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EFFECT OF THE THICKNESS OF INSULATION OF PROTECTED WIRES OF HIGH-VOLTAGE OVERHEAD TRANSMISSION LINES TO THEIR CURRENT CARRYING CAPACITY

Introduction. ***The main direction of technical policy in the design, construction and technical re-equipment of transmission lines is the modernization of electrical networks and increase their energy efficiency in order to increase the throughput and reliability. Problem. Existing calculation methods do not take into account the influence of insulation thickness on the long-term current load of the wires according to the values of the maximum permissible working temperature of the conductors. Purpose. The investigation of the influence of insulation thickness of the protected wires of high-voltage*** **electric transmission lines** ***on their current carrying capacity. Methodology. The long operating temperature of the wire when the rated load current flows is determined based on the heat balance equation. Results. A method has been developed for determining the optimum thickness of polyethylene cross linked and oxide insulation to provide the lowest thermal resistance to the heat transfer of protected wires, the use of which allows increasing the current carrying capacity by 20 % compared to bare wires. It is shown that the internal temperature drop in cross linked polyethylene insulation is an order of magnitude smaller in comparison with the oxide insulation at identical values of the dielectric loss tangent. Originality. The calculations take into account the presence on the surface of a non-insulated aluminum conductor of a natural dense film based on aluminum oxide, which protects it from further contact with air. The capacitance of a single phase conductor with insulation is determined on the basis of the calculation of the electric field in a piecewise homogeneous medium by the method of secondary sources.*** References 12, tables 3, figures 5.
Key words: **bare conductor, protected wire, cross-linked polyethylene insulation, oxide insulation, thermal resistance, optimal insulation thickness, heat balance, effective heat transfer coefficient, current carrying capacity.**

Разработана методика определения оптимальной толщины полиэтиленовой сшитой и оксидной изоляции для обеспечения наименьшего теплового сопротивления теплопередаче защищенных и неизолированных проводов. Обоснована применимость разработанной методики для оптимизации толщины изоляции защищенных проводов напряжением 20 кВ. Показана возможность повышения пропускной способности по току защищенных проводов на 20 % по сравнению с неизолированными проводами за счет оптимизации толщины их изоляции. Установлено, что внутренний перепад температуры в сшитой полиэтиленовой изоляции на порядок меньше в сравнении с оксидной изоляции при одинаковых значениях тангенса угла диэлектрических потерь. Библ. 12, табл. 3, рис. 5.
Ключевые слова: **неизолированные провода, защищенные провода, сшитая полиэтиленовая изоляция, оксидная изоляция, тепловое сопротивление, оптимальная толщина изоляции, тепловой баланс, эффективный коэффициент теплопередачи, пропускная способность по току.**

Introduction. The main direction of the technical policy in the design, construction and technical re-equipment of transmission lines (TLs) is the modernization of electric networks and increase of their energy efficiency with the purpose of increasing the capacity and reliability, reducing losses on the basis of an innovative approach to the development and modernization of the existing power transmission complex [1]. Technical re-equipment, reconstruction of electric networks and their development should be carried out on the domestic regulatory framework, taking into account the recommendations of the International Electrotechnical Commission and regional peculiarities regarding the conditions of reliability and environmental safety, taking into account the real cost of land and maximum use of basic materials and equipment of own production.

One of the main directions of work in the construction of high-voltage TLs with increased current carrying capacity is the creation of new types of wires: high-temperature non-insulated ones based on aluminum alloys [2] and protected [3, 4]. The use of high-temperature wires with increased current carrying capacity in two times at an increase in cost, practically by an order of magnitude, is most effectively for high-voltage TLs of 110 kV and above [2].

As a progressive alternative to standard non-insulated aluminum wires for high-voltage TLs of voltage class 6-110 kV, it is possible to consider protected wires (PW). The design of a protected wire is a single-stranded multiwire conductor covered with a protective sheath [3, 4]. The conductor is made of aluminum alloy, the protective layer is made of light-stabilized cross-linked polyethylene. The permissible long operating temperature of cross-linked polyethylene insulation corresponds to 90 °C [3, 4]. The operating temperature of non-insulated aluminum wires does not exceed 75 °C [5].

The use of PW provides an increase in the current carrying capacity of high-voltage transmission lines in comparison with non-insulated aluminum wires [3, 5] (Table 1).

Table 1

Current carrying capacity of aluminum non-insulated and protected wires based on cross-linked polyethylene insulation with thickness of 2.3 mm of high-voltage TL with voltage of 20 kV (ambient air temperature 25 °C)

Strand cross-section S, mm^2	70	120	150	185	240
Continuous load current of bare wire I, A	235	330	370	430	500
Continuous load current of PW I, A	310	430	485	560	600

Problem definition. The continuous operating current flowing through the solid conductor is determined on the basis of the thermal calculation [6] and depends on: the active resistance of the strand R_g, the strand temperature T_g and the ambient temperature T_c, the thermal insulation resistance R_{ts} and the environment (air) resistance R_{oc}, the dielectric loss power in insulation $P_d = U_f^2 \omega C \text{tg}\delta$ [7]

$$I = \sqrt{\frac{T_g - T_c - P_d (R_{ts} + R_{oc})}{R_g \cdot (R_{ts} + R_{oc})}}, \quad (1)$$

where U_f is the phase voltage, ω is the angular frequency, C – is the own capacitance of wire, tgδ is the tangent of the dielectric loss angle of insulation.

Existing calculation methods [4, 7] do not take into account the influence of insulation thickness on the continuous current load of the wires by the values of the maximum permissible working temperature of the conductors (strands). The need to analyze the effect of the thickness of cross-linked polyethylene insulation on the long-term permissible working temperature of protected wires is an urgent task, because it allows you to optimize the size of the wire.

The goal of the paper is investigation of the influence of the insulation thickness of the protected wires of high-voltage TLs on their current carrying capacity.

Method for calculating the heat balance. The continuous operating temperature of the wire when the rated load current flows is determined on the basis of the heat balance equation between the extracted P_v and the dissipated P_{otd} power [8]

$$P_v = P_{otd} \; . \quad (2)$$

The heat extract power is determined by the thermal resistance of the insulation R_{ts}, the temperature of the heated strand T_g and the surface temperature of the wire T_p [8]

$$P_v = \frac{T_g - T_p}{R_{ts}} \; . \quad (3)$$

For a wire in the air, the dissipated heat power P_{otd} depends on the thermal resistance of the ambient air R_{oc} and the surface temperature of the wire T_p and the medium temperature T_c [8]

$$P_{otd} = \frac{T_p - T_c}{R_{t0}} \; . \quad (4)$$

The thermal insulation resistance R_{ts}, the thermal resistance of the ambient air R_{oc} and the total thermal resistance R_t are defined as [8]

$$R_{ts} = \frac{1}{2\lambda} \ln\left(\frac{d_2}{d_{21}}\right), \quad R_{t0} = \frac{1}{\alpha_{ef} S_{ts}}, \quad R_t = R_{ts} + R_{t0}, \quad (5)$$

where λ is the insulation heat conductivity; d_1, $d_2 = d_1 + 2\Delta_{ins}$, $S_{ts} = \pi \cdot d_2 \cdot l_{pr}$ are the strand diameter, the insulated wire diameter, the insulation thickness and the cooling surface of a wire of length l_{pr}, respectively; $\alpha_{ef} = \alpha_c + \alpha_{rad}$ is the effective heat transfer coefficient to the environment due to convection of α_c and radiation α_{rad} [8, 9].

Optimum insulation thickness for minimum heat transfer resistance. The calculations take into account the presence on the surface of a non-insulated aluminum conductor of a natural dense film based on aluminum oxide, which protects it from further contact with air. The film thickness is unity – hundreds of nm, depending on the service life and environmental conditions [9].

Fig. 1 shows the dependence of the thermal insulation resistance R_{ts} (curve 1), the heat transfer to the environment R_{oc} (curve 2) and the total thermal resistance R_t (curve 3) on the ratio of the diameter of the insulated wire d_2 to the diameter of the aluminum strand d_1: $K_{kp} = d_2/d_1$. For PW with an increase in the thickness of the cross-linked polyethylene insulation Δ_{ins} with an unchanged diameter of the strand d_1, the thermal insulation resistance R_{ts} increases (Fig. 1,*a*, curve 1 for λ = 0.25 W/m·K), and the thermal resistance R_{oc} of the ambient air decreases (Fig. 1,*a*: curve 2 for R_{oc} = = 17 W/m^2·K). The total thermal resistance R_t (curve 3) has a minimum value at the intersection of the curves R_{ts} and R_{oc} corresponding to the critical (optimal) value K_{kp}. At $K > K_{kp}$, the thermal resistance to heat transfer increases, at $K < K_{kp}$ – decreases. The critical values of K_{kp} are 1.5 (Fig. 1,*a*) and 70 (Fig. 1,*b*) for a protected wire made of cross-linked light-stabilized polyethylene insulation and a wire with oxide insulation, respectively.

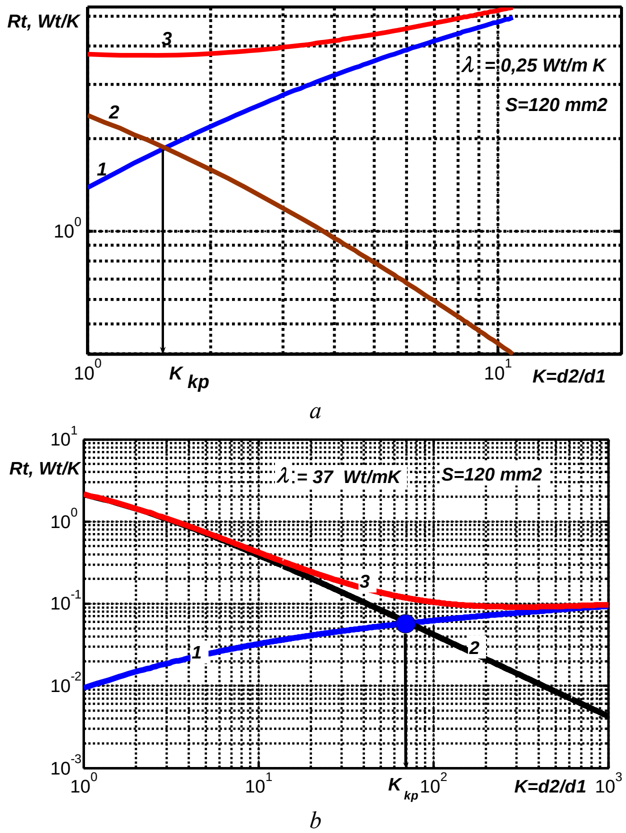


Fig. 1. To the determination of the optimum thickness of insulation of a protected wire and a wire with an oxide dielectric film at the cross-section of the strand 120 mm^2

The thickness of the wire insulation, corresponding to the minimum thermal resistance of heat transfer, is *optimal*. For a protected wire and an oxide-insulated wire, the optimum insulation thickness is $\Delta_{ins\,opt}$ =3.2 mm and 434 mm, respectively.

Critical values K_{kp} for PW at corresponding strand cross-sections are: K_{kp} =1.9 (70 mm^2), K_{kp} =1.5 (120 mm^2), K_{kp} =1.5 (150 mm^2), K_{kp} =1.4 (185 mm^2), K_{kp} =1.2 (240 mm^2).

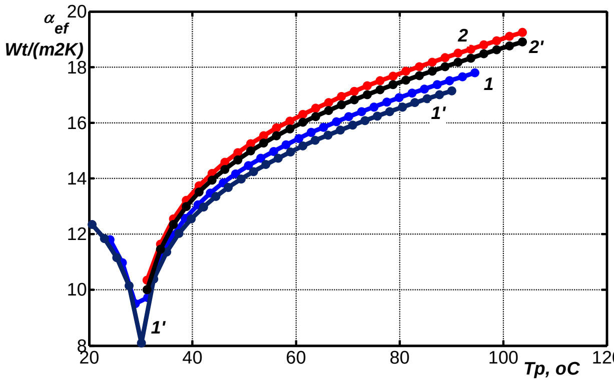
Effect of insulation thickness on the thermal stability of protected wires. On the basis of the presented technique, a thermal calculation has been performed for a continuous current load (see Table 1) of the protected and bare wires of a high-voltage TL with voltage of 20 kV (Table 2). At this stage of the calculation, the dielectric losses power P_d in insulation is not taken into account. The effective heat transfer coefficient (Fig. 2) is determined using the criterial equation of natural convection and the Stefan-Boltzmann equation [8, 9].

Table 2

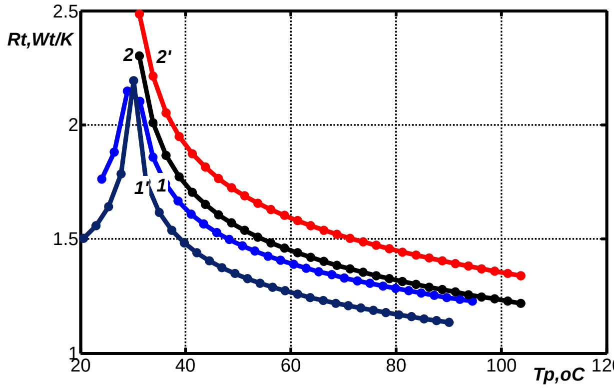
Effect of insulation thickness on heat resistance of PW of high-voltage TL with voltage of 20 kV

Aluminum strand cross-section S, mm^2				
70	120	150	185	240
Continuous current load I, A				
310	430	485	560	600
1. Ambient air temperature 25 °C				
1.1. PW of cross-linked light-stabilized polyethylene insulation				
The temperature of the aluminum strand T_g, °C: in the numerator – for the optimal insulation thickness, in the denominator – by 33 % less than the optimal				
81/85	**80/84**	**80/82**	**80/81**	**75/77**
The temperature of the wire surface T_p, °C: in the numerator - for the optimal insulation thickness, in the denominator – by 33 % less than the optimal				
75/80	**75/80**	**75/77**	**75/77**	**75/76**
1.2. Bare aluminum wire				
The strand temperature T_g, °C: in the numerator – for bare, in the denominator – with the oxide film of thickness of 100 nm				
105/105	**95/95**	**92/92**	**90/90**	**82/82**
2. Ambient air temperature 30 °C				
2.1. PW of cross-linked light-stabilized polyethylene insulation				
The temperature of the aluminum strand T_g, °C: in the numerator - for the optimal insulation thickness, in the denominator - by 33 % less than the optimal				
85/90	**85/85**	**85/85**	**85/87**	**77/79**
The temperature of the wire surface T_p, °C: in the numerator – for the optimal insulation thickness, in the denominator – by 33 % less than the optimal				
80/85	**80/85**	**80/82**	**80/82**	**76/78**
2.2. Bare aluminum wire				
The strand temperature T_g, °C: in the numerator – for bare, in the denominator – with the oxide film of thickness of 100 nm				
120/120	**105/105**	**95/95**	**95/95**	**87/87**

Fig. 2 shows the results of calculating the effective heat transfer coefficient (Fig. 2,*a*) and the thermal resistance of the surrounding medium (Fig. 2,*b*) of a protected and bare wire with different sections of the aluminum strand. An increase in the cooling surface of a protected wire in comparison with a bare wire with identical strand cross-sections leads to a decrease in the effective coefficient of heat transfer and thermal resistance (Fig. 2,*a*,*b*): curves 1 and 1' – for a protected wire with a cross-section of 120 mm^2 and 150 mm^2, 2 and 2' – for bare wire of cross-section of 120 mm^2 and 150 mm^2, respectively.



a



b

Fig. 2. The effect of the wire cooling surface on the temperature dependencies of the effective heat transfer coefficient (*a*) and thermal resistance of the environment (air) (*b*)

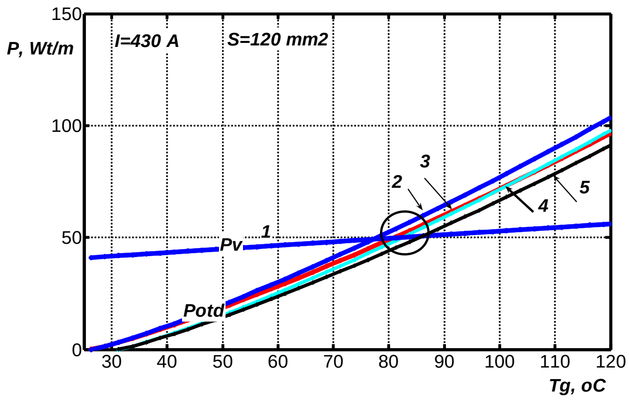
The results of the thermal calculation show that the protected wires, whose insulation thickness is 33 % less than the optimal one, provide current carrying capacity at an increased ambient temperature of 30 °C: the strand temperature does not exceed the permissible working temperature of the cross-linked polyethylene insulation (see Table 2, curve 4 of Fig. 3,*a*).

Reducing the thickness of cross-linked polyethylene insulation makes it possible to reduce the mass-dimensions of the protected wire.

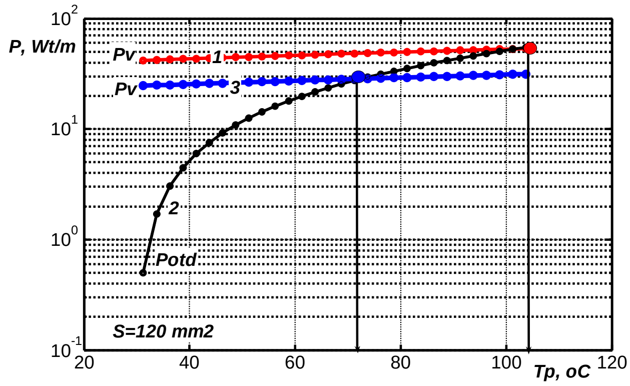
In Fig. 3,*a* curve 1 corresponds to the extracted power, curves 2, 3, 4 and 5 – dissipated power: curves 2 and 4 correspond to the optimal insulation thickness, curves 3, 5 – 33 % less than optimal at ambient air temperature of 25 °C (curves 2, 3) and 30 °C (curves 4, 5).

The wire temperature T_g of bare wires exceeds the permissible working temperature by 30 °C – 45 °C (for a 70 mm^2 wire) and 7 °C – 12 °C (for a 240 mm^2 wire) (see Table 2 and Fig. 3,*b*).

The presence on the bare wire surface of an oxide film of 100 nm thick does not affect the heat balance condition: the temperature on the wire surface remains constant.



a



b

Fig. 3. Heat balance in a protected (*a*) and bare (*b*) wire

The requirement to limit the working temperature of bare wires is due to the process of possible annealing of cold-drawn aluminum wires, an increase in plastic elongation and, as a consequence, sagging arrows. At load current of 430 A, the curves of the dissipated P_{otd} (curve 2) and the extracted power P_v (curve 1) intersect at a point corresponding to a temperature of 105 °C (Fig. 3,*b*). Reduction of the load current up to 330 A, i.e. by 20 %, leads to the intersection of P_v (curve 3) and P_{otd} (curve 2) at a point corresponding to a working temperature of 75 °C (Fig. 3,*b*).

Effect of dielectric losses in insulation on the current carrying capacity of the protected wire. The internal temperature drop in insulation (see (1)) ΔT_{ins} = $= P_d(R_{ts} + R_{oc})$ is determined by the dielectric losses power $P_d = U_f^2 \omega C \mathrm{tg}\delta$, which depends on the electrical characteristics of insulation: the dielectric losses angle tangent and the relative permittivity determining the wire capacity. The capacity of a single phase conductor with insulation is determined on the basis of the calculation of the electric field calculation in a piecewise homogeneous medium by the method of secondary sources [11], which reduces to solving a system of linear algebraic equations (SLAE). The first *Ne* rows of SLAE follow from the Fredholm integral equation of the first kind for potentials on the surface of a current-carrying strand (electrode). The following *Nd* rows are from the Fredholm integral equation of the second kind for jumps in the normal component of the field strength E_n, undergoing a break at the interfaces of dielectric media with relative dielectric permittivities ε_1 и ε_2 to satisfy the condition: $\varepsilon_1 \cdot E_{1n}$ = $= \varepsilon_2 \cdot E_{2n}$. The written form of the combined SLAE has the form [12]

$$\overline{A} \cdot \overline{\sigma} = \overline{U}\ , \qquad (6)$$

where $\overline{\sigma}$ is the matrix-column of unknown calculated densities of secondary charges, C/m^2; $\overline{U}$ is the matrix-column, the first *Ne* elements of which reflect the given potentials of the nodes lying on the electrode, and the remaining ones are equal to zero (the potentials of the nodes lying on the interface of dielectric media); $\overline{A}$ is the square matrix of coefficient.

The total number of nodes (the number of unknown of the charge density) is $N = Ne + Nd$. Solving SLAE (6) by a numerical method, the calculated density (in vacuum) of secondary charges is determined. The field strength for the electrode surface is determined by the calculated charge density $E_i = \sigma_i / \varepsilon_0$ and for the interfaces of dielectric media $E_i = \frac{\sigma_i}{2\varepsilon_0}(1 + \frac{1}{\alpha})$, where α is the parameter related to the permittivity of adjacent media: $\alpha = (\varepsilon_2 - \varepsilon_1)/(\varepsilon_2 + \varepsilon_1)$ [12]. The true density σ' of charges on the surface of the strand, which is insulated by a dielectric with relative dielectric permittivity ε_2, is greater by ε_2 times [12]. The desired capacitance is defined as the ratio of the true charge to the specified phase voltage. The wires are in the air with dielectric permittivity $\varepsilon_1 = 1$.

Fig. 4 shows the sweep of the electric field strength as a function of the length of the *SDL* generator (*SDL* corresponds to the reduction of «*sum of DL*» – the sum of a plurality of small length sections) for a PW and a 20 kV bare wire with a strand cross-section of 120 mm^2. Curve 1 – the optimal thickness of insulation (3.2 mm) and curve 2 – 33 % less than the optimal (2.3 mm) for a protected wire made of cross-linked polyethylene insulation (relative dielectric permittivity ε_2 = 2.3). Curve 3 – for a wire with oxide insulation thickness of 100 nm (relative dielectric permittivity ε_2 = 9: for a continuous oxide film obtained, for example, by high-voltage oxidation, the value of the relative dielectric permittivity is ε = 8-10 at a frequency of 50 Hz). Section I – distribution of the field strength along the surface of the strand, section II – along the insulation surface. The relative permittivity greatly influences on the distribution of the electric field strength (compare curves 1, 2 and 3, Fig. 4): the electric field strength on the surface of the wire with the oxide film is 30 % higher in comparison with the PW with the cross-linked polyethylene insulation.

Table 3 shows the results of calculating the intrinsic capacitance of the wires for different sections and the thickness of the insulation.

The results of the calculations show (Fig. 5) that adjacent phase protective wires located by a triangular at a distance of 50 cm from each other lead to a decrease in the intrinsic capacity of the wires: 18 % for the wire at the apex of the triangle (C_1 = 9.7 pF/m); 8 % for two other (C_2 = 10.6 pF/m and C_3 = 10.6 pF/m).

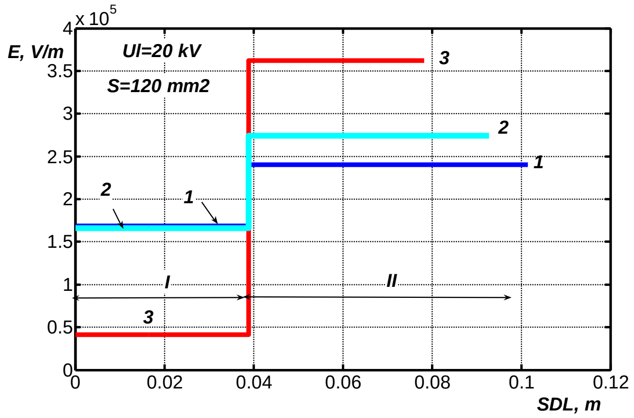


Fig. 4. The effect of the relative dielectric permittivity and insulation thickness on the distribution of the electric field strength over the wire surface

Table 3
Effect of insulation thickness on intrinsic capacitance of wires of high-voltage TL of voltage of 20 kV

Aluminum strand cross-section S, mm²				
70	120	150	185	240
1. Protected wire capacitance *C*, pF/m optimal insulation thickness				
11.1	11.5	11.7	11.9	12.1
insulation thickness by 33% less than the optimal				
10.9	11.4	11.5	11.7	12.0
2. Wire capacitance *C*, pF/m oxide insulation thickness 100 nm				
10.5	11.0	11.3	11.5	11.8

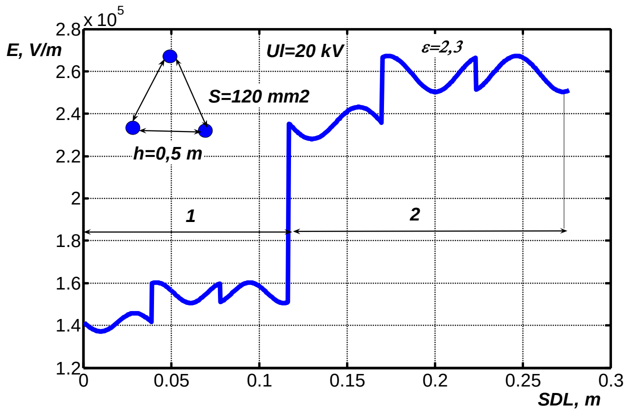


Fig. 5. The effect of near located protected wires on the distribution of the electric field strength along the surfaces of the strands (curve 1) and cross-linked polyethylene insulation (curve 2)

The dielectric losses power in XLPE insulation is $0.5 \cdot 10^{-3}$ W/m, 0.005 W/m for tgδ = 0.1 % and 1 %, respectively. The thermal resistance of the wire is 1 m·°C/W at core temperature of 90 °C and ambient air temperature of 30 °C (see Fig. 2,*b*). The internal temperature drop in the insulation $\Delta T_{ins} = P_d(R_{ts} + R_{oc})$ (see formula (1)) is 0.12 % and 1.2 % for the corresponding values of tgδ in comparison with the total temperature difference between the strand and ambient air $\Delta T = T_g - T_c$. For wire with oxide insulation ΔT_{ins} =10 % (tgδ =1 %), which causes a reduction in the permissible current load in the bare wire.

Conclusions.

1. For the first time, a method has been developed for determining the optimum thickness of polyethylene cross-linked and oxide insulation to provide the lowest thermal resistance to the heat transfer of protected wires, the use of which makes it possible to increase the current carrying capacity by 20% compared to bare wires.

2. The applicability of the developed technique for optimizing the thickness of insulation, both separated protected wires of various types, and for high-voltage transmission lines based on them, is justified, provided that the minimum distance between phase wires of the transmission line is limited to 0.5 m.

3. The results of the studies performed, provided they are appropriately experimentally substantiated, can become the scientific basis for the creation of a new class of compact high-voltage transmission lines with increased current carrying capacity.

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