Influence of Insulation on Thermal Behavior of Overhead Line Conductors

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***Abstract*—To provide the accurate thermal rating of overhead power lines is required to consider the conductor temperature depending on a variety of weather factors. New types of conductors, such as overhead insulation-covered conductors are widely used in electrical networks. Well-known IEEE 738 and CIGRE standards calculate the bare overhead conductors only and are not applicable for thermal rating of overhead insulation-covered conductors. Numerical methods are able to calculate the insulated conductors, but have many drawbacks, such as the difficulty of modeling and low computation speed. The authors propose an analytical mathematical model to determine the thermal rating both overhead insulation-covered and bare conductors. Results of temperature calculation and active power losses calculation for overhead insulation-covered and bare conductors with the same cross section at selected weather conditions and changes in load current have been presented. Neglect of insulation can lead to errors in calculating of temperature up to 30%.**

***Index Terms*—insulation-covered conductors; bare conductors; overhead lines; conductor temperature; thermal rating; active power losses; weather conditions**

I. Introduction

One of the priorities in the power sector is the energy losses reduction in grids. Losses are reduced due to energy saving measures implementation. When determining the payback period and the most accurate choice of measures we should consider the conductor temperature. It is equally important to know the real temperature of the current-carrying conductors to determine the maximum capacity of power lines. Two different approaches are considered to adjust the overhead lines capacity. The first approach involves the use of special mathematical models [1]-[8] to determine the conductor temperature, and it uses the information about the environment. The second approach involves the direct measurement of the conductor temperature with special devices to transmit information about the conductor temperature to the receiving device [9]-[11].

For uninterrupted power supply it is necessary to choose the overhead conductors correctly. Conductors are chosen for continuous current-carrying capacity and maximum conductor temperature [5], [12]. The conductor temperature depends on the mode and climatic factors: current density, ambient temperature, wind strength and direction, solar radiation intensity, the conductor type [4], [6]. To complete successfully the task of determining the conductor temperature and to increase capacity in real time we are to realize the current value flowing through the power line. Electrical load simulations give such notions [13] - [17]. Currently, due to the high performance the insulation-covered overhead conductors are widely used. Conductors covered with insulation are less studied compared to bare conductors particularly in terms of thermal behavior. Widely used standards IEEE 738 [5] and CIGRE [4] are aimed at determining the heat calculation only of bare overhead conductors. The article presents a complex mathematical model for the calculation of temperature and active power losses as for insulation-covered overhead conductors and as for bare overhead conductors considering climatic and mode factors.

Advantages of the developed complex mathematical model are shown in the example of the numerical experiments for insulation-covered overhead conductors and bare overhead conductors with the same cross-section. The insulation effect estimation in the heat processes course in overhead conductors was carried out. The verification of proposed model has been proved in the previous work [8].

II. Mathematical Model of Overhead Insulation-Covered Conductor

A. Temperature Gradient through Insulation-Covered Conductor

Considered a cylindrical conductor of infinite length with diameter d_1 (radius r_1), and it has the insulation diameter d_2 (radius r_2).When there are no dielectric losses in the insulation then the thermal conductivity equation for insulation has the form

$$\frac{d^2\Theta}{dr^2}+\frac{1}{r}\frac{d\Theta}{dr}=0 \tag{1}$$

where Θ is a temperature function from the conductor center distance r.

Heat flow through a cylindrical insulation surface is determined with the Fourier law [18] of equation (2) and

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with the total heat generation in conductor in accordance with equation (3):

$$Q = -\lambda_{ins} \frac{d\Theta}{dr} 2\pi r \tag{2}$$

$$Q = \Delta P = q_v \pi r_1^2 \tag{3}$$

where λ_{ins} is thermal conductivity of the insulation, ΔP is insulation-covered conductor active power loss, q_v is volumetric density of heat release.

Taking into account the equations (2), (3), one can solve the equation (1). If the temperature on the inner insulation surface is set approximately equal to the temperature at the conductor center Θ_{cen}, then the temperature function can be determined with equation (4)

$$\Theta(r_1) \approx \Theta_{cen} + \frac{q_v r_1^2}{2\lambda_{ins}} \ln \frac{r_1}{r} \tag{4}$$

The temperature gradient in the insulation is

$$\Delta\Theta_{ins} = \Theta_{cen} - \Theta_{sur} = \frac{q_v r_1^2}{2\lambda_{ins}} \ln \frac{r_2}{r_1} \tag{5}$$

where Θ_{sur} is the temperature on the outer insulation surface.

The nature of the temperature distribution inside the insulation-covered conductor is shown graphically in Fig. 1.

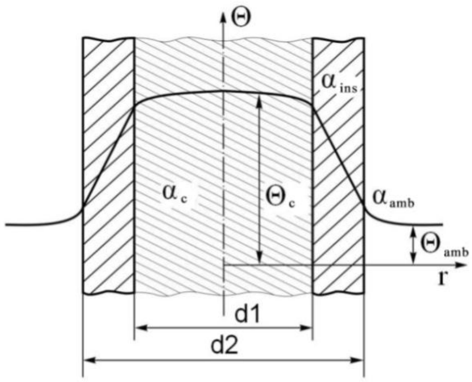

Figure 1. The temperature distribution in the insulation-covered conductor.

B. Determination of Active Power Losses and Temperature in Center of Overhead Insulation-Covered Conductor

The insulation-covered conductor active power loss per unit length with temperature dependence is determined with equation (6)

$$\Delta P = \frac{I^2 r_0 (1 + \alpha\Theta_c)}{1 - \alpha I^2 r_0 S_{ins}} \tag{6}$$

where I is current in the conductor, α is temperature coefficient of the resistance, r_0 is the pursuit of resistance at 0 ℃, S_{ins} is thermal insulation resistance

$$S_{ins} = \frac{1}{2\pi\lambda_{ins}} \ln \frac{r_2}{r_1}$$

Using equations (3), (5), (6) while $\Theta_c \approx \Theta_{cen}$, one can determine the temperature in center of insulation-covered conductor

$$\Theta_c = \frac{\Theta_{sur} + \Delta p_0 S_{ins}}{1 - \alpha \Delta p_0 S_{ins}} \tag{7}$$

where $\Delta p_0 = I^2 r_0$ is active power losses calculated according to resistance with temperature 0 ℃.

C. Temperature Determination on Outer Surface of Conductor's Insulation

The temperature of the outer insulation surface in the steady state mode can be determined based on the converted heat balance equation [6] for two models:

1) Calculation when there is natural convection;
2) Calculation when there is forced convection.

The heat balance of the insulation-covered conductor in a steady state mode can be written as follows:

$$\Delta p_0' \left(1 + \alpha\Theta_{sur}\right) = d_2 (\pi\alpha_c \left(\Theta_{sur} - \Theta_{amb}\right) + \pi\varepsilon C_0 \left(T_{sur}^4 - T_{amb}^4\right) - A_s q_s) \tag{8}$$

where α_c is coefficient of heat transfer with convection, T_{amb} is the environment temperature in Kelvin degrees, T_{sur} is the temperature of the outer surface of the insulation in Kelvin degrees, C_0 is radiation coefficient of blackbody, ε is the blackbody degree of the conductor surface, A_s is surface absorbance for solar radiation, q_s is solar irradiation density, $\Delta p'_0$ is active pover losses in insulation-covered conductor.

The value q_s is determined with the sum of the direct and diffuse components:

$$q_s = k_{sh} q_{s.dir} sin\varphi_s + \pi q_{s.diff} \tag{9}$$

where k_{sh} is shading coefficient, φ_s is the angle between the axis of the conductor and the direction of the sun's rays, $q_{s.dir}$ is direct solar radiation flux density on the surface perpendicular to sun's rays, $q_{s.diff}$ is diffuse solar radiation.

The heat transfer coefficient α_c can be determined with numerical criteria of similarity theory [18]. The equations for determining the coefficient with forced and natural convections can be calculated with equations (10) and (11) respectively

$$\alpha_c = 0.044 \frac{k_v (Pv)^{0.6}}{(T_{amb} d_2)^{0.4}} \tag{10}$$

$$\alpha_c = 0.0749 \sqrt{\frac{P}{T_{amb}}} \cdot \sqrt[4]{\frac{\Delta\Theta_{sur}}{d_2}} \tag{11}$$

where k_v is wind factor coefficient, v is wind speed, P is atmospheric pressure, $\Delta\Theta_{sur}$ is temperature difference between the outer conductor surface and the environment.

The recurrence formula for the calculation of the temperature on the conductor insulation surface for natural convection can be determined with heat balance equation (8) and has the form

$$\Theta_{sur}^{[k+1]} = \Theta_{amb} + \left(\frac{1}{x_c}\sqrt{\frac{T_{amb}}{P}}\left(\frac{\Delta p_0'}{d_2}(1+\alpha\Theta_{sur}^{[k]}) - \pi\varepsilon C_0(T_{sur}^{[k]4} - T_{amb}^4) + A_s q_s\right)\right)^{0.8} \quad (12)$$

$$x_c = \pi\frac{0.0749}{\sqrt[4]{d_2}} \quad (13)$$

where k is an iteration number.

The calculation formula for the temperature on the conductor insulation surface for the forced convection model takes the form:

$$\Theta_{sur}^{[k+1]} = \Theta_{amb} + \left(\frac{1}{\pi\alpha_c}\left(\frac{\Delta p_0'}{d_2}(1+\alpha\Theta_{sur}^{[k]}) - \pi\varepsilon C_0\left(T_{sur}^{[k]4} - T_{amb}^4\right) + A_s q_s\right)^{0.8} \quad (14)$$

Equations (12), (14) can be solved with the method of iterations. After calculating the temperature of the conductor insulation outer surface the conductor temperature is calculated according to equation (7) and active power losses according to equation (6).

Suggested mathematical model has been successfully verified in comparison with Std. IEEE 738 [5] in the previous paper [8] for numerical experiment with bare overhead conductors.

III. Simulation and Results

The designed generalized approach to analyze temperature and active power losses in overhead conductors is implemented as calculation software. The advantage of the software is the possibility of carrying out calculations both for insulation-covered conductors and bare conductors. We completed a comparative analysis of the calculation of the insulation-covered conductor SAX-120 with the calculation of bare conductor AS-120/19 and we calculated the SAX-120 conductor without insulation to study the insulation effect for heat and power losses in the conductor.

The conductor parameters and weather conditions of carrying out numerical experiments are presented in Table 1. The calculations results of temperature and active power losses are presented in Fig. 2 and Fig. 3. Calculations of the temperature and active power losses in the overhead conductors are carried out according to equations (7), (6).

One can see in Fig. 2 and Fig. 3 that temperature and active power loss at the same current load in the SAX-120 overhead insulation-covered conductor is always higher than in the AS-120 bare conductor. This dependence is due to the difference in SAX-120 and AS-120/19 resistivity conductors and the coefficients of blackbody degree and absorption capacity of the conductors (Table 1). SAX-120 conductor is made from an alloy with higher resistivity than the material of AS-120/19 conductor.

The study of insulation role in the overhead conductors' thermal processes is of great interest. Temperature and active power losses changes of SAX-120 conductor without insulation are presented in Fig. 2 and Fig. 3. The consequence of insulation removed from the SAX-120 conductor is a change in the external conductor radius (from 8.75 mm to 6.4 mm). Changing the conductor radius and the insulation properties influence the thermal course in the conductor. It is necessary to consider the differences between the coefficients of conductor surface blackbody. For insulation the coefficient is 0.8. For the current-carrying conductor material it is 0.6. We differ conductors in solar radiation absorptivity (Table 1). For SAX-120 conductors with insulation it is A_s = 0.9. For SAX-120 conductors without insulation it is A_s = 0.6. Dependences presented in Fig. 2 and Fig. 3 prove the complex insulation influence. When there are small load currents values then SAX-120 conductor with insulation temperature is higher (Fig. 2). When there are larger load currents values we observe temperature rise of SAX-120 conductor without insulation. The active power losses results (Fig. 3) are similar, but they are expressed less strongly than with temperature. One compared dependencies of AS-120/19 conductor and SAX-120 conductor without insulation. Due to the greater resistance (Table 1) the temperature and the active power losses (Fig. 2, Fig. 3) of SAX-120 conductor without insulation exceed the temperature and power losses of AS-120/19 conductor.

One can note strong insulation influence on the conductor temperature and active power losses when studying the insulation. The presence of insulation can reduce active power losses and overhead conductor temperature at high current loads.

TABLE I. Calculation Terms

Name and designation of parameters	The numerical values
Chase resistance of SAX-120 conductor at 20 ℃, R_0 Ohm/km	0.288
Chase resistance of AS-120/19 conductor at 20 ℃, R_0 Ohm/km	0.249
AS-120/19 conductor core radius, r_1 mm	7.6
SAX-120 conductor core radius, r_1 mm	6.4
SAX-120 outer conductor radius, r_2 mm	8.75
Resistance temperature coefficient α, ℃$^{-1}$	0.00403
AS-120/19 conductor surface blackbody degree, ε	0.6
AS-120/19 conductor surface absorption capacity for solar radiation, A_s	0.6
SAX-120 conductor surface absorption capacity for solar radiation, A_s	0.9
Air temperature Θ_{amb}, ℃	1.7
Atmospheric pressure P, Pa	100000
Wind speed v, m/s	1
Wind angle attack coefficient k_v	0.5
Direct solar radiation flux density on the surface perpendicular to the sun's rays $q_{s.dir}$, W/m^2	500
Flux density of diffuse solar radiation $q_{s.diff}$, W/m^2	100
Angle of the sun relative to the conductor axis, φ_s	π/4
Shading coefficient, k_{sh}	0.6

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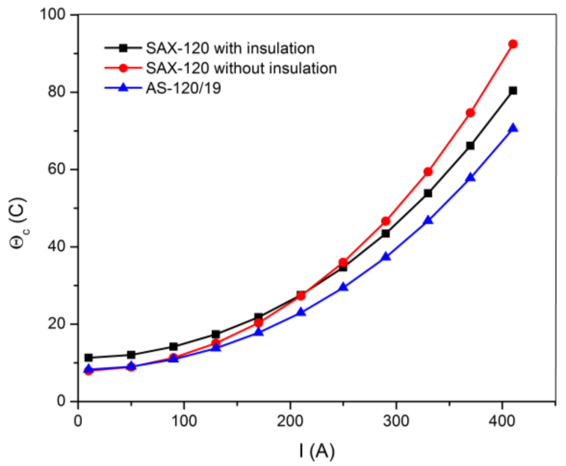

Figure 2. Current dependences for temperature of SAX-120 overhead insulation-covered conductor, SAX-120 conductor without insulation and AS-120/19 bare overhead conductor.

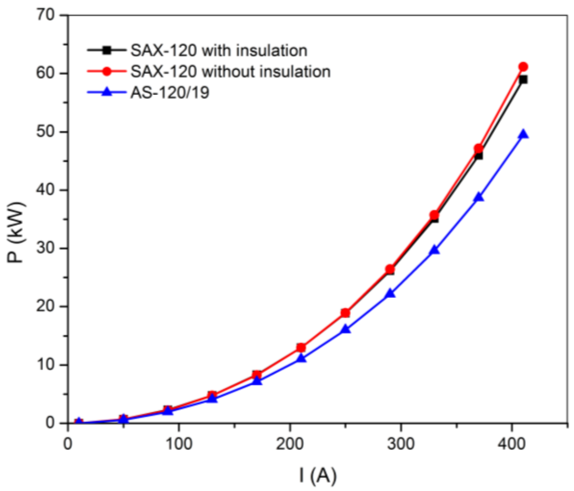

Figure 3. Dependences of active power losses from current for SAX-120 insulation-covered conductor, SAX-120 conductor without insulation and AS-120/19 bare overhead conductor.

The difference in the values in temperature and active power losses in relative terms is shown in Fig.4 and Fig.5.

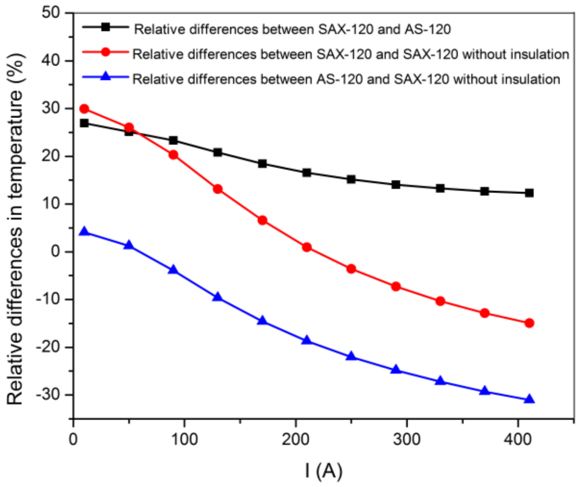

Figure 4. The relative difference between the temperatures of SAX-120 conductor with insulation, SAX-120 conductor without insulation and AS-120/19 bare conductor.

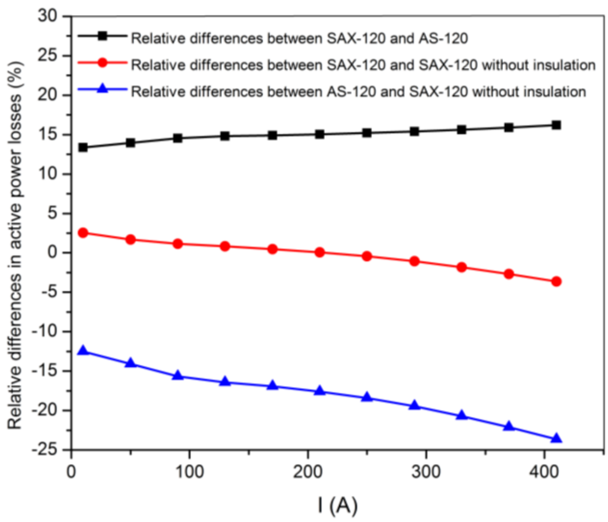

Figure 5. The relative difference of active power losses between SAX-120 conductors with insulation, SAX-120 conductors without insulation and AS-120/19 bare conductor.

The increasing tendency of temperature and active power losses differences in the insulation-covered conductors and bare conductors is explained with the conductor materials resistance temperature dependence. When the load current increases the conductor temperature also increases. The resistances difference of insulation-covered conductors and bare conductors does not remain constant, but increases with increasing current.

IV. Conclusion

The generalized mathematical model allows the calculation of temperature and active power losses in the overhead conductor power lines. A distinctive feature of this model is the ability to calculate as insulation-covered conductors as bare conductors, considering the current load and weather conditions. The proposed mathematical model is easy to use, and it is an important advantage over the complexity of the development of conductor thermal calculation in a computer simulation.

With the help of the developed model we investigated the thermal behavior of AS-120/19 bare overhead conductor, SAX-120 overhead insulation-covered conductor and SAX-120 conductor without insulation. As a result, we proved that AS-120/19 bare conductor has the best cooling properties on the given current load range.

Some sides of insulation effects on thermal processes in overhead conductors of power transmission lines have been investigated. We found that the conductor insulation influenced the conductor heating greatly. With intense current loads insulation cools the overhead conductors, and as a consequence, there is active power losses reduction. On the contrary, with small current loads the insulation-covered conductor temperature exceeds the temperature of the conductor without insulation.

The results can be used at the stage of designing overhead lines and the operation of power supply systems for the reliable determination of the maximum temperature and the continuous current-carrying capacity, as well as to evaluate the conductor sag, the choice of

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measures to reduce active power losses and Smart Grid technology development.

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