Recommendations for improving the accuracy of calculations of load losses of electricity in the wires of overhead power transmission lines

A S Shchepotin, G V Shvedov and O S Musorina
National Research University «Moscow Power Engineering Institute», Russia, 111250 Moscow, Krasnokazarmennaya, 14
Cfifshchepotin94@rambler.ru

Abstract. The calculations of load losses of electricity in the wires of overhead power transmission lines in the vast majority of cases are carried out by «traditional» methods, in other words without taking into account the change in the resistance of the wires. Such calculations have significant infelicities, and the existing methods of accounting for factors affecting the temperature of the wire are complex, volumetric in calculations, and require comprehensive information about the weather, and therefore are not used in practice. Recommendations for improving the accuracy of afore-referenced calculations through the application of the method of corrective coefficients were developed in this article. The focus is on the practical application of the recommendations.

1. Introduction
The temperature effect of the flowing current and the dependence of the resistance of metals on their temperature were discovered back in the 19th century. At the same time, overhead power transmission lines are liable to environmental factors. In the aggregate the following factors have the greatest influence on a wire temperature:

- ambient temperature;
- current density flowing through the wire;
- wind speed;
- airflow direction in relation to wire;
- intensity of solar radiation [1].

Load losses in the wires of the power transmission line for the base period can be determined by the method of operational calculations [2]:

$$\Delta W = \sum_{i=1}^{n} I_i^2 \cdot R_{20} \cdot \left[1 + \alpha_t \cdot (T_{\text{wire},i} - 20)\right] \cdot \Delta t_i,$$  

where $n$ is the number of time intervals; $I_i$ is the root mean square value of the line current for the $i$-th interval, A; $R_{20}$ is the effective resistance of wire at its temperature of 20°C, ohm; $\alpha_t$ is temperature...
coefficient equal to 0.00403 for electrotechnical aluminum, 1°F; $T_{\text{wire},j}$ is the temperature of wire at the $i$-th time interval, °C; $\Delta t$ is the time interval during which $I_i$ and $T_{\text{wire},j}$ are taken constant. At the same time in [2] it is indicated if a current density lower than the economical one, that the wire temperature can be taken equal to the air temperature $T_{\text{air}}$, and in the absence of data the wire temperature is taken equal to $T_{\text{wire}} = 20 ^{\circ} \text{C}$. These assumptions may cause significant infelicities. Investigations in [3] show that due to the neglect of the actual temperature of the wire, the infelicity in calculating the losses of electricity can reach 18%, and in the source [4] mention is made of 26%.

There are a number of verified methods that allow determining the temperature of wires with accuracy sufficient for engineering calculations (for example, [5], [6] and [7] taking into account improvements in [8]). They are widely used in the so-called “dynamic estimates” of lines ([9] - [11]) and are stepwise being refined by taking into account a lot of factors, for example, sedimentary cooling and air humidity ([12], [13]). Thereat all named methods are quite computationally complex and require exhaustive information about meteorological factors for each average-out interval (usually 1 hour or 3 hours). Therefore, these methods are not used in determining annual losses of electricity. The task of simplification the accounting of factors influencing the temperature of the wires in the calculation of electricity losses was solved by the authors of this article by developing a method of correction coefficients, described in detail in [14] and [15]. Based on this method, generalized recommendations on improving the accuracy of calculations of load losses of electricity in the wires of overhead power transmission lines were compiled and proposed in this article.

2. Corrective coefficients method

Corrective coefficients method was developed by processing a large amount of statistical data on weather and load schedules. It can be considered as adaptation of the method for determining the temperature of overhead lines' wires, presented in [7] and [8], for calculating the losses of electricity for a year taking into account the influence of the flowing current and meteorological conditions. The main idea of the method of corrective coefficients is obtaining of refined value of the losses of electricity $\Delta W$ using simply multiplying the results of the calculation of losses obtained in the "traditional" calculation, $\Delta W_{\text{trad}}$ by the corrective coefficient $k$.

$$\Delta W = \Delta W_{\text{trad}} \cdot k$$

The investigations presented in [14] and [15] show that the corrective coefficient has the following general form:

$$k = \left[ (a_1 \cdot K_{1f} + a_2) \left( \frac{F}{35} \right)^{0.65} \right] \cdot j_{\text{max}}^2 + c \cdot \left( \frac{F}{35} \right)^{0.001},$$

where $a_1$, $a_2$ and $c$ are the components of the corrective coefficient, determined solely by the characteristics of the place of passage of the line; $F$ is the cross sectional area of the wire in mm$^2$; $K_{1f}$ is the load factor, determined by the formula:

$$K_{1f} = \frac{j_{\text{av}}}{j_{\text{max}}},$$

where $j_{\text{av}}$ is the average current density, A/mm$^2$; $j_{\text{max}}$ is the highest current density, A/mm$^2$.

3. Recommendations on improving the accuracy of calculations

Those calculations in which it is allowed $T_{\text{wire}} = T_{\text{air}}$ or $T_{\text{wire}} = 20^\circ \text{C}$ fall into «traditional». The second alternative is used much more often in view of its simplicity, although the results of researches presented in [12] show that its accuracy is lower than that of the first option. Using the corrective coefficients method also gives the best accuracy for the first alternative of the «traditional» calculation. But because of the great popularity, it is necessary to detail the second method.
For this reason, recommendations are proposed below to improve the accuracy of calculations load losses of electricity in the wires of overhead power transmission lines in the form of an algorithm by way of increasing infelicity.

So, it should be for more accurate results:

1. To calculate the losses of electricity $\Delta W_{\text{rad}}$ for each line of the network in question by the method of operational calculations in the «traditional» method assuming the temperature of wires $T_{\text{wire}}$ equal to the average monthly air temperature $T_{\text{air}}$. If it is impossible to determine the values of $T_{\text{air}}$ go to step five.

2. Define a corrective coefficient $k_{\text{air}}$ for each line. As indicated in [4], when taking $T_{\text{wire}} = T_{\text{air}}$, the calculation error correlates with the value of the average daily temperature difference $\Delta T_{\text{av.daily}}$ in the area under consideration. This has been observed for $k_{\text{air}}$ also, since it is built on the basis of processing infelicity statistics, which gives motive for zoning the map. The territory of Russia was divided into five regions, each of which is limited to a certain range of average daily temperature difference $\Delta T_{\text{av.daily}}$. Each region has its own corrective coefficient function. The distribution by regions is shown in table 1 and shown in figure 1.

3. Calculate the updated value of the load losses of electricity $\Delta W$ by multiplying the values $\Delta W_{\text{rad}}$ and $k_{\text{air}}$ obtained in items 1 and 2 for each line.

4. Sum the $\Delta W$ values obtained for each line in item 3 for obtaining losses in all lines of the network in question.

5. If it is impossible to determine the values of $T_{\text{air}}$ to calculate $\Delta W_{\text{rad}}$ for each line of the network in question by the method of operational calculations in the «traditional» method assuming the temperature of wires $T_{\text{wire}}$ equal to 20 °C.

6. Define a corrective coefficient $k_{20}$ for each line. An analysis performed in [10] showed that when $T_{\text{wire}} = 20 ^\circ \text{C}$, the first (left) term of sum in expression (3) correlates with the average daily temperature difference $\Delta T_{\text{av.daily}}$, and the second (right) one with the average annual temperature $T_{\text{av.an}}$. For convenience of practical application, five regions were established for each of these factors ($\Delta T_{\text{av.daily}}$ and $T_{\text{av.an}}$). The distribution by regions is shown in tables 2 and 3 and for visibility in figures 1 and 2. Accordingly, the left term of the corrective coefficient $k_{20}$ is determined according to table 2 (figure 1), and the right term according to table 3 (figure 2).

7. Calculate the updated value of the load losses of electricity $\Delta W$ by multiplying the values $\Delta W_{\text{rad}}$ and $k_{20}$ obtained in items 5 and 6 for each line.

8. Sum the $\Delta W$ values obtained for each line in item 7 for obtaining losses in all lines of the network in question.

If the power transmission line passes in several regions, it is recommended that the losses' calculation be carried out separately for each part of the line with the subsequent summation of the results.

Note that the assignment to a particular region is not final due to the inconstancy of meteorological factors. Zoning should be reviewed every 10 years, and if there are correct data on $\Delta T_{\text{av.daily}}$ and $T_{\text{av.an}}$ it is recommended to choose corrective coefficients in accordance with the ranges of these factors given in tables 2 and 3.

Color zoning of the map shown in figures 2 and 3, was carried out at 150 design points and is only an approximate reflection of the real situation. Its use is recommended in the absence of more accurate data.

Consequently, depending on what type of calculation is carried out initially, either corrective coefficients $k_{\text{air}}$ or $k_{20}$ are used. As mentioned above, the «traditional» calculation when $T_{\text{wire}} = T_{\text{air}}$ is accepted followed by refinement using $k_{\text{air}}$ allows to obtain load losses of electricity in the wires of overhead power transmission lines with a lower infelicity.
Table 1. Zoning of the map of Russia to determine the corrective coefficient $k_{air}$

| Region by $\Delta T_{av.daily}$ | City | $k_{air}$ | $\Delta T_{av.daily}$, °C |
|---------------------------------|------|----------|--------------------------|
| I                               | Vladivostok, Makhachkala, Murmansk, Petrozavodsk, St. Petersburg, Sevastopol, Sochi, etc | $[0.0020K_{lt}+0.0002] \cdot (F/35)^{0.65} \cdot \frac{\Delta T}{\Delta T_{daily}} + 1.005 \cdot (F/35)^{0.001}$ | < 6.5 |
| II                              | Arkhangelsk, Vladimir, Kaliningrad, Moscow, Nizhny Novgorod, Rostov-on-Don, Tula, Khabarovsk, etc | $[0.0025K_{lt}+0.0004] \cdot (F/35)^{0.65} \cdot \frac{\Delta T}{\Delta T_{daily}} + 1.007 \cdot (F/35)^{0.001}$ | 6.5 – 7.7 |
| III                             | Yekaterinburg, Kazan, Krasnodar, Omsk, Chelyabinsk, etc | $[0.0042K_{lt}+0.0008] \cdot (F/35)^{0.65} \cdot \frac{\Delta T}{\Delta T_{daily}} + 1.008 \cdot (F/35)^{0.001}$ | 7.8 – 9.0 |
| IV                              | Vladikavz, Grozny, Irkutsk, Krasnoyarsk, Kurgan, Yakutsk, etc | $[0.0051K_{lt}+0.0016] \cdot (F/35)^{0.65} \cdot \frac{\Delta T}{\Delta T_{daily}} + 1.016 \cdot (F/35)^{0.001}$ | 9.1 – 10.3 |
| V                               | Abakan, Chita, etc | $[0.0070K_{lt}+0.0022] \cdot (F/35)^{0.65} \cdot \frac{\Delta T}{\Delta T_{daily}} + 1.022 \cdot (F/35)^{0.001}$ | > 10.3 |

Table 2. Zoning the map to establish the first term of the corrective coefficient $k_{20}$

| Region by $\Delta T_{av.daily}$ | City | Left term $k_{20}$ | $\Delta T_{av.daily}$, °C |
|---------------------------------|------|-------------------|--------------------------|
| I                               | Vladivostok, Makhachkala, Murmansk, Petrozavodsk, St. Petersburg, Sevastopol, Sochi, etc | $[0.0020K_{lt}+0.0002] \cdot (F/35)^{0.65} \cdot \frac{\Delta T}{\Delta T_{daily}}$ | < 6.5 |
| II                              | Arkhangelsk, Vladimir, Kaliningrad, Moscow, Nizhny Novgorod, Rostov-on-Don, Tula, Khabarovsk, etc | $[0.0025K_{lt}+0.0004] \cdot (F/35)^{0.65} \cdot \frac{\Delta T}{\Delta T_{daily}}$ | 6.5 – 7.7 |
| III                             | Yekaterinburg, Kazan, Krasnodar, Omsk, Chelyabinsk, etc | $[0.0042K_{lt}+0.0008] \cdot (F/35)^{0.65} \cdot \frac{\Delta T}{\Delta T_{daily}}$ | 7.8 – 9.0 |
| IV                              | Vladikavz, Grozny, Irkutsk, Krasnoyarsk, Kurgan, Yakutsk, etc | $[0.0051K_{lt}+0.0016] \cdot (F/35)^{0.65} \cdot \frac{\Delta T}{\Delta T_{daily}}$ | 9.1 – 10.3 |
| V                               | Abakan, Chita, etc | $[0.0070K_{lt}+0.0022] \cdot (F/35)^{0.65} \cdot \frac{\Delta T}{\Delta T_{daily}}$ | > 10.3 |

Table 3. Zoning the map to establish the second term of the corrective coefficient $k_{20}$

| Region by $T_{av.an}$ | City | Right term $k_{20}$ | $T_{av.an}$, °C |
|-----------------------|------|---------------------|----------------|
| I                     | Astrakhan, Vladikavz, Krasnodar, Rostov-on-Don, Sevastopol, Sochi, etc | 0.955 $\cdot (F/35)^{0.001}$ | > 8.1 |
| II                    | Vladivostok, Vladimir, Kazan, Kaliningrad, Moscow, Nizhny Novgorod, St. Petersburg, Yaroslavl, etc | 0.930 $\cdot (F/35)^{0.001}$ | 3.1 – 8 |
| III                   | Abakan, Yekaterinburg, Krasnoyarsk, Murmansk, Novosibirsk, Omsk, Khabarovsk, Chelyabinsk, etc | 0.905 $\cdot (F/35)^{0.001}$ | -1.9 – 3.0 |
| IV                    | Anadyr, Salekhard, etc | 0.880 $\cdot (F/35)^{0.001}$ | -6.9 – 2.0 |
| V                     | Norilsk, Yakutsk, etc | 0.855 $\cdot (F/35)^{0.001}$ | < 7 |
4. Examples of calculation of losses

Consider the following combination of basic data, the same for both examples:

- the model of wire AS 240/32;
- line's angle relative to the meridian is equal to –90°;
- mixed type of load, \( K_{lf} = 0.38 \);
- \( j_{\text{max}} = 1.24 \text{ A/mm}^2 \);
- real data on weather for 2013.

Example 1. Moscow.

Losses determined by the full methodology presented in [3] are \( \Delta W_{\text{exact}} = 50812.1 \text{ kW·h/km} \). The losses calculated by the average monthly air temperature are \( \Delta W_{\text{trad}, 1} = 49691.09 \text{ kW·h/km} \). Losses calculated at 20 °C are \( \Delta W_{\text{trad}, 2} = 53697.14 \text{ kW·h/km} \).

In accordance with tables 1, 2 and 3 are determined the corrective coefficients.

\[
k_{\text{air}} = \left[ (0.0025 \cdot K_{lf} + 0.0004) \cdot \left( \frac{F_{35}}{35} \right)^{0.65} \cdot j_{\text{max}}^{2} + 1.007 \cdot \left( \frac{F_{35}}{35} \right)^{0.001} \right] = 0.007 + 1.009 = 1.016
\]

(5)

\[
k_{20} = \left[ (0.0025 \cdot K_{lf} + 0.0004) \cdot \left( \frac{F_{35}}{35} \right)^{0.65} \cdot j_{\text{max}}^{2} + 0.930 \cdot \left( \frac{F_{35}}{35} \right)^{0.001} \right] = 0.007 + 0.932 = 0.939
\]

(6)

Then the specified losses for both types of calculation are equal:

\[
\Delta W_1 = \Delta W_{\text{trad}, 1} \cdot k_{\text{air}} = 50486.15 \text{ kW·h/km}
\]

(7)

\[
\Delta W_2 = \Delta W_{\text{trad}, 2} \cdot k_{20} = 50421.61 \text{ kW·h/km}
\]

(8)

The using of the corrective coefficient in the first method reduced the calculation error from -2.2% to -0.6%, and in the second case from 5.7% to -0.8%.

Example 2. Vladikavkaz.

Losses determined by the full methodology presented in [3] are \( \Delta W_{\text{exact}} = 51754.27 \text{ kW·h/km} \). The losses calculated by the average monthly air temperature are \( \Delta W_{\text{trad}, 1} = 49961.37 \text{ kW·h/km} \). Losses calculated at 20 °C are \( \Delta W_{\text{trad}, 2} = 53697.14 \text{ kW·h/km} \).

In accordance with tables 1, 2 and 3 are determined the corrective coefficients.
6

\[
\begin{align*}
k_{\text{air}} &= \left[ (0.0051 - K_{1\text{f}} + 0.0016) \left( \frac{F}{35} \right)^{0.65} + \frac{j_{\text{max}}}{1.016} \left( \frac{F}{35} \right)^{0.001} \right] = 0.0190 + 1.018 = 1.037. \quad (9) \\
k_{20} &= \left[ (0.0051 - K_{1\text{f}} + 0.0016) \left( \frac{F}{35} \right)^{0.65} + 0.955 \cdot j_{\text{max}} \left( \frac{F}{35} \right)^{0.001} \right] = 0.019 + 0.957 = 0.976. \quad (10)
\end{align*}
\]

Then the specified losses for both types of calculation are equal:

\[
\begin{align*}
\Delta W_1 &= \Delta W_{\text{trad},1} \cdot k_{\text{air}} = 51809.94 \text{ kW} \cdot \text{h/km.} \quad (11) \\
\Delta W_2 &= \Delta W_{\text{trad},2} \cdot k_{20} = 52408.41 \text{ kW} \cdot \text{h/km} \quad (12)
\end{align*}
\]

The using of the corrective coefficient in the first method reduced the calculation error from -3.5% to -0.1%, and in the second case from 3.8% to 1.3%.

As can be seen from these examples, both methods can reduce the error, but the first (by \(k_{\text{air}}\)) can be considered as more accurate.

Note that it is impossible to completely get rid of the infelicity due to the inconstancy of the meteorological factors, that is, the corrective coefficients reduce the mathematical expectation of the infelicity, but the dispersion cannot be reduced.

It should also be noted that the \(k_{\text{air}}\) is obtained more than unity due to the fact that in fact the wires are always overheated relative to the air due to the flow of current. At the same time, \(k_{20}\) can be either less or more than unity, depending on whether the average temperature of the wire is lower or higher relative to 20 °C (practice shows that in Russia \(k_{20}\) can be more than unity only in hot regions with a large enough evenly line’s load).

5. Conclusion

Due to the fact that the existing methods for taking into account the influence of the most important factors on the active resistance of overhead lines’ wires are complex and not adapted for determining losses of electricity for a year, the vast majority of calculations are carried out using «traditional» methods with significant infelicity.

To increase the accuracy of calculations on the ground of the method of corrective coefficients developed by the authors of this article, recommendations were made. In these recommendations taken into account that simplified calculations can be carried out with taking the wire temperature equal to both 20°C and the average monthly air temperature. The second case is used much less frequently than the first, however, it is its correction that allows to obtain more accurate results.

The article contains examples which show the simplicity and effectiveness of following the developed recommendations.

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