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Assessment of climatic factors influence on the time to reach maximum wire temperature of overhead power lines

***Abstract**. With the growth of electricity consumption, there is an increase in electrical energy losses and a decrease in the capacity of the lines. Also, the limited capacity affects the efficiency of energy use from renewable energy sources. Traditional and innovative methods are used to solve the existing problem. One of the methods is to increase the capacity taking into account climatic factors. This method is based on the heat balance equation. At present, dynamic thermal assessment of lines is widely used, as it allows determining more accurately the ampacities as compared with steady currents. In studies to determine continuous ampacities, it is necessary to take into account the inertia of the thermal process, which allows transmitting currents greater than the continuous ampacities. The studies to determine the time to reach maximum permissible temperature of the wire is performed in this work, and the influence of the ambient temperature, wind speed and its direction relative to the axis of the line on this time is revealed. The method of dynamic thermal assessment of lines based on the analytical solution of the heat balance equation in the transient mode of air lines operation on the basis of the least squares method is used in the research.*

Streszczenie.** Wraz ze wzrostem zużycia energii elektrycznej następuje wzrost strat energii elektrycznej i spadek przepustowości linii. Ograniczona wydajność wpływa również na efektywność wykorzystania energii ze źródeł odnawialnych. W celu rozwiązania istniejącego problemu stosuje się tradycyjne i innowacyjne metody. Jedną z metod jest zwiększenie wydajności z uwzględnieniem czynników klimatycznych. Ta metoda oparta jest na równaniu bilansu cieplnego. Obecnie szeroko stosowana jest dynamiczna ocena termiczna linii, ponieważ pozwala ona na dokładniejsze wyznaczanie wartości prądu w porównaniu ze stałymi prądami. W badaniach mających na celu określenie ciągłych prądów należy wziąć pod uwagę bezwładność procesu termicznego, która umożliwia przekazywanie prądów większych niż prądy ciągłe. W pracy tej prowadzone są badania mające na celu określenie czasu do osiągnięcia maksymalnej dopuszczalnej temperatury drutu oraz ujawnienie wpływu temperatury otoczenia, prędkości wiatru i jego kierunku względem osi linii. W badaniach wykorzystano metodę dynamicznej oceny termicznej linii opartą na rozwiązaniu analitycznym równania bilansu cieplnego w trybie przejściowym działania linii powietrznych na podstawie metody najmniejszych kwadratów. **Analiza wpływu czynników klimatycznych na czas osiągania maksymalnej temperatury przewodów linii napowietrznej

Keywords: transient thermal modes; heat balance equation; overhead power lines; wire temperature.
Słowa kluczowe: przejściowe tryby termiczne; równanie bilansu cieplnego; napowietrzne linie energetyczne; temperatura drutu.

Introduction

Due to the constantly growing demand for electrical energy, power lines are often operated in the maximum permissible mode [1-2]. In addition, recently there has been an increase in the share of electric power from renewable energy sources. Since there is a decentralization of power generation, power flows from one area to another increase, and this leads to excess load for the line. For the line load decrease, and therefore, efficiency increase and accident-free operation, it is necessary to reconstruct existing lines or build new lines, but these activities require significant investment and are time-consuming. To increase the capacity with the lowest capital expenditures, it is preferable to use methods based on the control of climatic factors [3].

To determine the capacity limit of overhead power lines taking into account climatic factors, methods based on solving the heat balance equation under the steady-state conditions are usually used [4-6]. The worst-case conditions for cooling the wires of the lines are considered in this assessment [8–10]. This approach is traditional. Modern approaches are based on methods for solving the heat balance equation in the transient thermal mode of line operation. Actual values of online monitoring, such as conductor temperature, current flow and weather conditions are used for calculations in dynamic thermal assessment. Taking into account all operating conditions and climatic factors continuous ampacity, the temperature of the wire, if it can not be measured, the loss of electrical energy can be determined more accurately [11-13].

When using the methods of dynamic thermal assessment of overhead lines, the inertia of the temperature change of the wire can be observed. This physical phenomenon can allow greater continuous ampacity of the line, which in turn permits not to switch off short-term overloads of the lines. In this work, a numerical experiment is performed to determine the time to reach maximum permissible wire temperature when climatic factors change..

Mathematical model

Deployment of systems for direct monitoring of overhead power lines parameters under certain conditions is challenging. Therefore, to control the temperature of both isolated and non-isolated wires in real time, mathematical models are used that take into account operating conditions and climatic factors. The mathematical model is based on the equation of heat balance in transient thermal mode. This equation can take the following form for an insulated wire [14]:

$$\begin{aligned}\Delta P_0\left(1+\alpha\Theta_c\right) &= C_{eq}\frac{d\Theta_c}{dt}+ \\ &+d_w\Big[\pi\alpha_f\left(\Theta_s-\Theta_{amb}\right)+ \\ &+\pi\varepsilon_w C_0\left(T_s^4-T_{amb}^4\right)-A_s q_{sol}\Big]\end{aligned} \tag{1}$$

where: $\Delta P_0 = I^2 r_0$ is the real power loss in the wire per unit length at Θ_c = 0°C, I is the current in the wire, r_0 is the active resistance per unit length of the wire at Θ_c = 0°C; α is the temperature coefficient of resistance; Θ_c is the temperature of a conducting core; C_{eq} is the equivalent heat capacity of the wire per unit length; d_w is the wire diameter; α_f is the heat transfer coefficient due to forced convection; Θ_s and Θ_{amb} are the temperature of the wire surface and the ambient temperature, respectively in °C; T_s and T_{amb} are the same in K (absolute temperatures); ε_s is the emissivity factor of the wire surface for infrared radiation; C_0=5,67·10^{-8}W/(m^2·K^4) is the constant of blackbody radiation; A_s is the absorptivity of the wire surface for solar radiation; q_{sol} is the flux density of solar radiation on the wire.

Since there is a significant temperature gradient in the insulation, in the general case the heating process is described by a partial differential equation. In order to make calculations it is appropriate to pass on from the partial differential equation to the ordinary differential equation (2). For the transition, we apply an approximate method, which is based on the introduction of the equivalent heat capacity concept. Also, the regular mode method is used to establish the relationship between $\Theta_{amb}(t)$ and $\Theta_c(t)$. To bring the heat balance equation in a transient mode of wire operation to an approximate form, the least squares method is used, which allows lowering the temperature degree to the second. As a result, (1) takes the form:

$$\frac{d\Theta_c}{dt} = A_1\Theta_c^2 + A_2\Theta_c + A_3 \tag{2}$$

The calculation expressions for the coefficients A_1, A_2, A_3 are defined in [13].

The solution of equation (2) has the following form:

$$\Theta_c(t) = \Theta_2 + \frac{\Theta_1 - \Theta_2}{1 - \Theta' e^{-t/T_n}} \tag{3}$$

$$T_n = -\frac{1}{A_1(\Theta_1 - \Theta_2)} \tag{4}$$

$$\Theta' = \frac{\Theta_0 - \Theta_1}{\Theta_0 - \Theta_2}, \tag{5}$$

where Θ_1 , Θ_2 are the roots of the equation, which are real and different, and Θ_0 is the initial temperature.

The inverse function (3) is used to determine the time to reach the continuous permissible temperature (90ºC):

$$t_{ad} = -\ln\left(\frac{1}{\Theta'} \cdot \frac{\Theta_{ad} - \Theta_1}{\Theta_{ad} - \Theta_2}\right) T_n \tag{6}$$

Numerical simulation

Studies on the influence of operating conditions and climatic factors on the time the wire reaches the continuous permissible temperature will be performed for the insulated wire SAX 50 (Fig. 1) [15] with the technical characteristics specified in table 1. Insulated wires are of the greatest interest, as they have insulation, which has a certain effect on the heating and cooling process, as well as undeniable advantages, such as reduced overhead power line dimension, high electrical safety, high operational reliability, and others.

Fig.1. Structure of SAX-50 wire

When conducting a numerical study, all the parameters but one are taken constant. Let us consider the first case where the ambient temperature changes from -10°C to 40°C. In this case the current is 299 A, the wind attack angle is 1, the wind speed is 1 m/s. Figure 2 shows the curves of the insulated wire heating. In this figure the wire is seen to be for more than an hour in the range of temperatures from -10°C to 0°C. A further increase in the ambient temperature will limit the operating time of the line with a specified current. Thus, at 10°C, the time for the wire to reach the continuous permissible temperature is 56.23 minutes. At 40°C, the time is 8.91 minutes, the continuous ampacity for these weather conditions is 207 A, which is 92 A or 30.77% less than the cut-off current (table. 2). Since the temperature change does not occur instantaneously (the process has a large inertia), there is enough time for a dispatching control office to make a decision.

Table 1. Design parameters for SAX-50 wire

Name and designation of the parameter	Numerical value
Emissivity coefficient for the surface of the wire ε_s	0.8
Radius of the wire R	0.00635 m
Radius of the conducting core r	0.004 m
Linear resistivity at 0°C r_0	0.000663 Ohm/m
Premissible wire temperature Θ_{ad}	90 ºC
Specific thermal resistance of insulation, σ_{ins}	2.67, ºC·m/W
Specific heat capacity of the core, C_c	920, J/kg·ºC
Specific heat capacity of the core insulation, C_{ins}	3750, J/kg·ºC
Density of aluminum, d_{Al}	2700, kg/m^3
Density of cross-linked polyethylene, p_{xlpe}	920, kg/m^3

Table 2. Continuous ampacity and time to reach the wire temperature of 90ºC at different ambient temperatures

Ambient temperature (ºC)	Continuous ampacity (A)	Time to reach the wire temperature of 90°C (min.)
-10	340	more than 60
0	317	more than 60
10	299	56.23
20	267	19.57
30	238	12.82
40	207	8.91

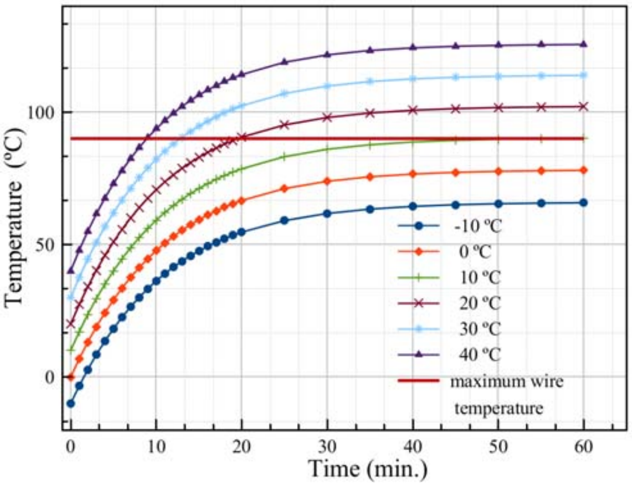

Fig.2. Dependence of wires SAX 50 heating on the ambient air temperature

The next important parameter of the environment, having a significant impact on the cooling of the wire, and, therefore, on the capacity and heating time of the wire up to a long permissible temperature, is the wind speed and its direction relative to the axis of the wire. For a more detailed study of the effect of wind, the wind parameters, such as wind speed and wind attack angle, were considered separately. In the first case, wind attack angle (kv) varied from 1 to 0 in increments of 0.2, the current was 299 A, the ambient temperature was 10°C, the wind speed was 1 m/s. The heating curves are shown in Fig. 3. Analyzing the obtained data (Fig. 3, table 3) it is seen that the temperature of the wire at a time of 60 minutes at kv= 1 and kv=0 differs by a factor of 3.33, the time of the wire to reach 90°C differs by a factor of 5.18, and the continuous ampacity differs by a factor of 2.43. A significant change in time requires an accurate determination of the wind direction relative to all segments of the line. Having determined the wind direction for all segments, it is necessary to select the segment with the lowest wind attack angle and to provide further control relative to it. It can also be seen that the change in the time to reach the maximum permissible temperature when changing the wind attack angle occurs exponentially.

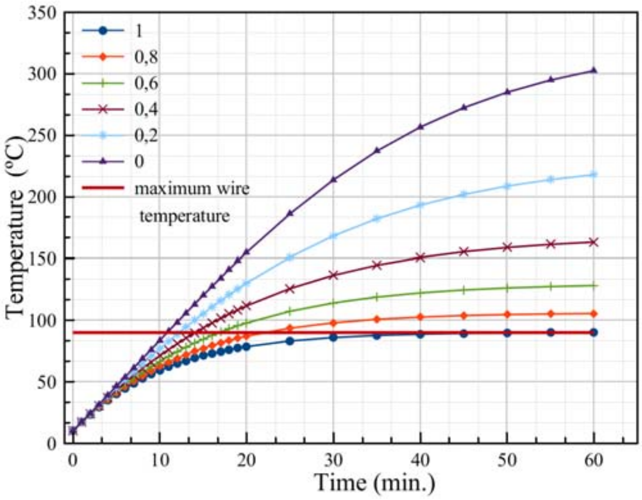

Fig.3. Dependence of wires SAX 50 heating on the wind attack angle

Table 3. Continuous ampacity and time to reach the wire temperature of 90ºC under the wind attack angle change

Wind attack angle	Continuous ampacity (A)	Time to reach the wire temperature of 90°C (min.)
1	299	56.23
0.8	267	22.004
0.6	240	16.846
0.4	208	14.073
0.2	171	12.222
0.1	123	10.855

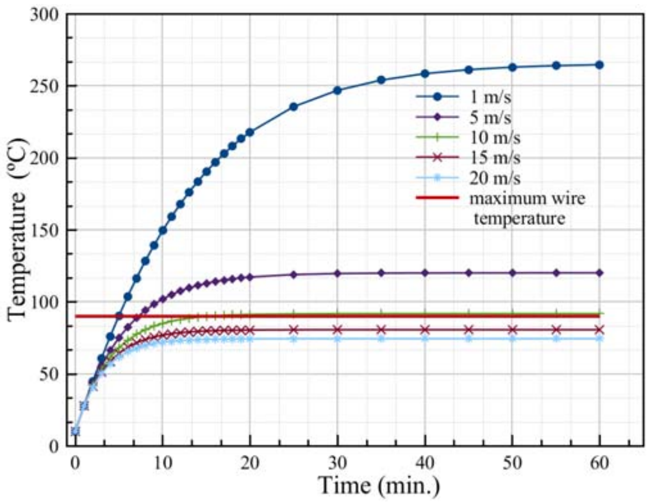

Fig.4. Dependence of wires SAX 50 heating on the wind speed

Table 4. Continuous ampacity and time to reach the wire temperature of 90ºC under the wind speed change

Wind speed (m/s)	Time to reach the wire temperature of 90°C (min.)
1	4.97
5	7.209
10	15.181
15	more than 60
20	more than 60

Let us consider the effect of wind speed on the time when the wire reaches a long-term permissible temperature (Fig. 4). The numerical experiment was conducted with the following parameters: the current was 450 A, the ambient temperature was 10°C, the wind attack angle was kv= 1, the wind speed took the values between 1 m/s to 20 m/s. At the wind speed of 15-20 m/s the lines with the specified load can operate continuously. As the wind speed decreases, the time reduces. This is explained by the fact that increasing the wind speed improves cooling conditions. The wind speed increases from 10 m/s to 15 m/s, and the time changes significantly, as it is shown in table 4.

Conclusion

Safe, trouble-free and efficient operation of an electric power grid is a priority focus area. In order to improve the safety and efficiency of the system, great attention should be paid to power lines. The efficiency of the lines is estimated by such indicators as the loss of electrical energy and capacity. These parameters are greatly influenced by weather conditions. Methods based on the solution of the heat balance equation in a transient thermal mode are used to coordinate loads on the line.

The method of dynamic thermal assessment of lines used in this work allows us to determine the maximum temperature of the wire, the maximum continuous ampacity (flow time is more than 60 minutes), and the loss of electrical energy during the thermal transients, as well as the time the conductor reaches the maximum long-term permissible temperature. The calculated time will allow us to be more precise in forecasting the transmission of electrical energy.

The results obtained in the work show that the dynamic thermal rating allows transmitting currents greater than the permissible ones. For example, at an air temperature of 40°C, a current of 299A (33% greater than the continuous ampacity under the specified weather conditions) can flow for 8.91 minutes without exceeding the thermal limit, which will allow the operating personnel to perform switches without loss of power supply to consumers.

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