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SCHEME OF THREE ELECTRICAL QUANTITIES METHOD

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ABSTRACT

The purpose of the paper is to develop a new calculation method. The subject area of the study is the calculation of the steady-state mode of a three-phase high-voltage overhead power line. The basis of the method is simple mathematical models that make it possible, in the presence of three initial data with a high degree of reliability, to manually calculate many electrical parameters, and to verify electrical calculations, including those made using computer programs. The key component of the models is the proportionality factor, which takes a different numerical value for each of them. The hypothesis for the development of the method was the application of the invariance principle to the basic laws and known relations of electrical engineering. The method is simple, operative and successfully verified. The hypothesis is proven. The calculation error when applying the method is less than 2%. Software systems are not required for the implementation of the method. According to the results of the study, conclusions were made and practical recommendations were given. The prospects for further research were presented. The method can be used by experts, engineers, and students of electrical power and electrical engineering programs of higher education institutions.

Nomenclature and Symbols

The parentheses given after the explanation of each parameter contain numerical values from the calculation example [7, pp. 7-8, 12-13]. This example shows verification of the accuracy of the proposed mathematical models designed to calculate the values of power lines (PLs).

L – power transmission distance, km (100);

P – active power, MW (120.1);

U – power transmission voltage, kV (220);

n – the number of wires in each phase of the PL, pcs. (3);

Digital indexes: m, n, l, f, j, q, i;

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k – numerical factors of proportionality;

ε, ψ, θ, α, β, ξ, τ – components that describe electrical parameters using indices;

$\varepsilon_1 = S_{trans.s}$ – the apparent power transmitted from the generators to the power plant high voltage switching substation, excluding losses in power plant step-up transformers, MVA (150.13);

$\varepsilon_2 = \Delta S_s$ – the apparent power losses in power plant step-up transformers, MVA (11.13);

$\varepsilon_3 = S_{PL.s}$ – the apparent power transmitted from the generators to the power plant high voltage switching substation, taking into account the losses in power plant step-up transformers, MVA (139);

$\varepsilon_4 = S_{PL}$ – the apparent power transmitted from the power plant high voltage switching substation to the main step-down substation, taking into account the losses in power lines, MVA (138.27);

$\varepsilon_5 = \Delta S_{PL}$ – the apparent power losses in power lines, MVA (0.727);

$k_{\varepsilon_1} = 4.314 \times 10^{-2}$; $k_{\varepsilon_2} = 2.36544 \times 10^{-4}$; $k_{\varepsilon_3} = 3.699 \times 10^{-2}$

$k_{\varepsilon_4} = 3.661 \times 10^{-2}$; $k_{\varepsilon_5} = 10^{-6}$;

$\psi_1 = Z_{PL}$ – full electrical impedance of power lines, Ohm (16.23);

$\psi_2 = X_{PL}$ – the full inductive impedance of power lines, Ohm (13.3);

$\psi_3 = R_{PL}$ – the full active impedance of power lines, Ohm (9.3);

$k_{\psi_1} = 150$; $k_{\psi_2} = 227.27$; $k_{\psi_3} = 472.58979$

$\theta_1 = P_{trans.s}$ – the active power transmitted from the generators to the power plant high voltage switching substation, excluding losses in power plant step-up transformers, MW (120.1);

$\theta_2 = \Delta P_{PL}$ – the active power losses in power lines, MW (0.41);

$\theta_3 = Q_{trans.s}$ – the reactive power transmitted from the generators to the power plant high voltage switching substation, excluding losses in power plant step-up transformers, MVAr (90.1);

$\theta_4 = \Delta Q_{PL}$ – the reactive power losses in power lines, MVAr (0.59);

$\theta_5 = \Delta P_{\uparrow m}$ – the active power losses in power plant step-up transformers, MW (3);

$\theta_6 = \Delta Q_{\uparrow m}$ – the reactive power losses in power plant step-up transformers, MVAr (15.01);

$k_{\theta_1} = 227.27$; $k_{\theta_2} = 6.5909 \times 10^4$; $k_{\theta_3} = 303.63636$;

$k_{\theta_4} = 4.5799 \times 10^4$; $k_{\theta_5} = 9090.9092$; $k_{\theta_6} = 1818.73866$;

$\alpha_1 = n$ – the number of wires in each phase of PL, pcs. (3);

$\alpha_2 = \Delta U$ – voltage loss in power lines, kV (9.6);

$k_{\alpha_1} = 8.33333 \times 10^{-2}$; $k_{\alpha_2} = 2.58131 \times 10^{-2}$;

$\beta_1 = \cos\varphi_г$ – the active power factor of the power plant generators (0.8);

$\beta_2 = s$ – section of one wire conductor for each of the three phases of the power line, mm^2 (120);

$k_{\beta_1} = 0.16$; $k_{\beta_2} = 3600$

$\xi_1 = \cos\varphi_{PL}$ – the active power factor of the power line (0.85);

$\xi_2 = n_{circuits}$ – the number of circuits in the power line (1);

$k_{\xi_1} = 0.21$; $k_{\xi_2} = 0.2475$;

$\tau_1 = I_{\max.rated.pl}$ – maximum rated current in the power line, A (365.2);

$\tau_2 = s_{economic}$ – the economic section of a *three-core* wire for each of the three phases of the power line, mm^2 (332);

$k_{\tau_1} = 1.8\times10^6$; $k_{\tau_2} = 1.5\times10^6$.

1. INTRODUCTION

The purpose and essence of the study is the development of a new method. The development of any method is one of the important scientific results of the study, which determine the subsequent development of the subject science [15, pp. 20, 25]. The development of science itself is inextricably linked with the continuous improvement of methods [15, p. 14]. *The idea of the study* is due to the fact that there is a gap in the methods of manual verification of computer electrical calculations, as well as the desire of the author to fill this gap. *The object of the study* is three-phase high-voltage (voltage 110-150-220 kV) overhead power lines. *The subject of the study* is a new method called the "three electrical quantities" method (TEQ).

1.1 ANALYTICAL REVIEW

The main purpose of the calculation of the steady-state (CSS) of electrical power systems is to determine their parameters characterizing the conditions in which equipment and consumers of networks operate [19, p. 43]. Calculation of operating parameters of electrical power systems is the *most important task in designing* power supply systems for objects since it is used as background information for selecting power transformers, conductor sections, switching and protection devices, as well as other electrical equipment [12, pp. 28, 33]. CSS of other elements of the electric power system (power plants and transformer substations) is not the subject of this study.

There are a lot of sources covering the methods and approaches to the CSS of power lines. There are more than a hundred published books; all of them were analyzed by the author. The brief analytical review of existing approaches to the CSS of the power lines, presented below, was made using selected sources [20, 21, 24].

In practice, several approaches are used for the CSS of power lines.

The first approach. *Initial values*: current and voltage of the load, resistance, and conductivity of power lines. *To be determined:* current in power lines, the voltage at the source, current at the source, apparent power loss in power lines. *Assumptions and instructions:* a) phase voltages and phase currents are used; b) the laws of Ohm and Kirchhoff are applied; c) the calculation is carried out from the end of the power line to the source. *The solution is to calculate the following parameters:* 1) charging current at the end of the power line; 2) current in the power line; 3) full resistance of the power line; 4) phase voltage at the source; 5) charging current at the beginning of the power line; 6) current at the source; 7) loss of apparent power in the power line.

The second approach. *Initial values*: apparent power of the load, resistance, and conductivity of power lines. *To be determined:* apparent power at the end of the power line, apparent power loss in the power line, apparent power at the beginning of the power line, the voltage at the source, apparent power at the source. *Assumptions and instructions:* a) linear voltages and phase currents are used; b) the laws of Ohm and Kirchhoff are applied; c) the calculation is carried out from the end of the power line to the source. *The solution is to calculate the following parameters:* 1) charging power at the end of the power line; 2) apparent power at the end of the power line; 3) full resistance of the power line; 4) current in the power line; 5) loss of apparent power in the power line; 6) full power at the beginning of the power line; 7) voltage in the power line; 8) voltage at the source; 9) charging power at the beginning of the power line; 10) apparent power at the source.

The third approach is called "method in two steps". The synonyms of this method are "iteration method" and "method of successive approximations". *Initial values*: load voltage, resistance, and conductivity of power line, apparent power of the load, the voltage at the source. *To be determined:* apparent power at the end of the power line, apparent power loss in the power line, apparent power at the beginning of the power line, apparent power at the source, apparent power at the source, the adjusted value of the load voltage. *Assumptions and instructions:* a) at the first stage, it is assumed that the voltage at the end of the power line is equal to the nominal voltage; b) calculation of power flows from the end of the power line to the source; c) at the second stage, the adjusted value of the load voltage is calculated using the given source voltage and the apparent power at the beginning of the power line calculated at the first stage. *The solution is to calculate the following parameters:* 1) calculation of the parameters is similar to the calculation procedures in paragraphs 1 ... 6, subsection 1.1.2; 2) charging power at the beginning of the power line; 3) apparent power at the source; 3) the specified load voltage.

Concepts of voltage drop and loss. These parameters are calculated along with other values characterizing the CSS of the power lines. Figure 1 shows the illustration on the complex plane. The voltage drop (see the left side of Figure 1) is the geometric difference between the voltage at the beginning (U_1) and the end (U_2) of the line. The voltage drop is a complex number and has a real part (ΔU), or the longitudinal component of the voltage drop, and the imaginary part ($j\delta U$), or the transverse component of the voltage drop. The formula for calculating the voltage drop: $\overline{AB} = U_1 - U_2 = \sqrt{3} I_{12} Z_{12} = \Delta U + j\delta U$. The voltage loss (see the right side of Figure 1) is an algebraic (vector) difference between the voltage at the beginning (U_1) and the end (U_2) of the line. The voltage loss is represented by a vector $\overline{BD} = U_1 - U_2$.

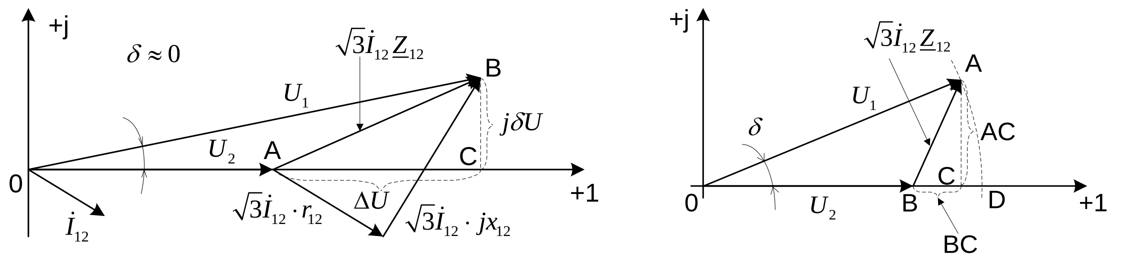

Figure 1: Drop and loss of voltage.

○

In distribution systems and in supply systems with voltage up to 110 kV inclusive (in which the angle δ between the voltages U_1 and U_2 is approximately zero), when calculating the power line modes, it is allowed to neglect the transverse component of the voltage drop, the longitudinal component can be assumed as equal to the voltage loss, and the calculation should be performed according to the voltage loss. In supply systems with voltage up to 220 kV and above (in which the angle δ between the voltages U_1 and U_2 is significant), it is necessary to take into account the longitudinal and transverse component of the voltage drop, and the calculation should be performed according to the voltage drop. With the initial data (P, Q, U), the voltage drop at the end of the power line is:

○ $$U_1 - U_2 = \sqrt{3}I_{12}Z_{12} = \sqrt{3}\frac{S_{12}^e}{\sqrt{3}U_2}Z_{12} = \frac{(P_{12}^e - jQ_{12}^e)}{U_2}(r_{12} + jx_{12}) = \frac{P_{12}^e r_{12} + Q_{12}^e x_{12}}{U_2} + j\frac{P_{12}^e x_{12} - Q_{12}^e r_{12}}{U_2} = \Delta U + j\delta U \quad \textbf{(1)}$$

○ With the initial data (P, Q, U) at the beginning of the power line, in these formulas, only the index "e" is replaced with the index "b".

1.2 STATEMENT OF THE PROBLEM, RELEVANCE, PURPOSE, OBJECTIVES, AND HYPOTHESIS OF THE STUDY

Based on the analysis of more than a hundred publications on the methods of the CSS of the power lines, the author found that, despite the need for simple methods of manual, operational and reliable verification of the calculated part of the power lines design, there are no such studies. That is, there is a contradiction between the lack of relevant knowledge and the need to obtain it in the course of scientific study. Based on this contradiction, the following statement of the *problem* is proposed: "Manual verification of computer electrical calculations using simple, operational and reliable methods".

It is known [12, pp. 63-58] determine the operating parameters of power lines, it is necessary to perform more than 20 calculation procedures if they are performed manually. Typically, calculations of the parameters of the designed electrical power systems, including power lines, are performed using software systems. At the same time, all engineering projects, including their design part, are subject to expert evaluation. The expert evaluation is carried out in a short time. To meet the deadlines, experts have several ways: 1) to believe the provided documents on the verification of the computer program using which the calculations were performed; 2) to use another computer program with which it is possible to check the correctness of the calculations; 3) to use manual verification of calculations based on simple, reliable and operational methods (which are almost nonexistent at present).

None of the computer programs are immune to errors. Plus, there is a "human factor": one can have a correct program, but incorrectly use the initial data for it. Therefore, the development of the method for manual verification of computer calculations and the corresponding theory for such a method is a *problem* that is *relevant* in the scientific and applied significance. The statement of the problem is timely, especially in the conditions of the constantly growing volume of engineering computing and the current transition of many countries to the digitalization of industries and processes [25-27].

To solve the problem, it is necessary to formulate the purpose and tasks of the study. *The purpose of the study* is to develop a new method that allows manual, quick and highly accurate verification of complex electrical calculations. Achieving the purpose involves solving a number of specific *research tasks*: 1) to develop a mathematical model for the method; 2) to develop a conceptual model for the method; 3) to justify the performance of the method; 4) to summarize the results of the study and draw conclusions; 5) to identify the scientific novelty, theoretical and practical significance of the study; 6) to develop recommendations for the practical use of the results and promising areas for further study.

The tasks set to make it necessary to formulate a theoretical concept in the form of a *research hypothesis*, the truth of which will have to be justified, proved and verified. A hypothesis is a form of new probabilistic theoretical knowledge (scientific scheme), as well as a path leading to a probable solution to a problem. The statement of the hypothesis: "The set problem can be solved by applying the principle of invariance to the basic laws of electrical engineering". The principle of invariance: the laws are constant and do not depend on changing the way they are described for the purpose of simplification [14, p. 531]. Invariance as a physical pattern reflects the general properties of physical objects, including electrical objects. Therefore, according to the author, the transformation (change of the form of representation) of the electrical engineering laws should not affect the quality of the result of calculations. In terms of the formation mechanism, the set hypothesis can be characterized as deductive, the construction of which is based on the analysis of theoretical material, and which involves the deduction of conclusions from the abstract to the concrete. In terms of the level of research being conducted, the hypothesis is theoretical, aimed at verifying theoretical knowledge and revealing the essence of the object of study.

1.3 RESEARCH STATEMENT

To check the reliability of the new method, the program code according to the description of the algorithm is not required. As one of the simplest and fastest options for checking the correctness of the developed mathematical models and formulas, the substitution of numerical values in them represented in parentheses in the section "Nomenclature and Symbols" can be used.

The proposed material is original and was not previously or simultaneously published. Some of the ratios presented in the "Mathematical Models" section and the interpretation of their designations were included as fragments in the publications [1, 2, 3, 4, 5, 6], which are mainly focused on electrical express-expertise, but in this paper they are given in a completely different context, as illustrative material to the newly developed method.

2. RESEARCH METHODS AND BASIC CONCEPTS

As a means to achieve this purpose, the author used the following well-known *research methods*: idealization and abstraction procedures, general methods of study – analogy and comparison, analysis and synthesis, induction and deduction, classification, hypothesis construction, as well as methods of the theoretical basis of electrical engineering, algebra, and mathematical simulation.

Below are the *basic concepts* that explain the meaning of keywords to the article.

1) *Method* – a set of values ratios, aimed at a quantitative study of simulated processes, and described by a system of components using abstract terms and concepts.

2) *Value* – any numerical indicator using which it is possible to perform calculations and quantify the object of study. The value can be represented by three properties – name, value, and type. Symbolic and semantic names of the values are given in the section "Nomenclature and Symbols". Examples of their variable values are given in parentheses of the same section. The type of values determines the ranges of their allowable values. For example, the initial electrical quantities (voltage – active power – power transmission length) have the following optimal ranges of the numerical type: 110 kV – 60-70 MW and 40-50 km; 150 kV – 70-100 MW and 50-80 km; 220 kV – 100-110 MW and 200-400 km [8].

3) *Proportionality factor* – a numerical value, determined solely by the nature of the relationship of the values included in a particular formula, and depending only on the units of measurement. In the case of replacement of the measurement unit of any value included in the formula, it will cause a change in the numerical value of the proportionality factor.

4) *Formula* – an expression, the results of which are unknown. To obtain the result, it is necessary to substitute values in the formula. A formula and an equation are different concepts. An equation is a formula, the result of which is known, but one or several values are not known (the roots of the equation) using which the result is obtained.

5) *Mathematical static model* – a set of mathematical relationships that reflect the basic laws of the process under study without taking into account their changes over time.

6) *Conceptual model* – a "hard" model of the study subject area and a theoretical basis for the construction of a mathematical model. The purpose of the conceptual model is to describe the components of the design method using abstract terms and concepts [9].

7) *Normal steady-state power transmission mode* – the state of the system when the parameters vary within small limits, which allows considering these parameters unchanged [11].

8) *The principle of invariance* – a principle that states that the values of physical quantities do not depend on the way they are described [10].

3. MATHEMATICAL MODELS

Mathematical models and formulas of the TEQ method are presented in Table 1.

Designations and explanations of model parameters are given in the "Nomenclature and Symbols" section.

Mathematical models and formulas of Table 1:

a) Are proposed without derivation, since their algebraic derivation would greatly exceed the page limit of this article;

b) Are developed by the author using the main transformation method – the method of substituting values from one formula to another.

The key component in each of the seven models presented in Table 1 is the proportionality factor, the numerical value of which is different, and is determined by the components ε, ψ, θ, α, β, ξ, τ.

Table 1. Mathematical models and formulas.

Number of the model, formula	Type of models (1-7) and formulas (8-9)	Number of the model, formula	Type of models (1-7) and formulas (8-9)
1	$L=\dfrac{k_{\varepsilon_m} P U^2 n^2}{\varepsilon_m^2}$	5	$L=\dfrac{k_{\beta_j} U^2}{P\beta_j^2}$
2	$L=\dfrac{k_{\psi_n} P\psi_n^2}{U^2}$	6	$L=\dfrac{k_{\xi_q} U^2}{P\xi_q}$
3	$L=\dfrac{56.8U^2}{k_{\theta_l}\theta_l}$	7	$L=\dfrac{U^4\tau_i^2}{P^3 k_{\tau_i}}$
4	$L=\dfrac{k_{\alpha_f} U^2\alpha_f}{P}$	8	$U=2\sqrt{PL}$
		9	$U=\dfrac{50}{\sqrt{\dfrac{1}{L}+\dfrac{5}{P}}}$

Due to the presence of the proportionality factor in the models, the latter acquires a simplified analytical form, and, most importantly, contain the minimum number of parameters. Since the result obtained using models is equivalent to the result based on the use of the known relations in the CSS of the power lines, the proportionality factor can be given another name – the equivalence factor. Replacing some relations (known electrical formulas in this case) with others (models in this case) is called an equivalent transition in algebra [22]. All seven models and two formulas in Table 1 belong to the class of linear equations of the form $a\times x=b$ with the only solution $x=\dfrac{b}{a}$ at $a\neq 0$. The solution obtained using these models is analytic, since it is presented in the form of algebraic formulas [23].

4. STUDY DETAILS: A CONCEPTUAL MODEL OF THE METHOD

Structurally, the TEQ *method* consists of two parts: 1) mathematical models and formulas presented in Table 1; 2) a conceptual model, used as a theoretical basis for their construction and describes the method using abstract terms and concepts. The conceptual model contains five aspects – methodological, substantive, procedural, evaluative, and final. The main components of the methodological aspect were described in sections 1 and 2. The complete structure of the names of components of each of the five aspects (without a description of the components) is given in [6]. In total, the structure of aspects contains more than 60 components. The limited scope of this article does not allow describing all of them; therefore, this section provides a brief summary of only a certain number of components of the substantive aspect, as well as the general characteristics and features of the method itself.

4.1 SUBSTANTIVE ASPECT OF THE METHOD

The nature and purpose of the method are the operative "manual" calculation of many electrical parameters describing the CSS of the power lines using simple mathematical models in the context of incomplete input data. *The tasks of the method* are the development of concepts as a basis for establishing relationships between individual parameters, as well as the construction of mathematical models and formulas containing these parameters. *The basis of the method is* the CSS of the power lines. *The principles of the method:* 1) the scientific nature (validity of the method and the reliability of the results obtained using it); 2) efficiency (efficiency in achieving the purpose); 3) accuracy (minimum calculation error); 4) reliability (ability to verify the results of calculations). *Interrelations of the method:* the TEQ method is connected with the methods of the theoretical basis of electrical engineering and the theory of power transmission, as well as with the methods of algebraic transformations. *Requirements to the method:* it is not allowed to round off the values of numerical coefficients in models, it is necessary to use units of measure correctly. *Limitations of the method* – the application of the method should be: a) within the boundaries of the designated numerical ranges of P, U, L (see p. 2, section 2); b) referred only to the normal steady state of three-phase high-voltage overhead power lines. *Assumptions of the method*: the values of voltages and currents are accepted as valid, therefore Ohm and Kirchhoff's laws are presented in the algebraic form in the form of static models. *Functions of the method:* 1) function of calculation and verification of electrical quantities calculations; 2) prognostic function (ability to evaluate the behavior of an object at a certain combination of parameters); 3) practical function (the method can be applied in practice); 4) explanatory function (the method helps to determine the hidden relationships between the components); 5) synthetic function (the method creates a single ordered structure of knowledge about its aspects and components); 6) methodological function (the method forms the methods for obtaining result and research methodology); 7) since the conduct of expert studies is typical for the case when the initial data is not fully presented, and since Table 1 presents mathematical models and formulas with a minimum initial data (P, U, L), then it can be argued that the method also has an expert function, that is, it can be used as a tool for conducting expertise of electrical calculations.

4.2 GENERAL CHARACTERISTICS AND FEATURES OF THE METHOD

The method is not based on differential and integral calculus, since the normal steady-state mode does not have a problem of determining the speed of the processes in the electric circuit. For this reason, it is sufficient to use linear static mathematical models in an algebraic form [12, p. 27], [13, pp. 8, 30, 79].

The method does not involve the use of software systems and does not need an algorithm and a phased calculation procedure. To obtain the result and calculate the required desired parameter, it is necessary to select the required model (according to the required parameter) from Table 1, present the selected model in a form more convenient for calculation, substitute the initial data into the model, and perform a simple calculation using a standard calculator. *Only three electrical quantities* can be used as the initial data – voltage, active power, and power transmission length. The relationships between the three initial values are represented by formulas No. 8 and No. 9 in Table 1.

The method is very quick and easy to use. This is its main advantage. For comparison, it should be noted that when using a typical solution to the problem, in order to calculate, for example, voltage loss, it is necessary to carry out 31 calculation procedures, and when applying the TEQ method, it sufficient to use Model No. 4 in Table 1 by selecting the index $\alpha_2 = \Delta U$ and the numerical proportionality factor $k_{\alpha_2} = 2.58131 \times 10^{-2}$.

The method is characterized by a high degree of accuracy. However, it should be borne in mind that an attempt to reduce the number of decimal places in numerical proportionality factors will inevitably affect the reliability of the calculation results, since the minimum error of the method (±2%) is due to the observance of the exact number of decimal places and does not imply rounding of numbers. In addition, it should be noted that the incorrect use of units of measurement and dimensions of electrical quantities will also lead to incorrect results. The values of the proportionality factors presented in the article were not obtained by experiment but as a result of algebraic transformations of known laws and relations of electrical engineering.

The method has an applied nature and is aimed at solving practical problems; it can be classified among specific methods of scientific knowledge.

The method was developed taking into account the specifics of the research subject area.

4.3 COMPARISON OF THE EXISTING METHODS OF CALCULATION WITH THE NEW METHOD

Comparison of the well-known methods of the CSS of the power lines with the proposed new TEQ method.

Each of the 7 mathematical models and each of the 2 formulas (see Table 1) were tested on a specific numerical example [7, p. 7-8, 12-13]. Test result: the calculation error is ±2%. The permissible error of power lines parameters calculations is usually within ±5% [12, p. 31].

Comparison of calculation errors using some well-known formulas and new formulas from Table 1. The error of calculation according to the well-known Illarionov formula $U = \dfrac{1000}{\sqrt{\dfrac{500}{L} + \dfrac{2500}{P}}}$ [17, p. 26] is -10.45%, according to the similar formula No. 9 (see Table 1), it is $U = \dfrac{50}{\sqrt{\dfrac{1}{L} + \dfrac{5}{P}}}$ +0.02%.

The error of calculation according to the Nikogosov formula $U = 16\sqrt[4]{PL}$ [18, p. 198] is -23.64%, according to the similar formula No. 8 (see Table 1) it is $U = 2\sqrt{PL}$ + 0.37%. Thus, the use of new formulas improves the quality of the calculation result.

5. DISCUSSION AND RESULT

5.1 PERFORMANCE OF THE METHOD

The performance of the TEQ method (and, accordingly, the proposed seven mathematical models and two formulas) in terms of its purpose and tasks is characterized by the following factors:

a) The accuracy of the calculation result with the minimum (minor) error using mathematical models and formulas is proved by a numerical example; the result of calculation using the TEQ method was compared with the result of calculation using known methods and methods of the CSS of the power lines and the calculation error did not exceed ±2%;

b) The method was developed on the basis of known laws and relations of electrical engineering, logical inference, and methods of algebra;

c) The method can be used to obtain complete information about the main parameters characterizing the power lines in a normal steady-state;

d) The correct use of fundamental and applied sciences (algebra, logic, theoretical electrical engineering, mathematical modeling in the electric power industry, the calculation method of electrical power systems and their modes).

Confirmation of the hypothesis

Successful verification of mathematical models confirmed the study hypothesis: the basic laws of electrical engineering represented on the basis of new models and formulas do not change when the structure (combinations) of parameters and the method for describing their interrelationships were changed. The hypothesis meets the necessary conditions: it is simple, verifiable, logically justified, applicable to the object of study, consistent with theories and laws applicable in science. Conducted practical (using numerical examples) proof of the hypothesis makes it possible:

- Firstly, to conclude that the hypothesis has the status of a true statement, and has become a means of transition from known knowledge to new knowledge;

- Secondly, to consider the new TEQ method, which has many functions, including an expert function, not only as an additional method to the known methods of the CSS of the power lines but also as a method that is included in the concept of a new scientific direction in electrical engineering and electric power engineering called electroexpertology (or the general theory of electrical engineering expertise) [16].

5.2 SCIENTIFIC NOVELTY, THE THEORETICAL AND PRACTICAL SIGNIFICANCE OF THE STUDY

The study has:

a) Scientific novelty: a new method – new mathematical models and formulas – an introduction of the new term "the method of three electrical quantities" to the scientific use – a new application of the known algebraic theory of invariants to the laws of electrical engineering;

b) Theoretical significance: the development of a new method – abstract terms and concepts are represented by a new conceptual model – the presented theoretical principles of the method contribute to the scheme of calculating the steady-state of electrical power systems – the method can be included in the toolkit of a new scientific direction called "electroexpertology";

c) Practical significance: the use of a new method for manual verification of computer electrical calculations – simplifying and speeding up calculation, verification, and expert procedures, and, therefore, reducing the complexity of calculations, time and money expenditures – improving the quality and accuracy of calculation results and, on its basis, improving the decisions made.

5.3 RECOMMENDATIONS FOR THE PRACTICAL USE OF THE RESULT

The developed method and its mathematical models and formulas can be used:

a) When teaching students of electrical engineering programs, in advanced training courses for electric power industry personnel, in the practice of designing electric power industry facilities by design and engineering companies, in engineering operational calculations related to power lines modes, during research and development activities;

b) By experts in the field of electrical engineering in the preparation of expert opinions on the electrical calculations of the designed high-voltage AC systems. On the basis of the study, training programs for electrical engineers-experts can be prepared.

c) As part of the structure of scientific disciplines: "Mathematical modeling in the power industry", "Fundamentals of expert activities in the power industry".

5.4 PROMISING AREAS FOR FURTHER STUDY

Research and development of new simple mathematical models and formulas in the presence of minimum initial data in the future can be carried out in relation to new areas. 1) Calculation of the emergency operation mode of three-phase electrical lines in the transitional (unsteady) mode (overcurrent, short circuit, wire breaks of power lines). 2) Calculation of the post-emergency operation of three-phase electrical lines during transients (caused by the simultaneous self-starting of a large number of electric motors) or at a steady state in the new power conditions (limited in power). 3) Calculation of special modes of power lines (idling, self-excitation, self-recovery, asymmetrical modes). 4) AC networks of other voltage classes: low (0.22-0.38 kV), medium (1-6-10-20-35 kV), super-high (330-500-750 kV), ultra-high (1150-1500 kV). 5) Power transmission over long distances. 6) Cable power lines. 7) DC networks.

5.5 REMARK ON THE STUDY

From the results of the study:

The purpose and tasks set in the introduction have been completed in full, the hypothesis has been confirmed, the performance of the developed new method and its mathematical models has been substantiated.

The existing alternative methods and methods for calculating the steady-state power line modes were reviewed and compared with the new TEQ method. An assessment of this comparison was given.

The study is methodologically sustained since all methodological categories were described and substantiated in detail.

The scientific novelty and significance of the study were substantiated, recommendations on its practical use were given, and promising directions for further research were proposed.

Remark:

The method is simple because its mathematical models contain the minimum number of initial electrical quantities. Consequently, its use reduces the time and, consequently, the financial costs. In this sense, the method is effective.

The method can be used as a design, verification, and expert (manual verification of computer calculations).

The method can be positioned as an addition to the existing methods of calculating the steady-state mode of power lines in the framework of electrical power systems calculation.

The method reflects the unity of theory and practice since it is checked for accuracy when applied to a specific typical calculation task.

The conclusions fully comply with the context of the study, because they are based on the results of a complete description of the main, fairly structured and interrelated aspects and components characteristic in the development of a new method.

6. CONCLUSION

A scheme of the new calculation method called the "three electrical quantities method" is presented, which is aimed at solving practical problems in the field of electrical engineering. The method is unique in that it can be used without software systems, in the manual calculation mode, to accurately and efficiently determine many electrical parameters characterizing the normal steady state of three-phase high-voltage overhead power lines using only three electrical quantities, such as active power, voltage, and power transmission distance. The method complements the well-known methods of calculating the steady-state mode of electrical power systems.

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