent circuit of extruded insulated core in transient thermal mode

The calculation of the DREC is performed by the method of nodal potentials [9, 10]. The system of linear algebraic equations (SLAE) of the method of nodal potentials for the case of M nodes (the number of layers along the insulation thickness) has the form [9]

$$\begin{pmatrix} G_{11} & G_{12} & G_{13} & G_{14} & \cdots & G_{1M} \\ G_{21} & G_{22} & G_{23} & G_{24} & \cdots & G_{2M} \\ G_{31} & G_{32} & G_{33} & G_{34} & \cdots & G_{3M} \\ G_{41} & G_{42} & G_{43} & G_{44} & \cdots & G_{4M} \\ G_{51} & G_{52} & G_{53} & G_{54} & \cdots & G_{5M} \\ \cdots & \cdots & \cdots & \cdots & \cdots & \cdots \\ G_{M-1,1} & G_{M-1,2} & G_{M-1,3} & G_{M-1,4} & \cdots & G_{M-1,M} \\ G_{M1} & G_{M2} & G_{M3} & G_{M4} & \cdots & G_{MM} \end{pmatrix} \cdot \begin{pmatrix} \varphi_1 \\ \varphi_2 \\ \varphi_3 \\ \varphi_4 \\ \varphi_5 \\ \cdots \\ \varphi_{M-1} \\ \varphi_M \end{pmatrix} = \begin{pmatrix} J_1 \\ J_2 \\ J_3 \\ J_4 \\ J_5 \\ \cdots \\ J_{M-1} \\ J_M \end{pmatrix}, \qquad (2)$$

where J_1 – J_M are the nodal «currents» (heat flow): J_1 – J_{M-1}=0; $J_M = \dfrac{T_c}{R_{to}}$; $G_{11} = \dfrac{1}{R_t + R_{cg}} + \dfrac{1}{R_{ct}} + \dfrac{1}{R_t}$ is the nodal conductivity of the first node (the sum of the conductivities of the branches converging at the first node); $G_{22} = \dfrac{1}{R_t} + \dfrac{1}{R_{ct}} + \dfrac{1}{R_t}$ is the nodal conductivity of the second node;

$G_{33} = G_{22}$; $G_{44} = G_{22}$; $G_{55} = G_{22}$; ... $G_{(M-1)(M-1)} = G_{22}$;

$G_{MM} = \dfrac{1}{R_t} + \dfrac{1}{R_{ct}} + \dfrac{1}{R_{to}}$; $G_{12} = -\dfrac{1}{R_t}$ is the mutual conductivity between the 1st and the 2nd nodes (taken with a minus sign the total conductivity between the 1st and the 2nd nodes); $G_{23} = G_{34} = G_{45} = ... = G_{12}$; $G_{13} = G_{14} = G_{15} = ... = G_{1M} = 0$.

As a result of solution of the three-diagonal SLAE (2) by the method of sweeping and finding at each discretization step (time interval) thermal power fluxes in the branches of the thermal equivalent circuit, the temperatures in the thermal capacitances, the temperature is determined in each insulation layer. The order of the resolving system of linear algebraic equations is determined by the product of the number of nodes and the number of discretization steps.

The influence of technological modes of cooling and design parameters of cables on the temperature distribution across the thickness of extruded polyethylene insulation. The calculation of the temperature distribution over the thickness of the insulation is carried out with given thermal characteristics (thermal conductivity λ, specific heat capacity c, density ρ): for copper conductor λ_g = 200 W/(m·K); c_g = 420 J/(kg·K); ρ_g = 8300 kg/m^3 [11, 12].

For polyethylene: the density is assumed to be ρ_d = 940 kg /m^3; the dependences of the thermal conductivity and specific heat capacity on temperature are given as approximating functions [1, 7]:

λ_d = 0,35 W/(m·K) at $T \geq$ 120 °C;

λ_d = 0,41 – 0,001·T at $T <$ 120 °C;

c_d = 3150 J/(kg·K) at $T \geq$ 115 °C;

c_d = 3750 – 4,78·T at $T <$ 115 °C;

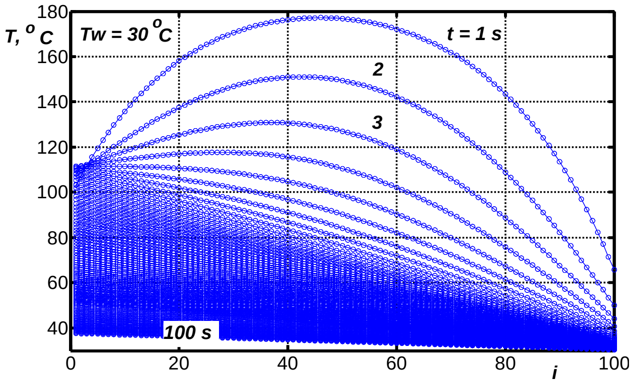
Thermophysical characteristics of cooling water required for the calculation of thermal resistance R_{to}: λ_w = = 0,24 W/(m·K); c_w = 5000 J/(kg·K); ρ_w = 1000 kg/m^3 [5].

The calculations are performed for initial insulation temperature of 200 °C at time t = 0 when extruded polyethylene insulation exits the vulcanization chamber.

1. The influence of the temperature of the cooling medium on the temperature distribution. Figure 3 shows the dynamics of the temporal variation of the temperature distribution in polyethylene insulation 2 mm thick (i is the layer number in the thickness of the insulation, measured from the core), depending on the cooling water temperature. The temperature of the water in the cooling bath is respectively:

- 30 °C (Fig. 3,*a*, curve 1 in Fig. 3,*d*);
- 60 °C (Fig. 3,*b*, curve 2 in Fig. 3,*d*);
- 90 °C (Fig. 3,*c*, curve 3 in Fig. 3,*d*).

The calculation results are obtained for a conductive copper core heated to 90 °C with cross section of 95 mm^2. As the calculations show (compare Fig. 3,*c* and Fig. 4), heating the core to 90 °C reduces the probability of formation of air cavities near the core, provides a more uniform temperature distribution across the insulation thickness during the same transient time and improves adhesion of the polymer melt to the metal conductor.



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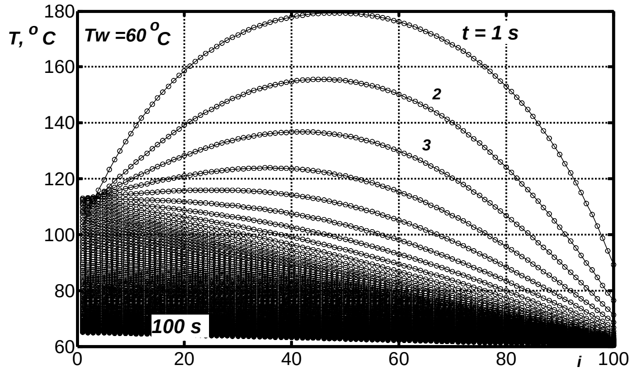

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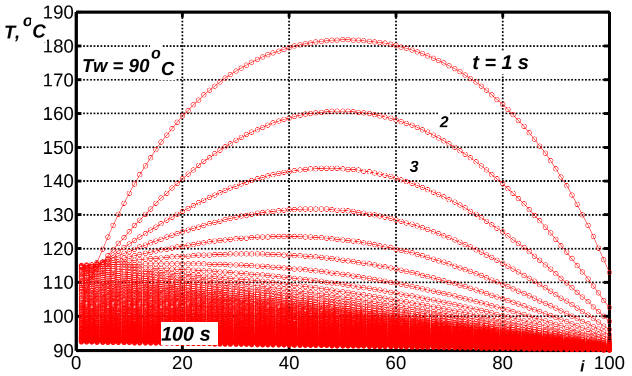

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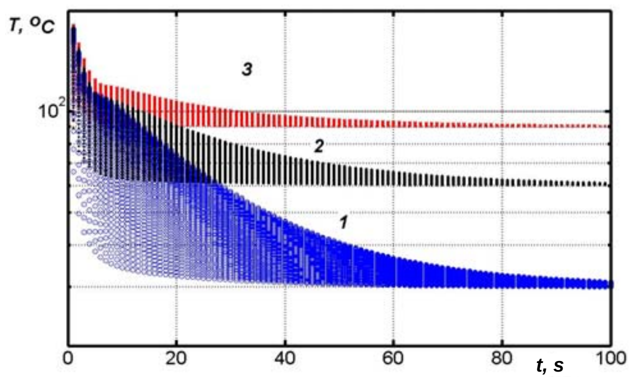


d

Fig. 3. The effect of cooling water temperature on temporal distribution dynamics of temperature through the thickness of polyethylene insulation

At cooling water temperature of 30 °C, the most sharp cooling of the insulation is observed (compare curve 1 with curve 3 in Fig. 3,*d*). The decrease in temperature starts from the surface of the insulation (see Fig. 3, layer i = 100 at t = 1 s). The surface layer, cooling over time t = 5 s, tends to reduce its volume, while the internal ones, which are not yet cooled, impede this reduction. In this case, the surface layer hardens under the action of radial pressure and is in a stretched state with frozen internal stresses. Upon subsequent cooling of the inner layers, their volume is reduced, but this occurs under conditions when the outer layers have already hardened. Volume reduction may occur unevenly, and at the most mechanically weak points, i.e. where insulation is last cooled.

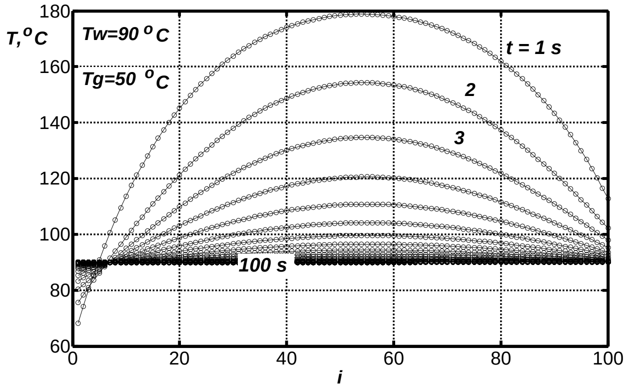


Fig. 4. Dynamics of temperature distribution over the thickness of the insulation at the temperature of the core equal to 50 °C

The probability of formation of bubbles and voids in the core, the temperature of which is higher in comparison with the outer layers of insulation, increases significantly. The time required to complete the transient thermal process in the first section of the cooling bath with water temperature of 90 °C (see Fig. 3,*c*, curve 3 in Fig. 3,*d*, curve 1 in Fig. 5) is about 100 s.

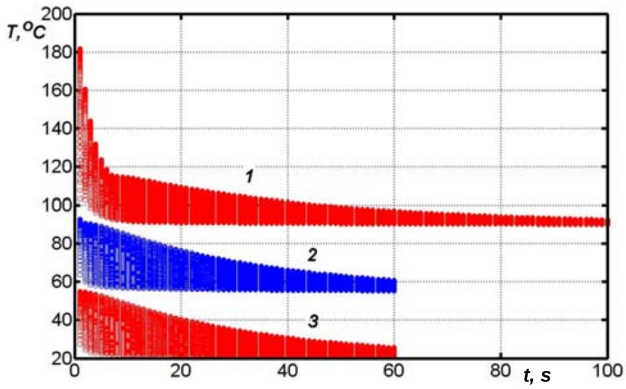


Fig. 5. Temporal diagram of the temperature distribution across the thickness of the polyethylene insulation with step cooling in a three-section bath

During this time, over the entire thickness of the insulation, practically the same temperature is established, equal to the cooling water temperature of 90 °C, which reduces the probability of formation of cavities and the concentrations of thermomechanical stresses in the thickness of the polyethylene insulation.

The transient time can be considered as a criterion to substantiate the relationship between the length L_1 (m) of the first section of the cooling bath and the reception speed v (m/s). For the case considered, the L_1/v value is 100 s. At a rewind speed of v = 0,2 m/s = 12 m/min, the length of the first section should be equal to 20 m. The length of the bath can be reduced at least twice with that same reception speed: at such a length, the temperature difference between the inner and outer layers of insulation does not exceed 10 °C (see Fig. 5, curve 1).

The insulation in the second and the third sections is cooled by water, the temperature of which is equal to 50 °C and 20 °C, respectively, in significantly less time (compare curve 1 and curves 2, 3 in Fig. 5). The length of the second section L_2 is 10 m, of the third (to ensure the insulation temperature of about 40 °C) is L_3 = 4 m. Thus, the total length of the three-section cooling bath will be 30 m. Such cooling mode parameters provide less probability of formation of voids, air inclusions and cracks in the thickness of the insulation. The results obtained are consistent with the data given in [1, 5].

2. The influence of cable design parameters on the temperature distribution across the thickness of extruded polyethylene insulation. The effect of the diameter of the conductive core on the temperature distribution across the insulation thickness at different points in time is shown in Fig. 6.

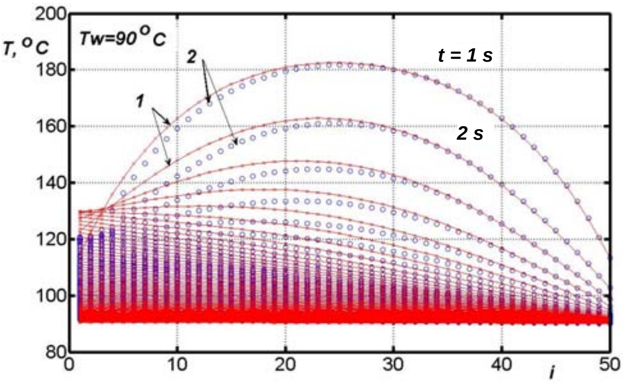
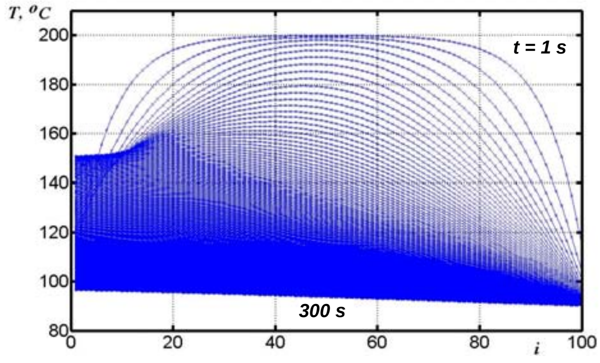


Fig. 6. The influence of the conductive core cross section on the temperature distribution across the thickness of the polyethylene insulation

The insulation thickness in both cases is 2 mm. Curve 1 corresponds to the cross section of a copper core of 95 mm^2, curve 2 – of 240 mm^2. At the initial cooling moment, for internal insulation layers located near the core of a larger cross section, the temperature is lower compared to the temperature distribution for insulation with a core of a smaller cross section. The difference is further leveled, which allows using a bath of the same length for cooling.

Increasing the thickness of the insulation leads to an increase in the time of the transient thermal process, and hence the length of the first cooling section (Fig. 7). To maintain the same length of the first section of the cooling bath when cooling cables with a greater insulation thickness, it is necessary to reduce the reception rate accordingly.

Figure 7 shows the effect of the number of layers on the temperature distribution: M = 100 (Fig. 7,*a*), M = 300 (Fig. 7,*b*). The core cross section is 95 mm^2, the insulation thickness is 6 mm. An increase in the number of layers along the insulation thickness improves the calculation accuracy by 8 %.



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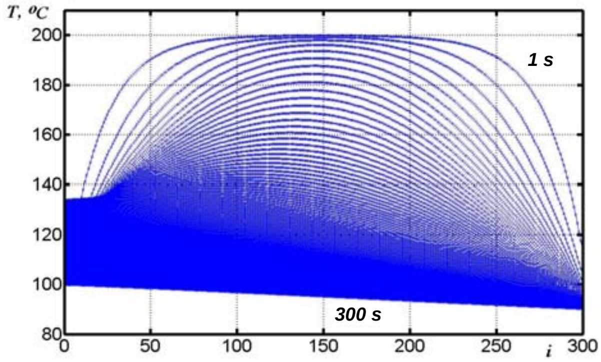

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Fig. 7. The influence of the number of layers on the temperature distribution over the thickness of the insulation

Conclusions.

A technique is developed for calculation of the technological parameters of the cooling mode of power cables. The technique is based on the calculation of the thermal equivalent circuit of a conductive core insulated with polyethylene in transient thermal mode, taking into account the dependence on temperature of thermal resistance and heat capacity using methods of discrete resistive equivalent circuits and nodal potentials.

The duration of the transient, corresponding to achieving the same temperature throughout total thickness of the insulation of power cables of different designs, is substantiated. It is shown that the duration of the transient can be considered as a criterion in determining the length of the sections of the cooling bath, depending on the rate of extrusion (reception).

The influence of the diameter of the conducting core and the thickness of the polyethylene insulation on the cooling mode of the power cables is established.

The proposed technique can be applied to select technological cooling modes for other types of cables, for example, symmetric, radio frequency and optical cables.

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Received 11.03.2019

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How to cite this article:
Bezprozvannych G.V., Mirchuk I.A., Kyessayev A.G. Technological parameters of the cooling mode of polymer insulation of power cables. *Electrical engineering & electromechanics*, 2019, no.3, pp. 44-49. **doi: 10.20998/2074-272X.2019.3.07.**