The Synthesis of Balancing Electrical Complexes Circuits for Induction-Resistive Electrical Heating Systems

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***Abstract*—The aim of this research paper is to synthesize circuits of electrical complexes that allow to balance the single-phase and two-phase load of induction-resistive electric heating systems, as well as to compensate their reactive power for effective use when connected to a three-phase power supply system. The object of the research is the connection diagram of three-phase transformer secondary semi-windings of a symmetric complex with a split secondary winding and their connection to the load and a balancing device. As a result, the study has confirmed the hypothesis of the existence of circuits that allow to perform the symmetry and compensation of reactive power load of induction-resistive electric heating using one balancing device with applying, if necessary, a device for correction of the load power factor. The initial phase angles of current and voltage at the input of the balancing complex and the condition of their control are determined.**

***Keywords*—single-phase load, two-phase load, load balancing, transformer, electric heating, skin effect trace heating.**

I. Introduction

The promotion of oil and gas production regions in Russia in the Arctic regions and Eastern Siberia has led to a significant increase in the share of electric heating systems load in the total electrical load of technological sites from 1.5-2.0% in the 80-90-ies of XX century to 18% now with a forecast growth of 30-40% [1]. Induction-resistive heating systems, represented mainly by skin effect trace heating systems for pipelines [1-4] and their analogues [4, 5], are also becoming more widespread and are characterized by an active-inductive nature and a high unit power of the system, usually exceeding 50 kVA, reaching 250 kVA or more. Since more than two heating tubes are used for heating one pipeline rarely, the load of the induction-resistive heating system is usually single-phase or two-phase and for this reason the usage of special devices is required when connected to a three-phase power supply system to eliminate load current asymmetry [6] and reactive power compensation. This is especially important if the power supply belongs to a small generation system and its stable operation depends on the nature of the load (hereinafter referred to, as the nature of the load is the ratio of active and reactive power of the load). In addition, the asymmetry of currents and voltages leads to a decrease in the capacity of transmission lines, an increase in losses in the transmission of electricity and other negative consequences [7].

The experience of using devices for two-phase load balancing is widely known, for example, from traction power supply and it can be limited extended to use in induction-resistive electric heating, since the result of symmetry depends little on the nature of the load [8-10]. However, the issues of the single-phase load of induction-resistive electric heating symmetry have not been studied enough, which leads to inefficient decisions in the development of power supply projects of these systems. In particular, in 2018, at a public conference in Russia, a report was presented on incidents in the oil fields related to the unstable operation of power supply systems with balancing complexes of single-phase induction-resistive electrical heating systems due to the capacitive nature of the load at the input of the balancing complexes, as well as subsequently accepted decisions to use in these fields for power supply, balancing devices of a simple design that do not provide complete balancing of the input currents and compensation of reactive power [11].

The purpose of this paper is to synthesize circuits of electrical complexes for balancing a single-phase and two-phase load of an induction-resistive electric heating, characterized by a simple design, a good level of symmetry of the input currents and the required nature of the input load.

II. The Hypothesis and Research Methods

A. Overview of Single-Phase Load Balancing Schemes

The most well-known circuit of single-phase load symmetry is the Steinmetz circuit, which when used with induction-resistive heating systems has the following disadvantages: it is necessary to correct the load power factor to a purely active one (hereinafter, the power factor is understood only as $cos\varphi$, since the asymmetry and nonlinearity of the load are not taken into account [12]), two balancing devices (inductive and capacitive) are used in the circuit, resonance between the balancing devices may occur; from the advantages of the Steinmetz circuit it can be noted that at the input of the symmetric complex the load has a purely active character [6, 8]. Similar characteristics have a circuit built on the basis of a three-phase transformer with a split into half-winding secondary winding, which are connected in a special way [13]. The circuit with a counter-serial connection of the secondary windings of a three-phase transformer and one capacitive-type balancing device [14] corresponds to the nature of a single-phase load of induction-resistive electric heating systems, since it symmetries the load of an active-inductive nature with a power factor equal to $\sqrt{3}/2$ [15, 16]; the disadvantage of this system is the capacitive nature of the load with a power factor $\sqrt{3}/2$ at the input of the balancing complex, which, as mentioned above, can lead to a violation of the stability of the power supply system, but in some cases this power factor can be an advantage, for example, if it is possible to use such a complex as a reactive power compensator of a third-party load.

B. The Hypothesis of the Research

The principle of the symmetry circuit operation with counter-sequential inclusion of windings [14] is to convert in the magnetic system of the transformer a three-phase asymmetric system of currents of the secondary winding formed by the load and the balancing device into a three-phase symmetric system of currents of the primary winding. Based on this principle, it can be assumed that if the current vector of the load or the balancing device is changed in the necessary way, it is possible to obtain a symmetrical three-phase current system in the primary winding of the transformer with a given power factor at the input of the balancing complex using a single balancing device. Under these conditions requires the formation of a three-phase system of currents of the secondary winding of the transformer as a set $\{\acute{I}_L, \Delta\acute{I}, \acute{I}_1\}$, where the $\acute{I}_L$ – complex load current, $\acute{I}_1$ – a set of current balancing devices, $\Delta\acute{I}$ is the difference or sum of complexes of the load current and the balancing device depending on the direction of currents: $\Delta\acute{I} = \acute{I}_L \pm \acute{I}_1$.

Setting a limit on the number of balancing devices that complicate and increase the cost of the symmetry circuit, the change in these current vectors can be carried out by changing the voltage vectors on the load or balancing device, which in turn can be performed using a special connection of the split secondary winding of the transformer of the balancing complex [17], it is not required to output and ground the neutral [3]. Separate symmetry circuits built on this principle are used in electric heating [6, 13, 18], but there is no detailed study of their characteristics and comparison with the characteristics of all possible schemes in this set. It should be noted that the production of transformers with split secondary winding is well mastered by the industry, since they are used in the connection circuit of the windings of the "zigzag" type [19-21], so the development and implementation of new circuit on their basis is simplified. Since the load power factor of induction-resistive electric heating depends on the various characteristics of the heating system and its design, and it is not exactly $\sqrt{3}/2$, the use of a device for correcting the load power factor, which is a purely reactive element, is also required in the balancing complex. The method of connecting this device to the load, in parallel or in series, affects the power of the load and the balancing device only, but not their nature in each particular scheme, and it does not affect the nature of the load of the whole complex, as will be shown below, so only the parallel connection of the correcting device to the load is considered below. The General circuit of the symmetry complex in accordance with these provisions is shown in Fig.1, where Z_L is the load of the induction-resistive electric heating system with a power factor equal to $\sqrt{3}/2$; Z_1 – balancing device; Z_2 – device for load power factor correction.

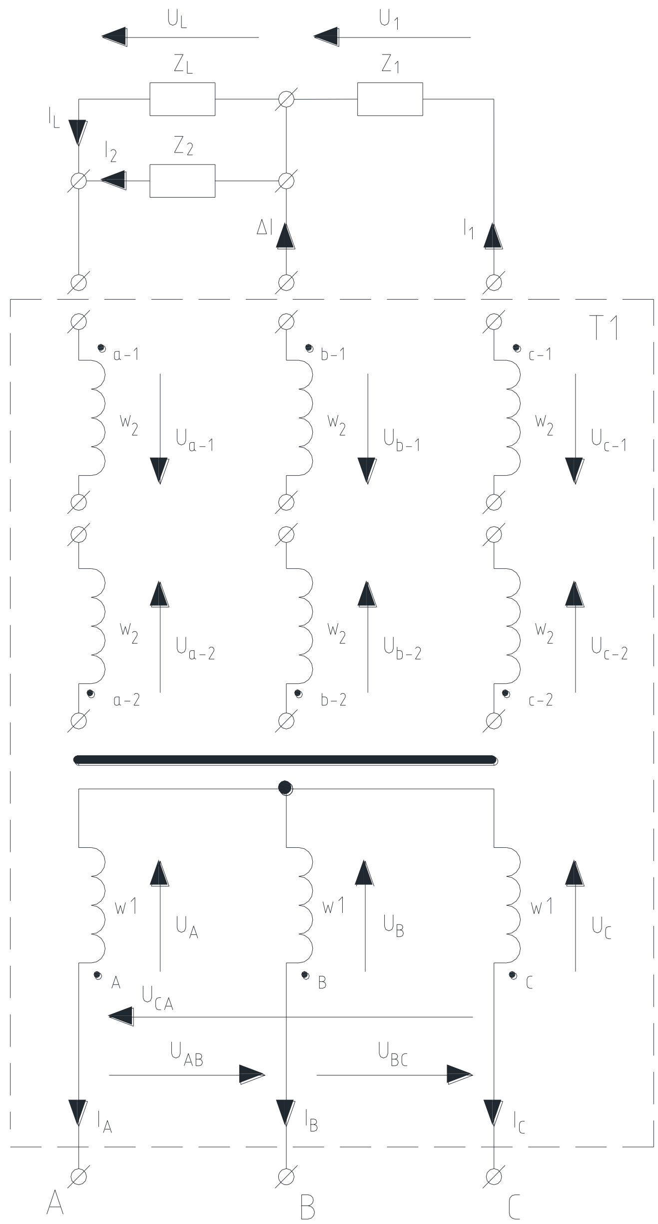

Fig. 1. General scheme of the symmetric complex.

The research hypothesis: there are such circuits for connecting the load of an induction-resistive electric heating, balancing device and semi-windings of a transformer with a split secondary winding, which form a symmetric three-phase current system in the primary windings of the transformer with a given character of the load at the input of the balancing electrical complex.

C. The research Methods

Determination of the fundamental possibility of symmetrization circuits' existence according to the hypothesis can be performed by analyzing the mathematical model of the idealized symmetric complex. This model is a system of linear equations, compiled in accordance with the laws of electrical engineering with a number of assumptions [22], as will be shown below, and the generalized analytical solution regarding the nature of the load and the balancing device depends only on the circuit connection of the windings, which is determined by a finite discrete set of connection methods. Therefore, in this paper we used the method of search using a program implemented in MathCAD, all possible solutions for the specified criteria. Criteria for the selection of circuits for balancing are the following: the equality to zero of the currents zero and negative sequence in the primary winding of the transformer is purely reactive balancing and corrective devices when balancing the single phase load; the balancing of a two-phase load without using corrective devices in the shoulder Z_L.

III. The Mathematical Model of the Symmetric Complex

A. The Assumptions Made in the Mathematical Model

The transformer is considered to be ideal, so the following expression is true for the voltage transformation coefficient:

$$\begin{cases} \dfrac{\acute{U}_A}{\acute{U}_{a-1}} = \dfrac{\acute{U}_B}{\acute{U}_{b-1}} = \dfrac{\acute{U}_C}{\acute{U}_{c-1}} = ne^{j180^\circ} \\ \dfrac{\acute{U}_A}{\acute{U}_{a-2}} = \dfrac{\acute{U}_B}{\acute{U}_{b-2}} = \dfrac{\acute{U}_C}{\acute{U}_{c-2}} = ne^{j0^\circ} \end{cases}, \tag{1}$$

where n = w_1/w_2 – transformation ratio of voltage; $\acute{U}_A$, $\acute{U}_B$, $\acute{U}_C$ – complexes of phase voltages of the primary winding of transformer; $\acute{U}_{a-1}$, $\acute{U}_{a-2}$, $\acute{U}_{b-1}$, $\acute{U}_{b-2}$,$\acute{U}_{c-1}$, $\acute{U}_{c-2}$ – complexes of the phase voltages of transformer secondary winding.

The power supply system is adopted symmetrical three-phase, the vector of phase voltage $\acute{U}_A$ is directed along the real axis of the complex plane, and then the complexes of phase voltages will be equal:

$$\acute{U}_A = U_f, \acute{U}_B = a^2 U_f, \acute{U}_C = aU_f, \tag{2}$$

where U_f – phase voltage of power supply system; $a = e^{j\frac{2\pi}{3}}$.

When neglecting the losses in a purely reactive balancing device and in a device for correcting the load power factor, their complex resistances are equal:

$$Z_1 = \pm jx_1, Z_2 = \pm jx_2, \tag{3}$$

where x_1, x_2 – resistance of the corresponding devices.

B. The Mathematical Model of a Symmetric Complex

Taking into account (1, 2), the method of connecting the semi-windings to each other, the balancing device and the load determines the voltage at the load $\acute{U}_L$and the balancing device $\acute{U}_1$; according to the scheme in Fig. 1, on the basis of the 2nd Kirchhoff law we have:

$$\begin{cases} \acute{U}_L + k_1\acute{U}_{a-1} + k_2\acute{U}_{b-1} + k_3\acute{U}_{c-1} + k_4\acute{U}_{a-2} + \\ \quad +k_5\acute{U}_{b-2} + k_6\acute{U}_{c-2} = 0 \\ \acute{U}_1 + m_1\acute{U}_{a-1} + m_2\acute{U}_{b-1} + m_3\acute{U}_{c-1} + m_4\acute{U}_{a-2} + \\ \quad +m_5\acute{U}_{b-2} + m_6\acute{U}_{c-2} = 0 \\ k_i \in \{1;\ -1;0\} \\ m_i \in \{1;\ -1;0\} \end{cases}, \tag{4}$$

where $k_i$and m_i are coefficients that specify the method of connecting the corresponding secondary half-winding of the transformer to the load or balancing device (in series, counter or not connected); $\acute{U}_L$ is the voltage complex at the load and the correction device; $\acute{U}_1$ is the voltage complex at the balancing device.

In accordance with the circuit of Fig. 1 and (4) on the basis of the law of equilibrium of the magneto motive force along a closed circuit along the transformer's magnetic circuit after transformations, we have:

$$\begin{cases} w_1(\acute{I}_A - \acute{I}_B) + w_2[(\acute{I}_L + \acute{I}_2)(k_1 - k_2 - k_4 + k_5) + \\ \quad +\acute{I}_1(m_1 - m_2 - m_4 + m_5)] = 0 \\ w_1(\acute{I}_B - \acute{I}_C) + w_2[(\acute{I}_L + \acute{I}_2)(k_2 - k_3 - k_5 + k_6) + \\ \quad +\acute{I}_1(m_2 - m_3 - m_5 + m_6)] = 0 \end{cases}, \tag{5}$$

where $\acute{I}_2$ is the current complex of the correction device.

The remaining equations of the mathematical model of the balancing complex are based on Ohm's law and the first Kirchhoff law:

$$\begin{cases} \acute{I}_A + \acute{I}_B + \acute{I}_C = 0 \\ \acute{I}_L + \acute{I}_2 - \acute{I}_1 - \Delta\acute{I} = 0 \\ \acute{U}_L = \acute{I}_L \cdot Z_L \\ \acute{U}_L = \acute{I}_2 \cdot Z_2 \\ \acute{U}_1 = \acute{I}_1 \cdot Z_1 \\ Z_L = R + j\dfrac{R}{\sqrt{3}} \end{cases}, \tag{6}$$

where R is the active resistance of the load.

The set of coefficients $k_i, m_i \in \{1;\ -1;0\}$ uniquely sets a specific method for connecting the secondary half-windings of a transformer of a balancing complex, the total number of different connection methods being is $3^{12} = 531{,}441$. However, in accordance with (4, 5), circuits that cannot be implemented are also set, since it is impossible to simultaneously provide the specified method of connecting a certain half-winding to the load and balancing device in accordance with the second Kirchhoff law, therefore, such options were excluded from the final set of circuits, and only matching options have been left:

$$\begin{cases} k_i \neq 0 \rightarrow m_i = -k_i \\ k_i = 0 \rightarrow m_i \in \{-1;\ 0;1\} \end{cases}. \tag{7}$$

Also, a number of circuits have no applied value due to the fact that they obviously cannot balance the load for the following reasons:

- No current flows through the windings located on a separate core of the magnetic circuit, which meets the condition: $k_i = k_{i+3} = m_i = m_{i+3} = 0, i \in \{1; 2; 3\}$.
- No voltage is applied to the load or balancing device due to the fact that none of the half-windings is connected, or the voltage of the half-windings cancels each other, which is specified by the following condition:

$$\begin{cases} \sum_{i=1}^{3} k_i a^{i-1} - \sum_{i=4}^{6} k_i a^{i-4} = 0 \\ \sum_{i=1}^{3} m_i a^{i-1} - \sum_{i=4}^{6} m_i a^{i-4} = 0 \end{cases}. \quad (8)$$

We also excluded from consideration the circuits $\{k'_i, m'_i\}$ satisfying the condition $k'_i = -k_i, m'_i = -m_i$: since characteristics are identical to the characteristics of the circuits $\{k_i, m_i\}$ due to the symmetry of the circuits with the reverse direction of the winding of the semi-windings. After exclusion of the circuits in accordance with the above conditions, including (7, 8), a total of 47,943 circuits remain. For these circuits, the parameters of the balancing and correcting device were calculated, as well as the phase shift of the currents relative to the voltage phases in the primary winding of the transformer of the balancing complex, if the reverse and zero sequence of currents $\acute{I}_A, \acute{I}_B, \acute{I}_C$.are equal to zero. For all these parameters, analytical expressions based on systems of equations (1-6) were found, but they are too large to accommodate in this paper. The generalized expression for calculating the complex resistance of the balancing device has the form:

$$\begin{cases} Z_1 = |Z_L| \cdot e^{j\,arg\,(Z_L)} \cdot f_1(k_i, m_i) \cdot e^{j\,f_2(k_i, m_i)} \\ f_1(k_i, m_i) = \dfrac{|Z_1|}{|Z_L|} \\ arg(Z_1) = arg(Z_L) + f_2(k_i, m_i) = arctg\left(\dfrac{Im(Z_1)}{Re(Z_1)}\right) \end{cases}. \quad (9)$$

Moreover, for each circuit $f_1(k_i, m_i)$ and $f_2(k_i, m_i)$ are uniquely determined, therefore the converse is also true that the magnitude and nature of the load for a certain balancing circuit with a given balancing device is uniquely determined. Hereinafter, by $arg(F)$ of some function $F = |F| \cdot e^{j\mu}$ we mean μ.

IV. The Results

To analyze the synthesized circuits, we studied the dependence of the phase angle φ between the current and voltage of the primary winding of the transformer of the balancing complex on the complex resistance of the balancing device without using a correction device. The scatter plot of the values $\varphi = f\big(f_1(k_i, m_i), arg(Z_1)\big)$, in accordance with (9) is shown in Fig. 2.

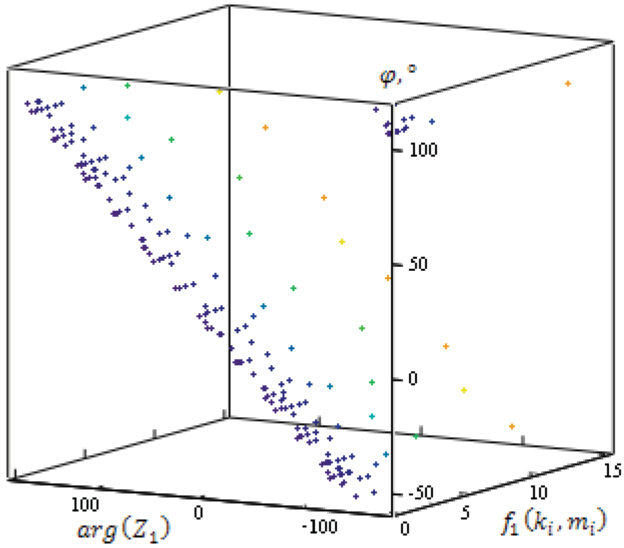

Fig. 2. The scatter plot of φ values from $f_1(k_i, m_i)$ and $arg(Z_1)$.

As follows from Fig. 2, despite the large number of synthesized circuits, the characteristics of some of them are identical, probably due to the presence of symmetries not considered in Section III. The set of different angles φ is 3 orders of magnitude smaller than the number of circuits and includes 49 different options, and with purely reactive resistance of the balancing device, only angles $\varphi \in$ $\in \{-30°; 60°\}$ with corresponding $arg(Z_1) \in \{-90°; 90°\}$, such values can be achieved in 10,872 circuits. The values of φ lie in one plane passing through the line parallel to the axis $f_1(k_i, m_i)$, that is, $f_1(k_i, m_i)$ does not affect φ and it is determined only by the connection circuit of the windings, and the relationship between φ and $arg(Z_1)$ is linear. Considering (9), it can be argued that for any symmetrizing scheme from the set is:

$$\Delta\varphi = \Delta arg(Z_1) = \Delta arg(Z_L). \quad (10)$$

The presence of a separate cluster $\varphi > 100°$ in Fig. 2 is associated with the periodicity of the $arg(Z_1)$ function.

The circuits with complex (active-reactive) resistance of a balancing device of type $A + jB$ correspond to two-phase load circuits with a second load arm connected to the balancing device arm of a balancing complex. 14,970 circuits with the complex resistance of the balancing device and positive A make it possible to form a collection of 22 different φ. The scatter plot of φ values from $arg(Z_1)$ for a purely reactiveZ_1 is shown in Fig. 3. Figure 3 shows that the load at the input of the balancing complex will be purely active with the active-capacitive nature of the load with a power factor of $\sqrt{3}/2$ in the arm of the circuit where the balancing device is connected, that is $Z_1 = R - jR/\sqrt{3}$, which can be reached by connecting to this the shoulder of the capacitive correction device in conjunction with an induction-resistive heating system. 22,101 circuits with integrated resistance of the balancing device have a negative A, which can be considered as connecting a single-phase voltage source to the shoulder of the balancing device, while 7,851 circuits do not consume electricity from the power supply system.

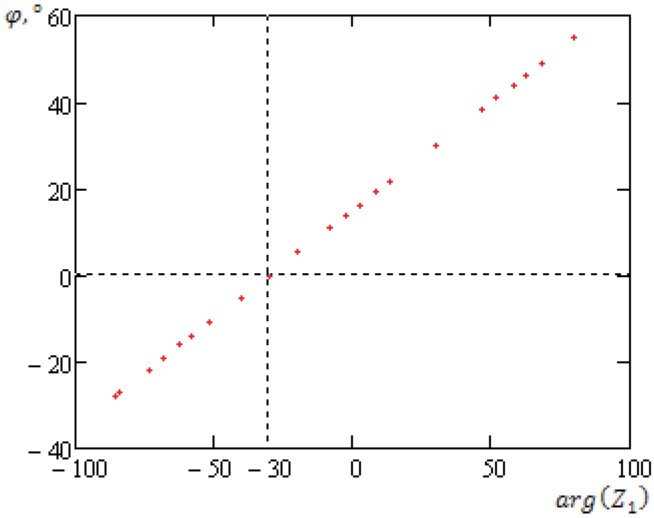

Fig. 3. The scatter plot of φ values from $arg(Z_1)$ for a purely reactive Z_1.

In accordance with (10), the use of a corrective device in the load arm allows one to increase the number of balancing circuits with a purely reactive resistance of the balancing device. Figure 4 shows the scatter of the values of $\varphi = f(|Z_L^{'}|, arg(Z_L^{'}))$ for a purely reactive Z_1, where $Z_L^{'}$ is the total complex resistance of the load and the correction device. In Fig. 4 it can be seen that the values of φ lie in two parallel planes passing through lines parallel to the axis $|Z_L^{'}|$, this confirms expression (10). Also from Fig. 4 it follows that the function $\varphi = f(|Z_L^{'}|, arg(Z_L^{'}))$ has symmetry: for the same values of $|Z_L^{'}|$, but opposite values of $arg(Z_L^{'})$, φ takes the same values modulo, but different in sign. However, 2 values of $\varphi \in \{30°; -60°\}$ are not included in this symmetry. Such symmetry means that the use of a corrective device allows to change the phase shift of the currents of the primary winding of the transformer of the balancing complex to $\pm\varphi^{'}$.

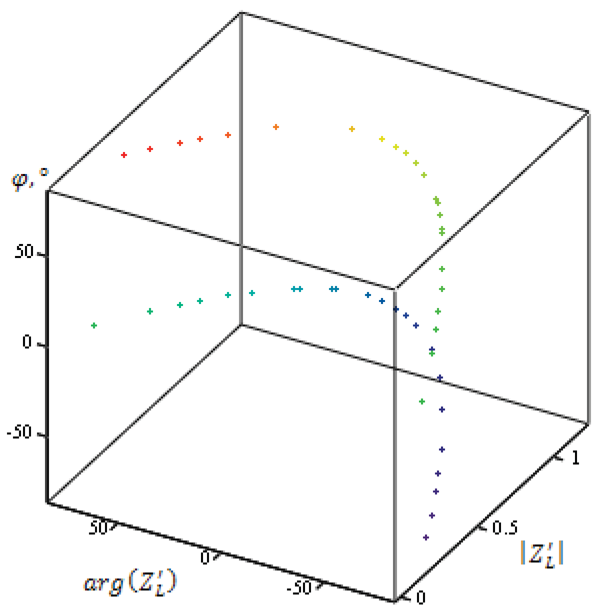

Fig. 4. The scatter plot of φ values from $|Z_L^{'}|$ and $arg(Z_L^{'})$.

Moreover, the number of options for various φ is limited and amounts to 46 with a total number of 25,584 transformer winding connection circuits. Summary data on the balancing circuits are shown in Table 1.

TABLE I. CHARACTERISTICS OF SYMMETRIC SCHEMES

Circuits defined by a condition	**Characteristics of Circuits**	
	Reachable angles φ	***Numder of circuits***
$Re(Z_1) = 0$, $Z_2 = 0$, $arg(Z_L) = 30°$	$-30°$; $60°$	10,872
$Re(Z_1) > 0$, $Z_2 = 0$, $arg(Z_L) = 30°$	$-27.8°$; $-27.0°$; $\pm21.8°$; $\pm19.1°$; $\pm16.1°$; $\pm13.9°$; $\pm10.9°$; $\pm5.2°$; $0.0°$; $30.0°$; $38.2°$; $40.9°$; $43.9°$; $46.1°$; $49.1°$; $54.8°$	14,970
$Re(Z_1) < 0$, $Z_2 = 0$, $arg(Z_L) = 30°$	$-54.8°$; $-49.1°$; $-46.1°$; $-43.9°$; $-40.9°$; $-38.2°$; $-33.0°$; $-32.2°$; $65.2°$; $70.9°$; $73.9°$; $76.1°$; $79.1°$; $81.8°$; $87.0°$; $87.8°$; $90.0°$; $92.2°$; $93.0°$; $98.2°$; $100.9°$; $103.9°$; $106.1°$; $109.1°$; $114.8°$	22,101
$Re(Z_1) = 0$, $Z_2 \neq 0$, $arg(Z_L) = 30°$	$\pm5.2°$; $\pm10.9°$; $\pm13.9°$; $\pm16.1°$; $\pm19.1°$; $\pm21.8°$; $\pm27.0°$; $\pm27.8°$; $30.0°$; $\pm32.2°$; $\pm33.0°$; $\pm38.2°$; $\pm40.9°$; $\pm43.9°$; $\pm46.1°$; $\pm49.1°$; $\pm54.8°$; $-60.0°$; $\pm65.2°$; $\pm70.9°$; $\pm73.9°$; $\pm76.1°$; $\pm79.1°$; $\pm81.8°$	25,584

V. DISCUSSION

Expression (10) is a condition for controlling the angle φ, that is, for the circuit to work in the symmetry mode for a given angle $\varphi^{'}$, it is necessary to equally change the nature of the load and the balancing device, the initial angle φ in this case depends on the connection circuit of the windings and the given initial character load. Thus, when balancing a two-phase load with corrective devices, you can get any desired angle $\varphi^{'}$, which fully meets the purpose of the paper. The most interesting for the further research are circuits with φ close to 0, since they allow to compensate for the reactive power of the load. Such circuits include, for example, $\{k_i; m_i\} \in \{1; -1; 0; 1; 1; 1; 0; 1; -1; -1; -1; -1\}$, $arg(Z_1) = -30°$, $arg(Z_L) = 30°$, $\varphi = 0°$.

For a single-phase load, this requirement is partially fulfilled, since a change in the nature of the balancing device is possible only from capacitive to inductive or vice versa, and the initial angles φ are limited by the values given in Table 1. As it can be seen in Fig. 4, obtaining small modulo φ, which means compensation of the reactive power of the load, is achieved with large values of the module $arg(Z_1)$, which requires a large adjustment by the corrective device of the nature of the load, if it is close to the nature of induction-resistive systems. Of interest for further research are schemes $\{k_i; m_i\} \in \{1; -1; 0; 0; 1; -1; -1; 1; -1; -1; -1; 1\}$, $arg(Z_1) = -90°$, $arg(Z_L) = 30°$ and $\varphi = -30°$, which corresponds to the circuit of [14]; $\{k_i; m_i\} \in \{1; 1; 1; 1; 1; 0; 0; -1; -1; -1; -1; 0\}$, $arg(Z_1) = -90°$, $arg(Z_L) = 68.2°$ и $\varphi = -10.9°$.

It should be noted that the choice of a specific circuit for balancing the load from circuits having the same or close to each other φ, could be based on technical and economic indicators that are not considered in this paper, since they require the calculation of an imperfect balancing complex.

VI. CONCLUSION

A generalized mathematical model of an idealized balancing complex has been developed, its research has confirmed the hypothesis that there are connection circuits for transformer windings with a split secondary winding and a balancing device that allow balancing a single-phase and two-phase load of induction electric heating and compensating for its reactive power with a given load at the input of the balancing complex. The condition for controlling the phase angle between the current and voltage vectors of the primary winding of the transformer of the symmetrizing complex using balancing and correcting devices has been established.

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