Mode and climatic factors effect on energy losses in transient heat modes of transmission lines

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Abstract. Electrical energy losses increase in modern grids. The losses are connected with an increase in consumption. Existing models of electric power losses estimation considering climatic factors do not allow estimating the cable temperature in real time. Considering weather and mode factors in real time allows to meet effectively and safely the consumer’s needs to minimize energy losses during transmission, to use electric power equipment effectively. These factors increase an interest in the evaluation of the dynamic thermal mode of overhead transmission lines conductors. The article discusses an approximate analytic solution of the heat balance equation in the transient operation mode of overhead lines based on the least squares method. The accuracy of the results obtained is comparable with the results of solving the heat balance equation of transient thermal mode with the Runge–Kutta method. The analysis of mode and climatic factors effect on the cable temperature in a dynamic thermal mode is presented. The calculation of the maximum permissible current for variation of weather conditions is made. The average electric energy losses during the transient process are calculated with the change of wind, air temperature and solar radiation. The parameters having the greatest effect on the transmission capacity are identified. Keywords – transient thermal modes; heat balance equation; overhead power lines; the conductor temperature; temperature dependence of resistance; power losses.

1. Introduction

Electricity consumption is constantly growing in the world [1, 2]. There is made systematic introduction of new generating capacity to reduce electricity deficit. There is a problem of insufficient capacity of transmission lines in economically developed areas in the maximum load consumption hours. With current increasing there is an increase of energy losses. To increase the transmission capacity and to reduce the losses made the construction of new lines is developed. The event is financially costly and time-consuming to be implemented. One solution to the problem is the usage of transmission lines dynamic thermal mode assessment. This method makes possible to increase the capacity of electric power systems equipment. [3–6].

When operating the power system to prevent malfunction associated with the overheating of the power lines when there is an increase in transmission power, static thermal models were developed [7–9]. The models are used to estimate the conductors’ temperature and maximum transmission capacity of power lines when designing and operation. The heat absorbed with a conductor includes: the heat from the flow of current and heat from the sun-light conductor surface (Figure 1). Heat transfer from the conductor into the environment is by convection \(Q_c\) and the thermal radiation \(Q_r\) [9, 10]. Static
models of the thermal mode of overhead lines conductors produce evaluation of conductor heating and maximum current based on the worst cooling conditions [11–12].

When calculating the permissible load of lines in a stationary mode, the permissible temperature of an aluminum conductor with a steel core is assumed equal to 70 °C. Ambient temperatures can vary from 20°C to 40°C. As a general rule, the average temperature for the hottest month is taken for the calculations. The wind speed is 0.2 m/s (calm). Solar radiation power is considered 1000 W/m². This power corresponds the most to radiation at noon. Real weather conditions when there is operation of power lines differ significantly from the worst cooling conditions the most time of the year. The fact consideration makes possible to increase the line capacity. [1, 13, 14].

Figure 1. Links between incoming and outgoing heat energy in the conductor.

According to the documents in the electricity a consumer should receive a high quality electricity and in full. This requirement shall not be violated, despite the emerging emergency situations in the system. In case of accidents, some of the lines are disconnected. Line disconnection occurs due to the conductor excessive heating. This fact makes necessary to use thermal dynamical state of the conductors of overhead power lines. This method will allow increasing the capacity of existing lines without modernization in compliance with all safety requirements. [15, 16]. The conductor temperature is monitored with direct or indirect temperature control devices. Indirect control devices are ambient temperature recording devices in real time, wind speed and direction devices, solar heating, and the degree of slack arrow tension of the conductors [16]. The findings are transferred to the calculation systems.

2. Mathematical Simulation

When there is no possibility of installing devices of the conductor temperature direct control one must use mathematical models that consider the mode-climatic factors and calculate the conductor temperature in real time. The mathematical model should be based on a heat balance equation of the conductor in the transient temperature conditions [9]:

\[
Q_c + Q_r = A_c (T - T_{amb})^k + A_r (T^4 - T_{amb}^4)
\]

\[
\Delta P_0 (1 + \alpha \Theta) = C \frac{d \Theta}{dt} + d_{cn} \left[ \pi \alpha_{forc} (\Theta - \Theta_{amb}) + \pi \varepsilon \sigma C_0 (T^4 - T_{amb}^4) - A_s q_{sol} \right]
\]

where \( T \) and \( T_{amb} \) are absolute temperature of the conductor and ambient temperature; \( A_c \) and \( A_r \) are constant coefficients; \( k \) is exponent that depends on convection conditions; \( \alpha_{forc} \) is heat transfer coefficient of forced convection; \( \varepsilon \) is conductor surface emissivity for the infrared radiation; \( C_0 = 5.67 \times 10^{-8} \) W/(m²·K⁴) is constant blackbody radiation; \( \Theta \) and \( \Theta_{amb} \) are temperature of conductors, respectively, and ambient temperature in °C; \( T \) and \( T_{amb} \) are the same but in K (absolute temperatures); \( A_s \) is absorptivity of the conductor surface for the solar radiation; \( q_{sol} \) is solar radiation flux density on the conductor; \( d_{cn} \) is the conductor diameter; \( \Delta P_0 \) is active power losses in the conductor per unit length at \( \Theta = 0 \) °C; \( I \) is current in the cable; \( r_0 \) is per unit length resistance of the cable at \( \Theta = 0 \) °C; \( \alpha \) is temperature coefficient of resistance.
The heat capacity per unit length $C$ and convection heat transfer coefficient $\alpha_{forc}$ are defined with [9, 15]:

$$
C = C_{sp,Al}M_{Al} + C_{sp,st}M_{st}
$$

(3)

$$
\alpha_{forc} = 0.044 \frac{kV(P_{amb}V^{0.6})}{(\frac{P_{amb}V}{Cn})^{0.4}}
$$

(4)

where $k$ is coefficient characterizing the wind attack angle; $P$ is atmospheric pressure; $v$ is wind speed; $C_{sp,Al}, C_{sp,st}$ are specific heat capacity mass of aluminum and steel; $M_{Al}, M_{st}$ is weight of aluminum and the steel portion of the conductor per unit length.

On the basis of the method of least squares, equation (2) can be transformed to the form:

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

(5)

Coefficients $A_1, A_2, A_3$ are given in [9, 15]. Equation (5) can have different solutions depending on the type of equation roots

$$
A_1\Theta^2 + A_2\Theta + A_3 = 0
$$

(6)

The case of real roots of equation (6) is of practical interest

$$
\Theta_{1,2} = \frac{-A_2 \pm \sqrt{A_2^2 - 4A_1A_3}}{2A_1}
$$

(7)

On the basis of (7) solution (5) can be written as:

$$
\Theta(t) = \Theta_2 + \frac{\Theta_1 - \Theta_2}{1 - \Theta_0^2} - \frac{\Theta_0 - \Theta_1}{1 - \Theta_0^2} T_n
$$

(8)

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

(9)

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

(10)

where $\Theta_0$ is conductor temperature at time $t=0$ (initial condition).

Real roots (7) of equation (6) take the values $\Theta_1 > \Theta_2$. Solution (8) is valid only when $\Theta_0 > \Theta_2$. Calculations show that the temperature $\Theta_2$ has strongly negative values not exceeding the ambient temperature.

Parameter $T_n$ determines the time scale (inertia) of the process. This parameter is equivalent to the time constant in standard exponential function. However, the quantitative meaning of this parameter is more complicated.

The average temperature $\Theta_{av}$ and power losses $\Delta W$ in the three-phase line of length $l$ during the time $T_p$ is determined with the equations

$$
\Theta_{av} = \Theta_1 + (\Theta_1 - \Theta_2) \frac{T_n}{T_p} \ln \left( \frac{1 - \Theta_0^2}{1 - \Theta'} \right)
$$

(11)
\[
\Delta W = 3\Delta I \left[ l + a \Theta_{av} \right] I \rho l
\]  

(12)

3. Results of numerical simulation
The developed approach for the analysis of transient thermal modes of overhead transmission lines is implemented in the form of an algorithm and a calculation program. Numerical simulating was conducted for the conductor mark ACSR Lynx 175 mm². The conductor parameters and conditions of the numerical experiment are presented in Table 1.

| Table 1. Conditions adopted in the calculation of the thermal process in the conductor acsr lynx 175 mm². |
|---------------------------------------------------------------|
| The parameter name and designation | Numeric value |
|-----------------------------------|---------------|
| The conductor diameter \( d_{cn} \) | 0.01953 m |
| Chase resistance at 0°C \( r_0 \) | 0.0001440 Ohm/m |
| Temperature coefficient of resistance \( \alpha \) | 0.0043 °C⁻¹ |
| Specific heat capacity of aluminum \( C_{sp,Al} \) | 922 J/(kg·°C) |
| Specific heat capacity of steel \( C_{sp,st} \) | 452 J/(kg·°C) |
| Aluminum mass per unit length \( M_{Al} \) | 0.497 kg/m |
| Steel mass per unit length \( M_{st} \) | 0.3276 kg/m |
| The emissivity of the conductor surface \( \varepsilon_{cn} \) | 0.6 |
| Absorption capacity of the conductor surface for solar radiation \( A_s \) | 0.6 |
| Atmospheric pressure \( P_{atm} \) | 100000 Pa |
| Coefficient of the wind attack angle \( k_V \) | 1 |
| Permissible conductor temperature \( \Theta_{cn} \) | 75 °C |
| The calculation period \( T_p \) | 60 min |

A model of transient temperature mode of conductors is developed. The average losses of electrical energy depending on the mode and climatic factors are calculated. The maximum permissible currents are obtained with the variation of ambient conditions.

![Figure 2. Change the temperature of ACSR Lynx cable on load current.](image-url)
Data given in Table 2 were obtained by carrying out a numerical experiment. The most interesting results are the graphs of a stationary mode with a change in any parameter. The above numerical experiment shows that the parameter $T_n$ when changing one of the parameters that affects the conductor temperature remains constant provided that the remaining parameters are not changed. Besides the possibility of determining the final temperature of transition temperature mode a proposed model allows to derive average temperature during the conductor cooling or heating. Figure 2 shows the curve of the conductor heating and cooling for a time interval 60 min and the wind speed 0.2 m/s. Current changes instantaneously from 0A till 200A, from 200A till 500A and from 500A till 0A. In practice, the current changes constantly. This change can occur in a wide range. The last fact demonstrates the need for using a dynamic thermal model of conductors.

![Figure 2. The curve of the conductor heating and cooling](image)

**Figure 3.** Links between the permissible current load and the ambient temperature.

**Table 2.** A slightly more complex table with a narrow caption.

| The wind speed | Solar radiation | Current power | Parameter $T_n$ (min) | Temperature of stationary mode | Initial temperature of the conductor, °C | Average temperature during transient process |
|----------------|----------------|--------------|-----------------------|-------------------------------|----------------------------------------|---------------------------------------------|
| 0.2            | 0              | 0→200        | 14.233                | 23.642                        | 15                                     | 21.701                                      |
| 0.2            | 0              | 200→519      | 14.233                | 80                            | 15                                     | 70.109                                      |
| 0.2            | 0              | 519→0        | 14.233                | 15                            | 15                                     | 29.371                                      |
| 5              | 0              | 0→200        | 2.799                 | 16.64                         | 15                                     | 16.566                                      |
| 5              | 0              | 200→519      | 2.799                 | 26.478                        | 15                                     | 26.477                                      |
| 5              | 0              | 519→0        | 2.799                 | 15                            | 26.478                                 | 15.509                                      |
| 15             | 0              | 0→200        | 1.462                 | 15.868                        | 15                                     | 15.847                                      |
| 15             | 0              | 200→519      | 1.462                 | 20.978                        | 15                                     | 20.853                                      |
| 15             | 0              | 519→0        | 1.462                 | 15                            | 20.978                                 | 15.137                                      |
| 0.2→5          | 0              | 519          | 2.799                 | 26.478                        | 80                                     | 26.255                                      |
| 5→15           | 0              | 519          | 1.462                 | 20.978                        | 26.478                                 | 21.112                                      |
| 15→0.2         | 0              | 519          | 14.233                | 80                            | 20.978                                 | 66.117                                      |
| 0.2→15         | 0              | 519          | 1.462                 | 20.978                        | 80                                     | 22.408                                      |
| 0.2            | 500            | 100          | 0                     | 13.737                        | 25.09                                  | 22.891                                      |
| 0.2            | 250            | 50           | 0                     | 13.979                        | 20.065                                 | 18.954                                      |
Figure 3 - Figure 8 show the effect of weather conditions on the maximum line current and average energy losses during the transition process. One considers the effect of climatic factors on the permissible current in detail. An analysis is started with the ambient temperature. The parameter during the day can be varied over a wide range.

Effect of ambient temperature (Figure 3) on the load current of the conductors shall be considered provided that the conductor temperature does not exceed 70 °C, and wind speed is 0.2 m/s. Solar light intensity is set equal to 0 W/m².

Figure 3 shows the necessity to reduce the current if other parameters remain unchanged. Based on the obtained dependence of the current on the air temperature, it can be seen that at a temperature - 40°C the current exceeds 1.5 times the current at 20 °C. The temperature of 20°C is accepted as the base. When the temperature is 40 °C the current is less than the basic one to 95A. Thus, the improvement in the capacity of transmission lines and its reliability is possible when considering the actual ambient temperature.

![Figure 4. Dependence of average energy losses on the ambient temperature.](image)

Figure 4 shows the dependence of electric energy losses on the ambient temperature. At the initial time period the conductor temperature was equal to ambient temperature of 15 °C. Later the current was changed to the maximum value. The maximum is to be taken in such a way and the conductor temperature does not exceed 70 °C. The estimated time was 60 min, and the length of the line was assumed to be 50 km. Wind speed is 0.2 m/s, the solar radiation is not considered. Figure 4 shows that losses are reduced with an increase in the ambient temperature. It is due to the fact that when the ambient temperature increases the current flowing through the conductor must be reduced, so that the conductor temperature would not exceed 70 °C. When the temperature is -40 °C the current is significantly higher than the current is at +40 °C. When calculating the average energy losses, the square of the current is taken into account. Therefore, the graph has the same form as the maximum permissible current.

To calculate the maximum current load in the Electrical Installation Code (EIC), it is proposed to use coefficients that correspond to a certain temperature. Temperatures indicated in the EIC range from -5°C till +50°C (Table 3). Time sampling is in increments of 5°C. The disadvantage of this change is that it is not possible to assess the permissible current in real time due to the fact that in reality the ambient temperature is not an integer. Minimum EIC temperature is limited to -5°C, although the Siberian, Ural and Far Eastern federal regions have average temperature of the winter months is -9 and below. This fact is also not in favor of using the proposed EIC factors when
calculating the permissible current and temperature of the conductor. When temperature is -40°C difference between the currents is 103.333 A, and it is 17.76%, i.e. the lines are under loaded. It is due to the fact that as the temperature decreases, the cooling conditions improve. Within the temperature range from -5°C till +40°C differences are no more than 4%. When temperature is +50 differences are 25A or 9.59%. The analysis showed that the proposed method for calculating is preferable when calculating the permissible current in real mode. As in the initial data temperatures may take any value. Also the fact is in favor of this method that it is possible to produce a solution at low temperatures over a wide range.

Table 3. A slightly more complex table with a narrow caption.

| Ambient temperature, °C | Correction coefficients for currents according to EIC | The current calculated with the coefficients of EIC, A | The current calculated on the basis of the proposed model, A | Difference of currents, A | Difference, % |
|------------------------|-----------------------------------------------------|-----------------------------------------------------|-----------------------------------------------------|------------------------|--------------|
| -40                    | 1.24                                                | 478.64                                              | 581.973                                              | 103.333                | 17.75563     |
| -35                    | 1.24                                                | 478.64                                              | 569.346                                              | 90.706                 | 15.93161     |
| -30                    | 1.24                                                | 478.64                                              | 556.456                                              | 77.816                 | 13.98421     |
| -25                    | 1.24                                                | 478.64                                              | 543.267                                              | 64.627                 | 11.89599     |
| -20                    | 1.24                                                | 478.64                                              | 529.742                                              | 51.102                 | 9646583      |
| -15                    | 1.24                                                | 478.64                                              | 515.837                                              | 71.805                 | 7210999      |
| -10                    | 1.24                                                | 478.64                                              | 501.505                                              | 22.135                 | 4.59277      |
| -5                     | 1.24                                                | 478.64                                              | 486.691                                              | 8.051                  | 1.654232     |
| 0                      | 1.2                                                 | 463.2                                               | 471.334                                              | 8.134                  | 1.72574      |
| 5                      | 1.17                                                | 451.62                                              | 455.361                                              | 3.741                  | 0.821546     |
| 10                     | 1.13                                                | 436.18                                              | 438.687                                              | 2.507                  | 0.571478     |
| 15                     | 1.09                                                | 420.74                                              | 421.213                                              | 0.473                  | 0.112295     |
| 20                     | 104                                                 | 401.44                                              | 401.813                                              | 0.373                  | 0.092829     |
| 25                     | 1                                                   | 386                                                 | 386                                                  | 0                      | 0            |
| 30                     | 0.95                                                | 366.7                                               | 362.591                                              | -4.109                 | -1.13323     |
| 35                     | 0.9                                                 | 347.4                                               | 340.319                                              | -7.081                 | -2.08069     |
| 40                     | 0.85                                                | 328.1                                               | 316.179                                              | -11.921                | -3.77033     |
| 45                     | 0.8                                                 | 308.8                                               | 289.677                                              | -19.193                | -6.60149     |
| 50                     | 0.74                                                | 285.64                                              | 260.64                                              | -25                    | -9.59177     |

Figure 5. Links between permissible current load and solar radiation.
An important factor affecting the capacity of lines is solar radiation. When absorbing solar radiation there is additional conductor heating. Limited allowable current is determined under the condition that the conductor temperature does not exceed temperature of 70 °C, and wind speed is not more than 0.2 m/s, ambient temperature is 15°C. The ratio of the light intensity and current carrying capacity of the conductors is shown in Figure 5. When the solar radiation is changed by 500 W/m the current change is 43 А. This feature makes possible to increase the load on the line in winter with the evening maximum of consumption. When the conductor heating is increased with solar radiation, the maximum current is reduced. This fact leads to reduction in both energy losses (Figure 6) proportional to the square of the current.

Figure 6. Dependence of average energy losses on solar radiation.

Figure 7. Links between wind speed and transmission capacity.
Figure 8. Dependence of the average losses on the wind speed.

One important parameter of the environment when calculating the permissible current and the conductor temperature is wind speed, as wind equal to ambient temperature significantly contributes to the conductor cooling. The dependence of the change in the current load on wind speed is shown in Figure 7. The minimum wind speed at calculation was assumed equal to 0.2 m/s, since there is always movement of air masses near the conductors. The wind speed value is classified as calm. The above dependence shows that an increase in wind speed leads to an increase in the permissible current. This fact is explained with the fact that increasing wind speed improves cooling conditions, and it in turn makes possible to load additionally the overhead transmission line. Figure 7 shows the wind changes from 0.2 m/s (calm) till 17.1 m/s (strong wind), as in most cases the wind speed changes in the range during the year. With an increase in wind speed from 0.2 m/s till 17.1 m/s the current is increased in 3.14 times. Current increase leads to an increase in electric power loss (Figure 8).

4. Conclusions
Thermal power lines calculations are important. Electric power losses, transmission capacity of electrical networks and sag depend on conductor temperature. In its turn the conductor temperature depends on the current load, ambient temperature, wind speed and solar radiation. Due to the fact that the active resistance of the conductor has temperature dependence, it is a nonlinear element. So it is necessary to calculate resistance based on the heat balance equations.

Mode and climatic factors continuously change over time. This fact makes relevant to the calculation of the dynamic thermal mode of the lines. Considering transient thermal modes is necessary for a fair determination of the maximum temperature of conductors. It makes possible to predict more accurately the possible maximum current load. The proposed method is an analytical solution of the heat balance equation of conductors in a transient mode allows determining both as current as electric power losses during the transit thermal process.

The difference between the maximum current value when there is no solar radiation and at 500 W/m² is 8.99%, electrical energy average losses are 17.02%. When changing conductor temperature from −40°C till +40°C difference between the currents is 46.8%, average losses are 68.9%. When the wind changes from calm to strong current difference is 68.2%, average losses are 90.3%. The presented data shows that solar radiation affects the transmission capacity in lesser extent. The next most important parameter is the ambient temperature. The wind has the biggest effect. Thus, in determining the ability to transmit more power through existing lines ambient temperature and wind should be considered.
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