Methods for reducing electricity losses in main electrical networks

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Abstract. The article deals with the problem of reducing the loss of electrical energy when transmitting it over long distances in electrical networks. In particular, technical measures are considered that can compensate for the inequality in the capacity of overhead power lines. A mathematical model is presented that makes it possible to determine the parameters of the electromagnetic field of a power line taking into account its real design. Effective measures have been proposed for equalizing electric charges in phases. Specific recommendations are given for a 500 kV line with horizontal phases. Also, safety issues are considered, namely, the dependences of the electric field strength near power lines are obtained.

1. Introduction
High voltage electrical installations, which include overhead power lines (PTL) of high and extra-high voltage (over 220 kV), are a source of an electromagnetic field (EMF) [1]. The study of the electromagnetic field created by high-voltage electrical installations, in particular, created by overhead power lines of ultra- and ultra-high voltage, is of great importance, both for technical and medical and social research [2].

As shown by energy surveys of a number of electrical network enterprises [3], measures to reduce electricity losses can be divided into six groups:
- Measures to optimize the modes of electrical networks and improve their operation.
- Measures for the construction, reconstruction, technical re-equipment and development of electrical networks, putting into operation energy-saving equipment.
- Measures to improve the settlement and technical accounting, metrological support for electricity measurements.
- Measures to clarify the calculations of loss standards, balances of electricity for feeders, power centers and the electrical network as a whole.
- Measures to identify, prevent and reduce theft of electricity.
- Measures to improve the organization of work, stimulate the reduction of losses, improve the qualifications of personnel, control the effectiveness of its activities.

2. Mathematical model
Thus, the problem associated with the transmission of electrical energy over long distances is the non-symmetry of currents and voltages in the transmission line, which increases with an increase in its length due to different values of inductance and capacitance of the phases. This problem is traditionally solved with the help of wire transposition; one of the disadvantages of transposition is the installation of expensive transposition supports.

As shown in [4], to equalize the charges in phases, you can use:
- an increase in the suspension height of the middle phase wire;
- an increase in the equivalent radius of the conductors of the extreme phases.

To analyze these measures and determine linear charges, we will use the first group of Maxwell's formulas in a complex notation [5] whose matrix form:

$$\begin{bmatrix} \alpha \end{bmatrix} [\phi] = [\phi]$$  \hspace{1cm} (1)
where \([\alpha]\) is a matrix of potential coefficients that depend only on the geometric dimensions of the conductors, their mutual arrangement and on the properties of the medium; \([\phi]\) is the matrix of conductor potentials, expressions for their definition are given in [6]. However, they do not take into account the influence of a massive metal structure, which is represented by the support of an overhead line of a voltage class of 220 kV or more, as well as sagging of wires.

It is known that structurally a high-voltage support consists of corners and strips of metal, which for the proposed technique can be replaced by cylindrical conductors of circular cross-section with such a radius that the capacitance of round and non-round conductors per unit length is the same, such a radius is called equivalent. Equivalent radii can be determined, for example, by the formulas given in [7], so the equivalent radius for a strip of small thickness and width a

\[
r_s = \frac{a}{4}
\]

and for an equilateral corner with side a

\[
r_s = \frac{a}{2.5}
\]

So, the metal support can be replaced by a set of \(N\) cylindrical conductors with length \(L_s\) and equivalent radii \(r_s\), where \(k \in N\). The charge induced on the conductors due to electric induction per unit length of the \(k^{th}\) conductor is denoted by \(\tau_k\). It is not constant along the entire length of the conductor and depends on its specific point. The total number of wires and lightning protection cables suspended on a support will be denoted by \(N_{wp}\). The linear charge on the wire is not constant along the entire length and is denoted by \(\tau_{wp}\), and the radius of the wire is \(r_{wp}\).

When choosing the coordinate system \(xyz\) so that \(z=0\) corresponds to the earth's surface, the potential of an arbitrary observation point \(M(x, y, z)\), will be determined from the principle of superposition and is equal to the algebraic sum of potentials from all \(N\) conductors and from mirror images, as well as from all \(N_{wp}\) of wires and their images

\[
\varphi_M = \frac{1}{4\pi \varepsilon_0} \left[ \sum_{k=1}^{N} \left( \frac{\tau_k(l_k)dl_k}{R_{kM}} + \frac{\tau_k^*(l_k)dl_k}{R_{k^*M}} \right) + \sum_{v=1}^{N_{wp}} \left( \frac{\tau_{wp}(l_v)dl_v}{r_{wp}} + \frac{\tau_{wp}^*(l_v)dl_v}{r_{wp}^*} \right) \right] + \sum_{k=1}^{N} \frac{\tau_k(l_k)dl_k}{R_{kM}} \left[ \left( \frac{R_{k^*M}}{R_{k^*M}^2} - \frac{R_{kM}^2}{R_{kM}^2} \right) + \frac{1}{2} \frac{1}{R_{kM}^2} \right] + \sum_{v=1}^{N_{wp}} \frac{\tau_{wp}(l_v)dl_v}{r_{wp}} \left[ \left( \frac{r_{wp}^*}{r_{wp}^*} - \frac{r_{wp}}{r_{wp}} \right) + \frac{1}{2} \frac{1}{r_{wp}^2} \right]
\]

where \(\tau_k(l_k)\) is the linear charge of the \(k^{th}\) conductor on its elementary section \(dl_k\); \(R_{kM}\) is the distance from the elementary section \(dl_k\) of the \(k^{th}\) conductor to point \(M\); \(R_{k^*M}\) is the distance from the elementary section \(dl_k\) of the mirror image of the \(k^{th}\) conductor to point \(M\); \(r_{wp}\) is the distance from the \(v^{th}\) elementary section \(dl_v\) of the wire to the point \(M\); \(r_{wp}^*\) is the distance from the elementary section \(dl_v\) of the mirror image of the \(v^{th}\) wire to the point \(M\); \(l_{wp}\) is the length of one span.

Functional equation (4) includes an integral transformation over the unknown function \(\tau_k(l_k)\) and \(\tau_{wp}(l_{wp})\) is an integral equation, namely the Fredholm equation of the first kind, taking into account that \(\tau'_k = -\tau_k\) and \(\tau'_{wp} = -\tau_{wp}\), we will rewrite it in the form

\[
\varphi_M = \frac{1}{4\pi \varepsilon_0} \left[ \sum_{k=1}^{N} \left( \int l_k\frac{\tau_k(l_k)dl_k}{R_{kM}} - \int l_k\frac{\tau_k^*(l_k)dl_k}{R_{k^*M}} \right) + \sum_{v=1}^{N_{wp}} \left( \int l_v\frac{\tau_{wp}(l_v)dl_v}{r_{wp}} - \int l_v\frac{\tau_{wp}^*(l_v)dl_v}{r_{wp}^*} \right) \right] + \sum_{k=1}^{N} \frac{\tau_k(l_k)dl_k}{R_{kM}} \left[ \left( \frac{R_{k^*M}}{R_{k^*M}^2} - \frac{R_{kM}^2}{R_{kM}^2} \right) + \frac{1}{2} \frac{1}{R_{kM}^2} \right] + \sum_{v=1}^{N_{wp}} \frac{\tau_{wp}(l_v)dl_v}{r_{wp}} \left[ \left( \frac{r_{wp}^*}{r_{wp}^*} - \frac{r_{wp}}{r_{wp}} \right) + \frac{1}{2} \frac{1}{r_{wp}^2} \right]
\]

We place the observation point one by one on the surface of all cylindrical conductors and, taking into account that the potential of all conductors is zero, and then, sequentially on the surface of all wires, we obtain a system of integral equations
One of the most common methods for solving integral equations and their systems is the method of quadrature formulas (finite sums) and consists in replacing the integral equation with an approximating system of algebraic (finite) equations for the discrete values of the desired function and its solution [8, 9].

To compose a system of linear algebraic equations, we divide each conductor into g equal sections, length \( h_k \), and each wire and cable into \( g_{np} \) of equal sections, length \( l_{np} \). We will assume that the linear charge density at each section of the conductor, wire and cable \( \tau \) remains constant. In this case, the total charge of each electrode with a smooth change in linear density and with a stepwise change is the same. In order not to increase the number of equations in the system, taking into account expression (3), we write down the resulting potential from the section \( g, k^{th} \) conductor and its image, as well as from the section \( g_{np}, \) \( v^{th} \) wire (cable) and its image

\[
\phi_i = \frac{1}{4\pi\varepsilon_0} \left[ \sum_{k=1}^{N} \int_{l_k}^{l_k+R_{k}} \frac{\tau_s(l_k) dl_k}{r_{k1}^2} - \int_{l_k}^{l_k+R_{k}} \frac{\tau_s(l_k) dl_k}{r_{k1}^2} + \sum_{v=1}^{N_{np}} \int_{l_{np}}^{l_{np}+R_{np}} \frac{\tau_{np}(l_{np}) dl_{np}}{r_{v1}^2} - \int_{l_{np}}^{l_{np}+R_{np}} \frac{\tau_{np}(l_{np}) dl_{np}}{r_{v1}^2} \right] \]

(6)

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Let us introduce the coefficient \( K \) showing the ratio of the equivalent radius of the extreme phase to the equivalent radius of the middle phase. The dependences of the electrical parameters, given as a percentage of the parameters of the middle phase, on the coefficient \( K \), are shown in Figures 2 and 3. They show 1 - the deviation of the charge at the extreme phases as a percentage of the charge at the middle phase

\[
\left| \frac{\tau_{sp} - \tau_{mp}}{\tau_{mp}} \right| \times 100\% \]

the middle phase ; 2 - deviation of the working capacity in the extreme phases as a percentage of the working capacity in the middle phase

\[
\left| \frac{C_{sp} - C_{mp}}{C_{mp}} \right| \times 100\% \]

3. Results and Discussion

We will consider the identification of the effectiveness of measures to equalize electric charges in phases using the example of a 500 kV power transmission line, made by the supports shown in Figure 1. The equivalent height of the suspension of the wires is assumed to be 15 m. The equivalent phase radius is 0.16 m, for the AC 400 wire and the number of conductors in the split phase 3. Distance between the phases is 12 m.

Let us introduce the coefficient \( K \) showing the ratio of the equivalent radius of the extreme phase to the equivalent radius of the middle phase. The dependences of the electrical parameters, given as a percentage of the parameters of the middle phase, on the coefficient \( K \), are shown in Figures 2 and 3. They show 1 - the deviation of the charge at the extreme phases as a percentage of the charge at the middle phase

\[
\left| \frac{\tau_{sp} - \tau_{mp}}{\tau_{mp}} \right| \times 100\% \]

the middle phase ; 2 - deviation of the working capacity in the extreme phases as a percentage of the working capacity in the middle phase

\[
\left| \frac{C_{sp} - C_{mp}}{C_{mp}} \right| \times 100\% \]

Figure 1. Scheme of supports for a 500 kV AC line.
Figure 2. Dependence of electrical parameters on the ratio of the equivalent radius of the extreme phase to the equivalent radius of the middle phase.

Figure 3. Dependence of electrical parameters on the change in the height of the suspension of the middle phase $\Delta h$.

Figure 4. Dependence of the difference between the modulus of the arguments of the charge and the potential of the extreme phases $|\varphi_e - \varphi_U|$ on the ratio of the equivalent radius of the extreme phase to the equivalent radius of the middle phase.

Figure 5. Dependence of the difference between the modulus of the arguments of the charge and the potential of the extreme phases $|\varphi_e - \varphi_U|$ on the change in the height of the suspension of the middle phase $\Delta h$.

It follows from the graph that charge modules do not differ from each other at all phases, if the equivalent radius of the outer phases is 1.53 times the equivalent radius of the middle phase, or if the height of the middle phase is increased by 8.2 m. Phases are the same provided that the ratio of the equivalent radius of the extreme phase to the equivalent radius of the middle phase is 1.57, or with an increase in the height of the middle phase by 8.6 m.

It is known [10] that due to geometric symmetry, the charge and potential at the middle phase coincide with each other, i.e. the phase difference between them is zero. The dependence of the difference between the modulus of the arguments of the charge and the potential of the extreme phases $|\varphi_e - \varphi_U|$ on $K$, and the change in the height of the suspension of the middle phase is shown in Figures 4 and 5.

It follows from the graphs that with the optimal ratio of the equivalent radii of the extreme and middle phases, the difference between the modulus of the arguments of the charge and the potential of the extreme phases decreases, compared with the initial value equal to 5.45, to 5.17 degrees, or by 5%.

4. Conclusion

Based on the above, the following conclusions can be drawn:

The sequence of the phase arrangement does not affect the dependence of the electrical parameters on the ratio of the equivalent radius of the extreme phase to the equivalent radius of the middle phase.

To equalize the capacities of each phase, first of all, it is necessary to focus on the alignment of the charge modules, and not their arguments.

The working capacitances of all phases are the same, provided that the ratio of the equivalent radius of the extreme phase to the equivalent radius of the middle phase is 1.57, or with an increase in the height of the
middle phase by 8.6 m.

For all considered options for suspending the wires of power lines with a voltage of 500 kV, the discrepancy between the effective value of the electric field strength and the effective value of the electric field strength along the major semiaxis of the polarization ellipse is insignificant, almost completely disappears outside the power line limited by the extreme wires. Therefore, to control the level of the electric field created by traditional transmission lines, it is possible to use the effective value of the electric field strength with an error not exceeding 5.5%.

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