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Issues of Increasing the Capacity of Overhead Power Transmission Lines by Reducing the Environmental Impact

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Issues of Increasing the Capacity of Overhead Power Transmission Lines by Reducing the Environmental Impact

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Abstract. Overhead power transmission lines (OPTL) are one of the main elements of the energy infrastructure, ensuring the transmission of electrical energy over long distances. However, the efficiency of OPTL is often limited by environmental influences, such as strong winds, precipitation, temperature, humidity, etc. These factors can cause an increase in line resistance and, as a result, a decrease in line capacity. Under the influence of these factors, the resistance of the lines increases, which leads to a decrease in their capacity and, ultimately, to the risks of accidents and loss of electricity. Therefore, increasing the power transmission of overhead power lines by reducing the environmental impact is an urgent task of the modern energy complex. In this article, based on the equations of thermal balance, analytical expressions are obtained for calculating the temperature of insulated and non-insulated wires of overhead power lines. In addition, a comprehensive study of the influence of ambient temperature, wind speed, and atmospheric pressure on the thermal condition of conductors has been conducted.

INTRODUCTION

Due to the increasing demand for electricity and the aging of existing infrastructure, overhead transmission lines are often operating at the edge of their thermal limits. The main factors affecting the capacity of overhead lines are [1, 2]:

1. Temperature fluctuations. As the temperature increases, the wire expands, which can lead to tension and, in some cases, deformation or damage to the insulation. In cold conditions, a decrease in temperature causes compression of the wire, which affects its mechanical characteristics and electrical parameters.
2. Strong wind creates mechanical stress on the supports and wires, causing them to oscillate and possible damage. Constant wind loads can worsen contact connections and increase the risk of breakages.
3. Precipitation and humidity. Rain, snow and fog contribute to the accumulation of moisture on the surface of wires and insulation, reduces the electrical strength of lines, and increases the risk of breakage.
4. Corrosion and exposure to chemicals. Exposure to aggressive substances from the environment, such as acid rain or air pollution, accelerates the corrosion of metal OPTL elements, which reduces their reliability.
5. The use of modern materials and coatings; improvements in the construction and design of lines; automation and monitoring of the condition of lines, also reduce the impact of the environment.

The above factors, reducing the impact of which can increase the transmission line capacity, are an urgent task and encourage researchers to increasingly pay attention to climatic conditions, the temperature of conductors depends on many factors that can be described using mathematical models. This makes it possible to quickly respond to changes in the temperature of the conductors.

STATEMENT OF THE PROBLEM

In modern conditions of growing energy consumption and increasing load on the electric grid, there is an urgent need to increase the efficiency of operation of overhead power transmission lines (OPTL). One of the key performance indicators is the maximum throughput of the line – the maximum allowable load at which reliability and safety of operation are maintained. However, the increase in load is limited by the thermal conditions of operation of wires and supporting structures, since exceeding the permissible temperatures can lead to a decrease in the strength characteristics of materials, increased deflection of wires, damage to insulation and, ultimately, to emergency situations.

Today, existing methods for calculating the permissible load are often based on simplified models that do not take into account a complex of interrelated factors: climatic conditions, wind and solar loads, characteristics of materials and structures, dynamic loads and temperature variations in real time. The lack of an integrated approach leads to conservative estimates that reduce the capacity of the line and the economic efficiency of its operation.

Thus, there is a need to develop a methodology and algorithm that would take into account a set of influencing factors and ensure optimal load management of OPTL. This will maximize the capacity of overhead lines while maintaining operational parameters within acceptable temperature limits, which will significantly increase the reliability, durability and efficiency of the power grid [3].

SOLVING THE PROBLEM

An increase in current loads on overhead power lines inevitably leads to an increase in the temperature of the conductors, thereby imposing restrictions on the capacity of the lines. To ensure reliable operation and safe operation of the wires in various conditions, manufacturers set specific recommendations regarding the upper limits of the operating temperature. In order to achieve the maximum possible throughput while remaining within the acceptable wire temperatures, many factors must be considered. This includes not only the inherent properties of the conductor itself, such as its constituent materials, cross-sectional area, and electrical resistance, but also wind speed, atmospheric pressure, solar radiation, and ambient temperature. The aging of conductors, expansion of metals under the influence of heat, rapid fluctuations in weather conditions and many other influencing factors significantly complicate mathematical models used to predict and analyze the capacity of lines. As a result, these difficulties introduce a level of uncertainty that reduces the accuracy of the models.

The following mathematical models are used to estimate maximum current loads: IEEE 738 [4], CIGRE 601 [5] and the standard of Joint Stock Company Federal Grid Company of the Unified Energy System STO 56947007-29.240.55.143-2013 [6].

Recently, wires with an insulating layer have become widespread in networks up to 35 kV [7]. However, the methods listed above are intended only for calculations of non-insulated conductors. Therefore, this limitation highlights the need for additional research to create appropriate methods adapted to the unique requirements of insulated wires.

The standards listed above support the concept of thermal balance, which assumes that the heat absorbed by the conductor is compensated by the heat dissipated during the cooling process and the thermal balance, which is expressed by the following formula:

$$P_s + P_j = P_c + P_r \quad (1)$$

where P_s – is the intensity of solar radiation, *Vt/m*; P_j – is the load power loss, *Vt/m*; P_c – is the power provided by convective heat transfer, *Vt/m*; P_r – is the power provided by radiation, *Vt/m*.

The convective heat loss of a conductor depends on the temperature difference between it and the environment, as well as on the speed and direction of the wind. If the wind speed exceeds *0.2–0.6 m/s*, convection should be considered forced.

The components of the heat balance can be described according to [5] and [9]:

$$P_s + d_w \cdot A_s \cdot q_{solar} \quad (2)$$

$$P_j = \frac{\Delta P_0 \cdot [1 + \alpha_0 \cdot T_{out} - 273{,}15 \cdot \alpha_0]}{1 - \alpha_0 \cdot \Delta P_0 \cdot S_{isol.}} \quad (3)$$

$$P_c = d_w \cdot \alpha_f \cdot \pi \cdot [T_{out} - T_{amb.}] \quad (4)$$

$$P_r = d_w \cdot \pi \cdot \varepsilon \cdot C_0 \cdot [T_{out}^4 - T_{amb.}^4] \quad (5)$$

where d_w – is the diameter of the wire, *m*; A_s – is the absorption capacity of the wire for solar radiation; q_{solar} – is the density of the solar radiation flux per wire, *Vt/m²*; ΔP_0 – active power losses calculated from the resistance reduced to *0°C*, *Vt/m*;

α_0 – is the temperature coefficient of electrical resistance at *0°C*, *1/°C*;

T_{out} – is the absolute temperature of the outer surface of the wire, *K*;

$S_{isol.}$ – is the thermal isolation resistance, $m \cdot K/Vt$;

α_f – is the heat transfer coefficient during forced convection, $Vt/(m^2K)$;

$T_{amb.}$ – is the absolute ambient temperature, *K*;

ε – is the radiation coefficient; $C_0 = 5.67 \cdot 10^{-8}$ - is the radiation constant of an absolutely black body, $Vt/(m^2 \cdot K^4)$.

By substituting equations 2-5 into the heat balance equation, we obtain:

$$\frac{\Delta P_0 \cdot [1+\alpha_0 \cdot T_{out} - 273{,}15 \cdot \alpha_0]}{1-\alpha_0 \cdot \Delta P_0 \cdot S_{u3}} + d_w \cdot A_s \cdot q_{solar} = d_w \cdot \alpha_f \cdot \pi \cdot [T_{out} - T_{amb.}] + d_w \cdot \pi \cdot \varepsilon \cdot C_0 \times \times [T_{out}^4 - T_{amb.}^4] \quad (6)$$

Divide both sides of the equation by $d_w\ \pi\ \varepsilon\ C_0$:

$$\frac{\Delta P_0 \cdot [1-273{,}15 \cdot \alpha_0]}{[1-\alpha_0 \cdot \Delta P_0 \cdot S_{isol}] \cdot [d_w \cdot \pi \cdot \varepsilon \cdot C_0]} + \frac{\Delta P_0 \cdot \alpha_0 \cdot T_{out}}{[1-\alpha_0 \cdot \Delta P_0 \cdot S_{isol}] \cdot [d_w \cdot \pi \cdot \varepsilon \cdot C_0]} + \frac{A_s \cdot q_{solar}}{\pi \cdot \varepsilon \cdot C_0} = \frac{\alpha_f \cdot [T_{out} - T_{amb.}]}{\varepsilon \cdot C_0} + T_{out}^4 - -T_{amb.}^4. \quad (7)$$

Let's put all the variables on one side of the equation and take out the total coefficient of T_{out}:

$$T_{out}^4 + \left[\frac{\alpha_f}{\varepsilon \cdot C_0} - \frac{\Delta P_0 \cdot \alpha_0}{[1-\alpha_0 \cdot \Delta P_0 \cdot S_{isol}] \cdot [d_w \cdot \pi \cdot \varepsilon \cdot C_0]}\right] \cdot T_{out} + \left[-T_{amb.}^4 - \frac{A_s \cdot q_{solar}}{\pi \cdot \varepsilon \cdot C_0} - \frac{\Delta P_0 \cdot [1-273{,}15 \cdot \alpha_0]}{[1-\alpha_0 \cdot \Delta P_0 \cdot S_{isol}] \cdot [d_w \cdot \pi \cdot \varepsilon \cdot C_0]} - -\frac{\alpha_f \cdot T_{amb.}}{\varepsilon \cdot C_0}\right] = 0 \quad (8)$$

We reduce the expression to an equation of the fourth degree using auxiliary coefficients A_1 and A_0:

$$T_{out}^4 + A_1 \cdot T_{out} + A_0 = 0, \quad (9)$$

$$A_1 = \frac{\alpha_f}{\varepsilon \cdot C_0} - \frac{\Delta P_0 \cdot \alpha_0}{[1-\alpha_0 \cdot \Delta P_0 \cdot S_{isol}] \cdot [d_w \cdot \pi \cdot \varepsilon \cdot C_0]}, \quad (10)$$

$$A_0 = -T_{amb.}^4 - \frac{A_s \cdot q_{solar}}{\pi \cdot \varepsilon \cdot C_0} - \frac{\Delta P_0 \cdot [1-273{,}15 \cdot \alpha_0]}{[1-\alpha_0 \cdot \Delta P_0 \cdot S_{isol}] \cdot [d_w \cdot \pi \cdot \varepsilon \cdot C_0]} - \frac{\alpha_f \cdot T_{amb.}}{\varepsilon \cdot C_0}. \quad (11)$$

This equation can be solved by the Ferrari method [9] using the auxiliary parameter β:

$$[T_{out}^2 + \beta]^2 - [2 \cdot \beta \cdot T_{out}^2 - A_1 \cdot T_{out} + \beta^2 - A_0] = 0. \quad (12)$$

The coefficient β must be chosen so that the following equality holds

$$A_1^2 - 8 \cdot \beta \cdot [\beta^2 - A_0] = -8 \cdot \beta^3 + 8 \cdot \beta \cdot A_0 + A_1^2 = \beta^3 - A_0 \cdot \beta - \frac{A_1^2}{8} = 0. \quad (13)$$

Using the Cardano formula [9], we find the roots of the cubic equation:

$$\beta = \sqrt[3]{-\frac{1}{2} \cdot \left[-\frac{A_1^2}{8}\right] + \sqrt{\frac{1}{4} \cdot \left[-\frac{A_1^2}{8}\right]^2 + \frac{1}{27} \cdot [-A_0]^3}} + \sqrt[3]{-\frac{1}{2} \cdot \left[-\frac{A_1^2}{8}\right] - \sqrt{\frac{1}{4} \cdot \left[-\frac{A_1^2}{8}\right]^2 + \frac{1}{27} \cdot [-A_0]^3}} = \sqrt[3]{\frac{A_1^2}{16} + \sqrt{\frac{A_1^4}{256} - \frac{A_0^3}{27}}} + \sqrt[3]{\frac{A_1^2}{16} - \sqrt{\frac{A_1^4}{256} - \frac{A_0^3}{27}}}. \quad (14)$$

The roots of the equation of the fourth degree with the found auxiliary coefficient β:

$$\begin{cases} T_{out}^2 - \sqrt{2 \cdot \beta} \cdot T_{out} + \left[\beta + \frac{A_1}{\sqrt{8 \cdot \beta}}\right] = 0 \\ T_{out}^2 + \sqrt{2 \cdot \beta} \cdot T_{out} + \left[\beta + \frac{A_1}{\sqrt{8 \cdot \beta}}\right] = 0 \end{cases}. \quad (15)$$

Using the discriminant, we will find the roots of the quadratic equations:

$$T_{out_{1,2}} = \frac{\sqrt{2 \cdot \beta} \pm \sqrt{2 \cdot \beta - 4 \cdot \left[\beta + \frac{A_1}{\sqrt{8 \cdot \beta}}\right]}}{2} = \sqrt{\frac{\beta}{2}} \pm \sqrt{-\frac{\beta}{2} - \frac{A_1}{\sqrt{8 \cdot \beta}}} \quad (16)$$

$$T_{out_{3,4}} = \frac{-\sqrt{2 \cdot \beta} \pm \sqrt{2 \cdot \beta - 4 \cdot \left[\beta + \frac{A_1}{\sqrt{8 \cdot \beta}}\right]}}{2} = \sqrt{\frac{\beta}{2}} \pm \sqrt{-\frac{\beta}{2} - \frac{A_1}{\sqrt{8 \cdot \beta}}}. \quad (17)$$

The desired solution is a single root. Through repeated practical calculations, it is deduced that the 1st, 2nd and 4th roots are in the range of either negative or complex numbers. Thus, the only true one is the third root:

$$T_{out} = -\sqrt{\frac{\beta}{2}} + \sqrt{-\frac{\beta}{2} - \frac{A_1}{\sqrt{8 \cdot \beta}}} \quad (18)$$

The equation relating the temperature of the upper part of the wire and the temperature of the wire core [8]:

$$\theta_w = \frac{T_{out} - 273{,}15 + \Delta P_0 \cdot S_{isol}}{1-\alpha_0 \cdot \Delta P_0 \cdot S_{isol}}. \quad (19)$$

where θ_w – is the temperature of the wire core, $°C$.

From the analysis of existing sources, it follows that the detailed impact of meteorological factors can be considered separately. For example, the presence of wind helps to cool the conductor, which leads to a decrease in its temperature due to forced convection, and this effect becomes more pronounced as the air flow velocity increases. Figure 1 shows the effect of wind speed on the temperature of the power line wires at different amperage values. At the same time, accounting for wind speed along the entire line is a difficult task due to the complex trajectory of air masses [11,15].

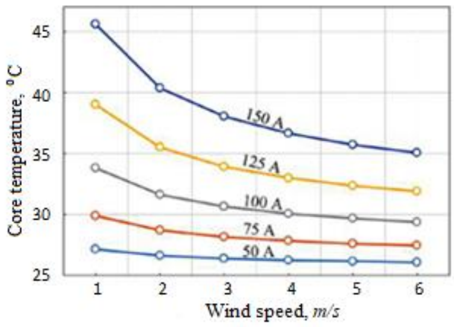

FIGURE 1. The effect of wind speed on the temperature of power line wires at different amperage values.

The ambient temperature also has a significant effect on the thermal condition of the conductors. As the air temperature increases, the conductor is able to dissipate less heat through convection and radiation, which leads to an increase in its temperature [12, 13, 14]. Figure 2 shows the effect of the air temperature around the conductor on the conductor core temperature with varying current strength.

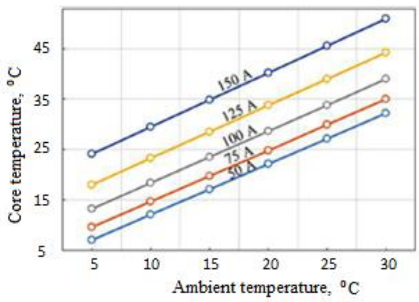

FIGURE 2. The effect of the air temperature around the conductor on the conductor core temperature with varying current strength

In the figure, you can see that the temperature change is linear, which makes this factor more accurate for calculations, unlike the influence of wind. Atmospheric pressure has a less pronounced effect on the thermal condition of the conductors compared to the ambient temperature and wind. A decrease in atmospheric pressure leads to a decrease in the efficiency of heat exchange, which, in turn, increases the temperature of the conductor. Figure 3 shows the relationship between atmospheric pressure and the temperature of the conductor core at certain values of current strength.

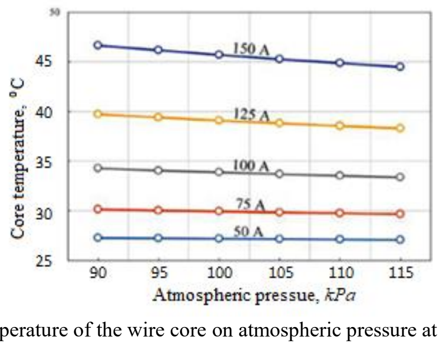

FIGURE 3. Dependence of the temperature of the wire core on atmospheric pressure at different values of current strength

The issues discussed in the article emphasize the importance of taking weather factors into account when operating overhead power lines, especially in conditions of increasing electricity consumption and deterioration of the infrastructure of the electric grid complex. As the thermal loads on power transmission lines reach their maximum values, the ability to accurately assess the thermal conditions of wires becomes necessary to ensure reliability and increase transmission line capacity.

CONCLUSION

The dependences obtained in this work offer a simplified but effective approach to calculating the temperature of both insulated and non-insulated conductors under various environmental conditions. The analysis confirms that the presented model not only has a high level of accuracy, but is also practical for implementation in engineering processes. It should be borne in mind that computer modeling, mathematical models, and even temperature sensors have a certain level of error. This inherent uncertainty must be carefully considered and taken into account with a certain margin of safety in any practical application.

Increasing the capacity of overhead power transmission lines is the main focus of energy infrastructure development. Reducing the environmental impact on the line is achieved through the use of modern materials, innovative design solutions, automation of monitoring and the introduction of intelligent operation systems. These measures make it possible not only to increase the transmission capacity of overhead lines, but also to increase their reliability, safety and durability, which contributes to the sustainable development of the energy system as a whole.

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