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 of 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.

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).

| Strand cross-section $S$, mm² | 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 |

Table 1

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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 $T_a$, the thermal insulation resistance $R_\text{ins}$ and the environment (air) resistance $R_\text{ac}$, the dielectric loss power in insulation $P_d = U_j^2 \alpha \text{Ctg} \delta [7]$

$$I = \frac{T_g - T_a - P_d (R_\text{ins} + R_\text{ac})}{R_g (R_\text{ins} + R_\text{ac})}, \quad (1)$$

where $U_j$ is the phase voltage, $\omega$ is the angular frequency, $C$ – is the own capacitance of wire, $\text{Ctg} \delta$ 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 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 $P_e$ and the dissipated $P_{\text{old}}$ power [8]

$$P_e = P_{\text{old}}. \quad (2)$$

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

$$P_e = T_g - T_p. \quad (3)$$

For a wire in the air, the dissipated heat power $P_{\text{old}}$ depends on the thermal resistance of the ambient air $R_\text{ac}$ and the surface temperature of the wire $T_p$ and the medium temperature $T_e$ [8]

$$P_{\text{old}} = T_p - T_e. \quad (4)$$

The thermal insulation resistance $R_{\text{ins}}$, the thermal resistance of the ambient air $R_{\text{ac}}$ and the total thermal resistance $R_t$ are defined as [8]

$$R_{\text{ins}} = \frac{1}{2 \lambda} \ln \left( \frac{d_1}{d_2} \right), \quad R_{\text{ac}} = \frac{1}{\alpha_{\text{cf}} S_{\text{ins}}}, \quad R_t = R_{\text{ins}} + R_{\text{ac}}, \quad (5)$$

where $\lambda$ is the insulation heat conductivity; $d_1, d_2 = d_1 + + 2\Delta_{\text{ins}}, S_{\text{ins}} = \pi d_1 l_p$ are the strand diameter, the insulated wire diameter, the insulation thickness and the cooling surface of a wire of length $l_p$, respectively; $\alpha_{\text{cf}} = \alpha_c + \alpha_{\text{rad}}$ is the effective heat transfer coefficient to the environment due to convection of $\alpha_c$ and radiation $\alpha_{\text{rad}}$ [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 $R_\text{ins}$ (curve 1), the heat transfer to the environment $R_\text{ac}$ (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 $d_1$; $K_{\text{kp}} = d_2/d_1$. For PW with an increase in the thickness of the cross-linked polyethylene insulation $\Delta_{\text{ins}}$ with an unchanged diameter of the strand $d_1$, the thermal insulation resistance $R_{\text{ins}}$ increases (Fig. 1,a, curve 1 for $\lambda = 0.25$ W/m·K), and the thermal resistance $R_{\text{ac}}$ of the ambient air decreases (Fig. 1,a: curve 2 for $R_{\text{ac}} = 17$ W/m²·K). The total thermal resistance $R_t$ (curve 3) has a minimum value at the intersection of the curves $R_{\text{ins}}$ and $R_{\text{ac}}$ corresponding to the critical (optimal) value $K_{\text{kp}}$.

At $K > K_{\text{kp}}$, the thermal resistance to heat transfer increases, at $K < K_{\text{kp}}$ decreases. The critical values of $K_{\text{kp}}$ 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 mm²

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 $\Delta_{\text{ins, opt}} = 3.2$ 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

| 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 $T_p$, °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 $T_{ps}$, °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 $T_p$, °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 $T_{ps}$, °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. 2a) and the thermal resistance of the surrounding medium (Fig. 2b) 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. 2a,b): curves 1 and 1’ – for a protected wire with a cross-section of 120 mm$^2$ and 150 mm$^2$, and 2 and 2’ – for bare wire of cross-section of 120 mm$^2$ and 150 mm$^2$, respectively.

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.

\[
P = P_0 \left(1 - \frac{T_{ins}}{T_p}\right)
\]

where \( P_0 \) is the current carrying capacity of the protected wire.

The current of 430 A, the curves of the dissipated elongation and, as a consequence, sagging arrows. At load cold-drawn aluminum wires, an increase in plastic bare wires is due to the process of possible annealing of the surface of a current-carrying strand (electrode).

Fredholm integral equation of the first kind for potentials (SLAE). The first reduces to solving a system of linear algebraic equations (SDLAE). The first

\[
\Omega \cdot \sigma = \mathbf{U}
\]

where \( \sigma \) is the matrix-column of unknown calculated densities of secondary charges, C/m^2; \( \mathbf{U} \) 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); \( \Omega \) 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 \( E_i = \sigma_i / (2\varepsilon_0 \alpha) \), where \( \alpha \) is the parameter related to the permittivity of adjacent media: \( \alpha = \varepsilon_2 / (\varepsilon_2 + \varepsilon_1) \). The true density \( \sigma' \) of charges on the surface of the strand, which is insulated by a dielectric with relative dielectric permittivity \( \varepsilon_2 \), is greater by \( \varepsilon_2 \) times. 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 \( \varepsilon_1 = 1 \).

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 \( P_{ad} \) (curve 2) and the extracted power \( P_e \) (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 \( P_e \) (curve 3) and \( P_{ad} \) (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)) \( \Delta T_{sw} = \frac{P_d \left(R_{ro} + R_{ro}\right)}{U_j^2 \alpha C_0 g_0} \), 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 \( \varepsilon_1 \) and \( \varepsilon_2 \) to satisfy the condition: \( \varepsilon_1 E_{1a} = \varepsilon_2 E_{2a} \). The written form of the combined SLAE has the form [12]

\[
\Omega \cdot \sigma = \mathbf{U}
\]

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

![Figure 3](image)

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 (C1 = 9.7 pF/m); 8% for two other (C2 = 10.6 pF/m and C3 = 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](image)

**Table 3**

| 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)](image)

The dielectric losses power in XLPE insulation is 0.5 \times 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. 2a). The internal temperature drop in the insulation \( \Delta T_{ins} = \frac{P}{R_{in}} \) (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 \( \Delta T = T_s - T_a \). For wire with oxide insulation \( \Delta T_{ins} = 10 \% \) (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 scientifically 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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