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DISTRIBUTION OF POWER LOSSES ON HIGH-VOLTAGE SUPPORTS

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Abstract

The process of transporting electricity through high-voltage overhead power lines (HVOPL) is accompanied by technical losses. Technical losses during the transportation of electricity include variable (load) technical losses of electricity, which depend on the flowing electric current through the elements of the electric network, and conditionally constant technical losses of electricity, which practically do not depend on the flowing current in the network. When transporting electricity at the operating high-voltage overhead power lines, the reduction of the load technical losses is unlikely, since replacement or modernization of electrical equipment for consumers or changing the section of current-carrying wires is required. This paper describes the development of a universal model. It describes all the circuits of induced currents and leakage currents on the structural elements of the supports and allows you to perform their analysis. The method of model parameters calculation is given. As well as the proposed technical solution which is aimed at reducing losses and at the same time reducing the electrochemical corrosion of underground structural elements of supports. The description of experimental studies confirming the adequacy of the described studies is given.

Keywords: high-voltage overhead power lines; a universal model; technical solution; electrochemical corrosion

1. Introduction

It is known that the process of transporting electricity high-voltage overhead power lines is accompanied by technical losses. Technical losses during the transportation of electricity include variable (load) technical losses of electricity, which depend on the flowing electric current through the elements of the electric network, and conditionally constant technical losses of electricity, which practically do not depend on the flowing current in the network [1], [2], [3]. In normal operating conditions, a «background» leakage current flow through the power line insulators. According to experts, long-term background current varies in the range of 0.5-1 mA [2]. Specific standard annual losses of electric power from leakage currents for HVOPL located in different regions of Russia make for lines on voltage of 220 kV from 1.08 to 2.1 thousand kWh / km per year, and the voltage of 500 kV from 2.43 to 4.75 thousand kWh / km per year [4].

The actual loss in the operation of HVOPL exceeds the standard, as the operation process is the aging of insulators, increase the leakage currents. Similar problems exist in the HVOPL of the CIS countries, China. Taking into account that the total length of HVOPL for a voltage of 110 kV and above in Kazakhstan exceeds 71.6 thousand km. [5], in Russia 460 thousand km [5], and in China more than 440 thousand km for a voltage of 220 kV and above [5], the development of methods to reduce energy losses during transportation through HVOPL is an urgent scientific and technical task.

At the same time, there are no universal mathematical models describing the distribution of losses among the structural elements of supports. The purpose of this work is to develop a universal model and the development of methods to reduce losses. To achieve this goal must solve the following tasks: as development of a universal model as conducting research to clarify the calculations of model parameters also validation of the model and development of a method for reducing losses in structural elements of supports.

2. Development of a universal mathematical model

In the process of transportation of electric energy through the HVOPL in the structural elements of the supports, flow currents of different origin. These are currents induced from external electromagnetic fields in closed conductive circuits, eddy currents, currents for magnetization, currents of spreading along underground structural elements of supports and leakage currents [6]. All of these currents are the sources of electrical losses. Therefore, to conduct a comprehensive analysis of the distribution of losses on structural elements of supports, it is necessary to develop mathematical models that adequately describe their main components.

The analysis did not reveal the presence of models describing the complex effect of all components of currents flowing through the structural elements of the HVPL supports. In the famous work the mathematical model of the individual elements of the structures including the equivalent circuit of the insulator, the model of corona discharge, the model according to the discharge voltages from the leakage currents of porcelain insulators, the process of transportation of electricity and so on [6] .

In this connection, it is advisable to develop a universal mathematical model that allows evaluating qualitatively and quantitatively the main components of losses in the structural elements of the support and to develop methods to reduce them. The task is to develop a scheme of electrical circuits of the support, describing all the circuits of induced currents and leakage currents through the elements of its design, and perform its comprehensive analysis.

Classical methods of nodal currents and contour voltage based on Kirchhoff's laws are applied for these purposes [7], [8], [9], [10]. Perform the analysis of the distribution of losses for high voltage support type PB – 500 for high-voltage power line with voltage of 500 kV [7], [8], [9], [10].

This is the support of the gantry with racks pivotally mounted at the foundations and cross-arm, and the struts of the metal rope, taken out the plane of the portal. Racks and traverses are usually hollow reinforced concrete pipes. The struts are made of a flexible steel cable or round low-alloy steel. The struts of the support are made of two flexible steel cables, twisted together. Struts and anchor rings are placed on both sides of the support. The design and design scheme of the PB-500 support is shown in Figure 1, were 1 – traverse, 2 – phase wires, 3 – struts, 4 – racks, 5 – anchor bolt, 6 – U-bolt.

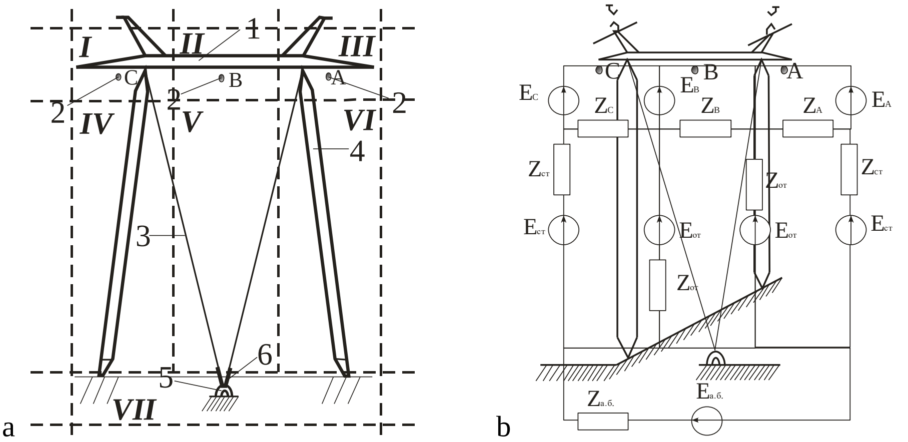


Fig. 1. High-voltage support type PB-500.
(a) the design of high-voltage support type PB-500; (b) design scheme

A number of assumptions are made in the development of the model. It is accepted that the overall parameters of the supports of this type are strictly identical, with the same lengths of struts and the parameters of the supports. The support is symmetrical; the contours for the two sides are identical, so in the model, including the fastening elements, only one side is considered.

The capacitive component of the resistances is assumed constant, the active resistances are unchanged. The model does not take into account possible voltage fluctuations. The model does not take into account all the air resistance of the contours obtained from the phases, due to their large values [8], [11]. In the design scheme:

1) $E_{A,}$ E_B E_C, respectively, consists of:

- the electromotive force generated by the electromagnetic fields induced during the crown formation by fasteners phase conductors A, B, C;
- electromotive force generated by the electromagnetic fields in the flow of currents in phases A B, C.

2) $E_{sт}$ - electromotive force generated by the electromagnetic field between the wires and ground.

3) $E_{от}$ - electromotive force created by the electromagnetic field between the wires and the U-bolt.

4) $E_{a.b.}$ - electromotive force created by all electromagnetic fields acting on the elements of support;

5) Z_A - air resistance of phase A;

6) Z_B - air resistance of phase B;

7) Z_C - air resistance of phase C;

8) $Z_{sт}$ consists of:

- resistance of reinforced concrete rack;
- capacitive reactance between the ground and traverse.

9) $Z_{от}$ consists of:

- resistance of the metal struts;
- resistance of the metal U-bolt;
- capacitive reactance between the ground and traverse.

10) $Z_{a.b.}$ consists of:

- resistance of the metal anchor bolt;
- resistance of reinforced concrete slab support mounting in the ground;
- resistance of the soil.

The distribution of the induced electromagnetic fields along the support (Fig. 1, a) can be divided into 7 area. Vertical planes of the space section pass in the place of fastening of a rack and a traverse. The seventh area is located underground; it is limited by the space of fixing the struts and foundations of the support pillars and includes the most vulnerable to electrochemical corrosion anchor ring. Within each area, contours are formed, consisting of EMF sources and complex resistances.

In the process of experimental research carried out by the authors [8,12], it was found that at a current of up to 300A flowing in phases, the inductive coupling between the non-conducting elements of the support gives an error of up to 1%, so it is not taken into account in the model. Also in the process of experimental research found that the capacitive coupling between the current-carrying wires due to small values is not taken into account (less than 1 %). The calculations take into account the constant operating conditions and do not take into account seasonal fluctuations in temperature, humidity, dielectric conductivity of air and solar radiation. The substitution scheme for the PB-500 support, divided into the corresponding contours, is shown in figure 2.

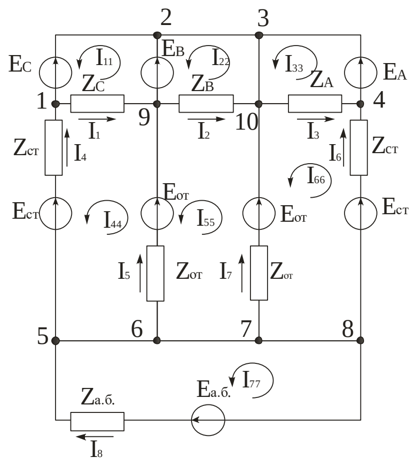


Fig. 2. The substitution scheme for the PB-500 support

In accordance with the first Kirchhoff's law, 9 equations for 10 knots and 7 equations for 7 contours are compiled [12], [13], [14], [15]. The equations have a complex form to take into account the variable nature of the transmitted voltage and the phase shift of 120^0. After the transformation, we obtain a system of equations describing the equivalent circuit for the electromotive forces (1 -7):

$$Z_{11}\cdot I_{11}+ Z_{12}\cdot I_{22}+Z_{13}\cdot I_{33}+Z_{14}\cdot I_{44}+Z_{15}\cdot I_{55}+Z_{16}\cdot I_{66}+Z_{17}\cdot I_{77}= E_{C}; \quad (1)$$

$$Z_{21}\cdot I_{11}+ Z_{22}\cdot I_{22}+Z_{23}\cdot I_{33}+Z_{24}\cdot I_{44}+Z_{25}\cdot I_{55}+Z_{26}\cdot I_{66}+Z_{27}\cdot I_{77}= E_{B}; \quad (2)$$

$$Z_{31}\cdot I_{11}+ Z_{32}\cdot I_{22}+Z_{33}\cdot I_{33}+Z_{34}\cdot I_{44}+Z_{35}\cdot I_{55}+Z_{36}\cdot I_{66}+Z_{37}\cdot I_{77}= E_{A}; \quad (3)$$

$$Z_{41}\cdot I_{11}+ Z_{42}\cdot I_{22}+Z_{43}\cdot I_{33}+Z_{44}\cdot I_{44}+Z_{45}\cdot I_{55}+Z_{46}\cdot I_{66}+Z_{47}\cdot I_{77}= E_{\text{ст}}; \quad (4)$$

$$Z_{51}\cdot I_{11}+ Z_{52}\cdot I_{22}+Z_{53}\cdot I_{33}+Z_{54}\cdot I_{44}+Z_{55}\cdot I_{55}+Z_{56}\cdot I_{66}+Z_{57}\cdot I_{77}= E_{\text{от}}; \quad (5)$$

$$Z_{61}\cdot I_{11}+ Z_{62}\cdot I_{22}+Z_{63}\cdot I_{33}+Z_{64}\cdot I_{44}+Z_{65}\cdot I_{55}+Z_{66}\cdot I_{66}+Z_{67}\cdot I_{77}= E_{\text{ст}}; \quad (6)$$

$$Z_{71}\cdot I_{11}+ Z_{72}\cdot I_{22}+Z_{73}\cdot I_{33}+Z_{74}\cdot I_{44}+Z_{75}\cdot I_{55}+Z_{76}\cdot I_{66}+Z_{77}\cdot I_{77}= E_{\text{а.б.}}. \quad (7)$$

The equations for the currents (8-16), [7], [9]:

I_4-I_1=0 *(node 1);* (8)

I_1+I_2=0 *(node 2);* (9)

I_2+I_3=0 *(node 3);* (10)

I_3+I_6=0 *(node 4);* (11)

I_8-I_4=0*(node 5);* (12)

I_7-I_5=0*(node 6);* (13)

–I_6-I_7=0 *(node 8);* (14)

I_1+I_5-I_2=0 *(node 9);* (15)

I_2-I_3+I_7=0 *(node 10).* (16)

This model allows:

- describe the nature and magnitude of leakage currents and induced currents on all elements of the support;
- determine the interaction of leakage currents and spreading currents in the soil on the support elements located underground;
- identify the most vulnerable elements of supports exposed to electrochemical corrosion;
- develop recommendations for changing the design of the support to minimize leakage currents;
- calculate the required currents for cathodic protection.

A similar model can be developed for any support structure [10]. This model is universal and applicable for a comprehensive analysis of the current distribution on the elements of the support, which allows to identify possible closed circuits of currents from induced electromagnetic fields and to develop recommendations for changes in the design of the supports to reduce losses.

3. The method of calculation of parameters of the equivalent circuit support PB-500

An important step in the simulation is to determine the quantitative parameters of the equivalent circuit. Reference data and data presented in [16], as well as data on technical losses presented in [17] were used to calculate the parameters of the high-voltage support replacement circuit PB-500. The method of calculation of the equivalent circuit parameters is as follows:

1) when calculating the EMF generated by electromagnetic fields induced in the process of crown formation on the elements of fastening wires of phases A, B, C, the formula given in [18] is used:

$$P_K = b \cdot U(U - U_0) \quad (17)$$

Where, $P_К$ - is the power loss of the overall crown at AC,

b - coefficient depending on the geometry of the overhead line and the geometry of the volume charge,

U_0 - overall crown voltage,

U - the amplitude value of the phase voltage of the overhead line.

Then EMF will be equal to U0 with the reverse sign by the formula (18):

$$-U_0 = \frac{P_K}{b \cdot U} - U \qquad (18)$$

2) EMF generated by electromagnetic fields during the flow of currents through the phases of the ABC, will be equal to the voltage at the top of the support, according to [19].

3) EMF generated by the electromagnetic field between the wires and the ground is taken from [20].

4) EMF generated by the electromagnetic field between the wires and the U –bolt is obtained similarly to the previous one [20].

5) the data for the calculation of EMF generated by all electromagnetic fields affecting the support elements are contradictory, so the experimentally obtained value is used.

6) the value of air resistance is obtained from the reference data [21], but it varies depending on weather conditions, so the average value is taken.

7) the resistance of the rack consists of two components: the resistance of the reinforced concrete rack and the capacitive resistance between the ground and the traverse. The resistance value of reinforced concrete is calculated from the data obtained in [22], [23]:

$$R = \rho \frac{l}{S} \qquad (19)$$

where ρ is the resistivity of the conductor,

l - conductor length,

S - the cross-sectional area.

8) Capacitive resistance is the inverse of the capacitive conductivity of the line, the value of which is given in the reference literature [24].

9) the Resistance of the metal of the support is calculated similarly to the equation of claim 7, the resistivity of the steel is taken at an average temperature of 200C.

10) the Resistance of the metal U-shaped bolt is calculated similarly to the equation of claim 7.

11) soil resistance to current spreading is calculated by the formula (20) obtained from [25], the data for the calculation are taken from [19], [20]:

$$R = \frac{\rho}{2\pi l} ln \frac{4l}{d} \qquad (20)$$

where ρ is the soil resistivity,

l - length of the underground part of the vertically positioned conductor,

d - the diameter of the conductor.

According to [24], in Central Kazakhstan is dominated by loess-like loamy soil, therefore the resistivity of the soil chosen from [25]. After calculation the table 1 with parameters of the substitution scheme of the high-voltage support PB-500 is received.

Name	Designation	Numerical value
EMF, V	E_A, E_B, E_C	$412,5 \cdot 10^3$
	E_{ST}	$8 \cdot 10^3$
	E_{OT}	$8 \cdot 10^3$
	$E_{a.b.}$	0,5
Resistance, Ohm	Z_A, Z_B, Z_C	10^7
	Z_{ST}	R_{ST}=6817
		$X_c=408 \cdot 10^3$
	Z_{OT}	R_{OT}=3,23
		$X_c=408 \cdot 10^3$
	$Z_{a.b.}$	49,1

Table 1. Parameters of the replacement circuit support PB-500

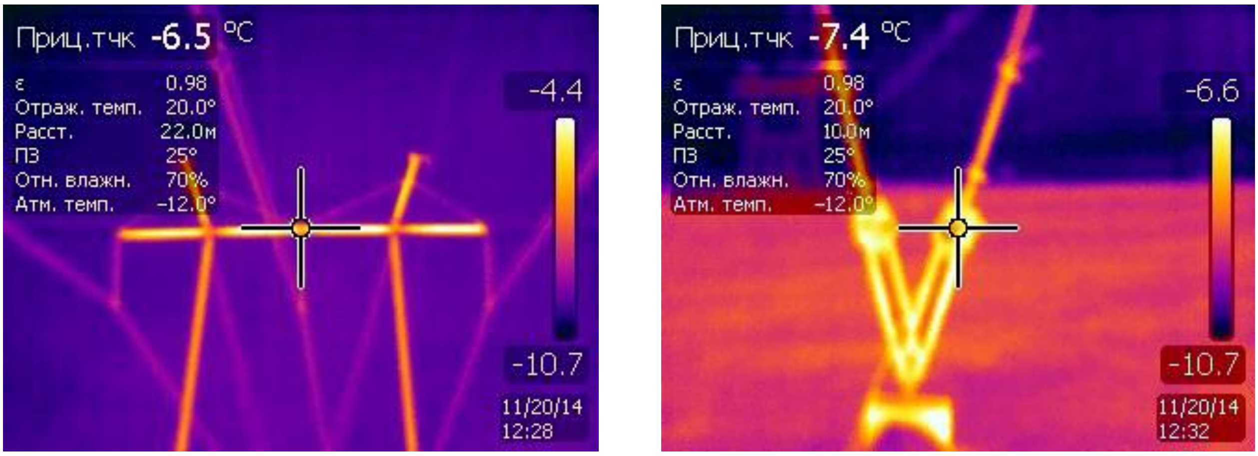
This technique allows you to calculate the parameters of the equivalent circuit for any structure of supports.

4. Assessment of the adequacy of the universal model

To assess the adequacy of the model and verify the accuracy of the calculation of its parameters, experiments were carried out on the operating HVOPL with a voltage of 500 kV. As a result, with the help of ammeter of the type of tick was determined the currents in the contour, formed by the upper traverse supports and struts, are installed, that the magnitude of currents in different delays on different supports vary in the range of 7-80 mA, a voltage in the range of - 0.2-0.3 V. The discrepancy between the calculated value of currents and the obtained experimentally was 15-20%, which confirms the adequacy of the developed model with accuracy sufficient for engineering calculations.

In the experiments with the use of thermal imaging camera obtained the images of different elements of support (fig. 3). It is established that the excess of the heating temperature of individual structural elements over the ambient temperature is 3-8 degrees metal structural elements of the supports, converting the induced energy into heat, are the following three contours:

- the upper traverse of the support; the left and right racks of support and their earthling contours;
- upper traverse of the support; struts and U-shaped bolt securing the struts on one side of the support;
- upper traverse of the support; struts and U-shaped bolt securing the struts on the other side of the support.



a) b)

Fig. 3. Thermograms of metal structural elements of support № 250.
(a) upper traverse of the support; (b) U-shaped bolt

The induced energy in the second and third circuits is used not only for heating, but also is a component of electrochemical corrosion of metal elements of anchorage of supports located underground. As a result of experimental studies, the presence of closed electromagnetic circuits formed by the structural elements of the support is established. These contours correspond to the calculated ones selected in the model.

5. Methods for reducing electrical losses in supports

In the process of simulation and experimental studies of the processes of distribution of electricity losses on the supports proposed technical solutions that are aimed at reducing losses and at the same time to reduce the electrochemical corrosion of underground structural elements of supports [26].

The support of the overhead power line contains a horizontal traverse, to which three garlands of suspended insulators and wires connected in parallel to the insulating elements are connected. The technical solution is that semiconductor diodes are connected in parallel to the insulating elements, the cathodes of which are connected to the ends of the beginning of the upper parts of the struts, and the anodes to the beginning of the lower parts of the struts.

The horizontal traverse is also connected to the supports of the portal type and the beginning of the upper parts of the struts (figure 1, a). The ends of the cable ties are connected by an anchor ring and attached to a reinforced concrete slab buried in the soil. Pillars of the support are installed on surface foundations and grounded.

Semiconductor diodes included in parallel to the isolating elements of the struts ensure the passage of only a positive half-wave of rectified voltage in closed conductive circuits. This compensates for the action of spreading currents in the soil and provides cathodic protection, the anchor ring is converted into an anode, and rectified currents provide protection against electrochemical corrosion. Figure 4 explains the proposed technical solution.

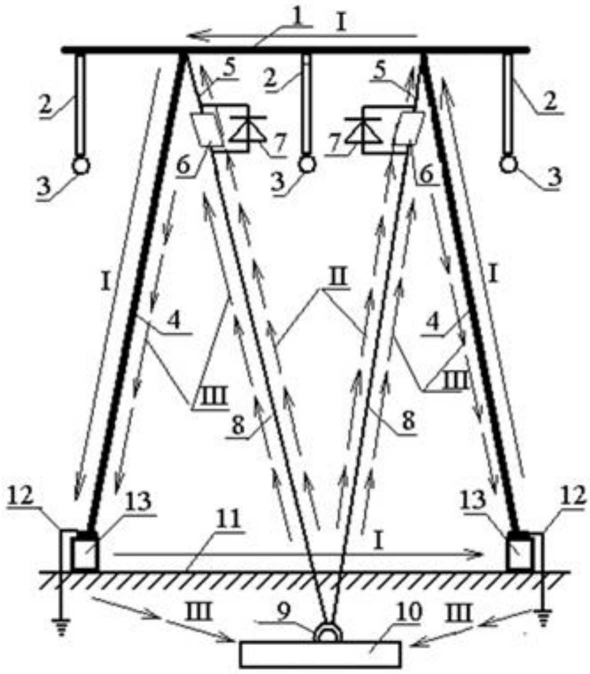


Fig. 4. Flow current compensation scheme

The action of leakage currents flowing in the circuits I, which are sources of electrical losses in high-voltage lines and increase the electrochemical corrosion of the underground elements of the support, is compensated by the action of rectified leakage currents flowing in the circuits III and providing cathodic protection. And through the contours of the II due to the presence of insulating elements 6 and a counter included semiconductor diode 7, the currents will not occur [10].

For the support of the portal type, taking into account the fact that the braces are placed on both sides of the support, there are two circuits I and four circuits III, so the destructive effect of leakage currents of the circuit I is compensated by the anticorrosive action of the circuits III [10].

This eliminates the losses caused by the flow of currents induced in the closed circuits of the metal supports of the overhead line, and provides a corresponding reduction in the loss of transmitted electricity.

The inclusion of a semiconductor diode in parallel to the insulating elements in the cable braces leads to compensation of the spreading currents. It will also reduce the intensity of the process of electrochemical corrosion of the most vulnerable structural element of the support, subject to electrochemical corrosion: fixed in the reinforced concrete support of the anchor ring, to which the struts are attached.

6. Conclusion

Losses during transportation of electricity are diverse and depend on many factors. The absence of universal mathematical models of the loses distribution among the constructive elements of high-voltage lines makes it difficult to analyze them, and also makes it difficult to develop methods for reducing them. This work provides solutions to these problems:

• This universal mathematical model has been developed, which makes it possible to evaluate qualitatively and quantitatively the main components of the losses in the structural elements of the various support of the HVOPL

• This method was developed for calculating the quantitative parameters of the replacement circuit of the PB-500 high-voltage support;

• The experiments were carried out on the existing 500 kV high voltage power lines to assess the adequacy of the model and verify the accuracy of the calculation of its parameters. The discrepancy between the calculated value of the currents and the experimentally obtained was 15–20%, which confirms the adequacy of the developed model with accuracy sufficient for engineering calculations; a technical solution was proposed, which is aimed at reducing losses and at the same time reducing electrochemical corrosion of underground structural elements of supports.

Currently, work is underway to analyze losses on poles with a voltage of 110-220 kV. In the future, it is planned to use the obtained method for calculating losses for existing power lines. These methods are supposed to be used in the design of new high-voltage power lines.

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