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MATHEMATICAL MODELING OF THE OPERATION OF A THREE-PHASE POWER TRANSFORMER AT LOW VOLTAGE QUALITY

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Abstract- The article examines the main issues of phase symmetry breaking and distortion of the voltage form, characteristics of the short-circuit mode of a three-phase transformer at low voltage. For this purpose, the mathematical method of superposition is used. Using the parameters for the higher harmonic components, the values of the zero, forward and reverse sequence currents are determined. the current flowing through the windings is calculated, which is equal to the sum of the currents of the forward, reverse and zero sequences of the main and higher harmonic components. The parameters that are part of the voltage applied to the transformer are determined. The analysis of the inductive resistance of the well-left sequence of three-phase oil transformers is given. The parameters are considered based on the losses in the transformer windings from all harmonics of the spectrum included in the non-sinusoidal curve and the analytical Equation for the power coefficients. The method of detecting emerging defects in the windings and initial damage to the transformer is considered. The flowchart of the method of low-voltage nanosecond pulses, a model of a power transformer for calculating the elements of a replacement circuit for the purpose of its diagnosis by low-voltage pulses and Subcircuit simulating a chain model of a transformer winding are analyzed.

Keywords: Three-Phase Power Transformer, Higher Harmonic, Short Circuit, Asymmetric Currents, Additional Losses, Single-Phase Loads, SPS-Model, Low-Voltage Pulses, Replacement Circuit, Power Transformer, Nanosecond Pulses.

1. INTRODUCTION

The electrical equipment of electrical systems and networks of normal design is designed to work in conditions of symmetrical voltage of sinusoidal shape. The widespread use of single-phase loads and amplifiers that create non-sinusoidal currents has recently led to a violation of the symmetry and sinusoidal voltage of the system greater than the permissible norms [1, 2], which causes a deterioration in the technical and operational and economic indicators of electrical equipment, including transformers as the main element of the network.

With symmetry and sinusoidal of the applied voltage, the parameters and characteristics of the transformer are physically real values and are unambiguously determined by calculation or experimentally. Determining the exact values of parameters and characteristics at low-quality voltage is associated with some difficulties [1, 8, 9].

As is known, the essence of the parameter value is revealed by mathematical modeling of processes and modes in technical devices, including in a transformer. One of the methods of mathematical modeling of the steady-state mode of a transformer with non-sinusoidal tension can be the overlay method [7, 8, 9, 10, 14]. When designing, it is necessary to take into account the resistance of the installed electrical equipment to the manifestation of various factors of influence from the network. The following are the power features of some types of loads. Electrical equipment equipped with a switching power supply (computer equipment, office equipment, appliances, audio-video equipment, etc.) is not critical to the voltage level and, as a rule, operates steadily in the range from 185 to 250 V). It is even permissible to interrupt the voltage up to 0.3 s, if it is not accompanied by significant interference. However, high-frequency interference from 150 kHz and above easily passes through the power supply unit into the device. Pulsed over voltages are also dangerous, which can cause a breakdown of the transistor in the converter of the power supply unit. In most cases, the source itself has both a filter and a varistor to protect against interference, but they are able to protect only from weak influences over the network. For three-phase motors, the main danger is a phase misalignment, in which the overheating of the engine increases sharply with subsequent failure. They are uncritical to interference and short-term interruption of voltage.

When the voltage at the input of the transformer (transformer power supply) increases sharply, the current increases, the transformer enters saturation mode, makes noise, overheats and fails. Magnetic contactors, power relays, etc. When the input voltage is low, they either do not start, or they start with a rattle. The situation worsens when a powerful inductive load is connected to the output of the contactor. At the time of connecting the voltage to the load due to large inrush currents, a sharp voltage drop occurs, and the contactor disconnects the load.

The voltage rises again, the contactor tries to connect the load again, and the whole cycle repeats until the contactor fails. Halogen lamps, in addition to the general sensitivity to the voltage level, are very sensitive to short-term power interruption. Inrush currents of switching on the lamp are the main cause of failure.

An attempt to improve the situation with the help of a stepwise voltage stabilizer only worsens the situation. This article is devoted to the study of the short-circuit characteristics of a three-phase power transformer with asymmetry and non-sinusoidal voltage of the supply network.

2. CHARACTERISTIC FEATURE OF THE ANALYZED MODE

A characteristic feature of this transformer mode is that the magnetic flux, which is a scattering flux, is strictly proportional to the current in the winding, i.e., a rectilinear relationship is assumed between the applied voltage and current, which makes it possible to use overlay methods in the study. In this case, if the applied voltage is asymmetric in phases and has a distorted shape, then the currents flowing through the windings will be distorted and contain reverse and zero sequences. Then the current flowing through the windings is equal to the sum of the currents of the forward, reverse and zero sequences of the main and higher harmonic components [4, 5]:

$$I_k = \sum_{v=1}^{n} I_{1v} + \sum_{v=1}^{n} I_{2v} + \sum_{v=1}^{n} I_{rv} \tag{1}$$

The currents of the higher harmonic components can be stressed through the currents of the main harmonic, as [4]:

$$I_{1v} = a_{1v} I_{11} \frac{Z_{11}}{Z_{1v}} \tag{2}$$

$$I_{2v} = a_{2v} I_{21} \frac{Z_{21}}{Z_{2v}} \tag{3}$$

$$I_{rv} = a_{rv} I_{r1} \frac{Z_{r1}}{Z_{rv}} \tag{4}$$

where, a_{1v}, a_{2v}, a_{rv} are ratio of voltage of higher harmonic components of the forward, reverse and zero sequences to voltage of main harmonic, respectively; I_{11}, I_{21}, I_{v1} are current of the forward, reverse and zero sequences of main harmonic, respectively; z_{11}, z_{21}, z_{rv1} are total resistances of the forward, reverse and zero harmonic sequences, respectively; and Z_{11}, Z_{21}, Z_{rv1} are total resistances of the forward, reverse and zero sequences of higher harmonics, respectively.

The arrangement of asymmetric currents and voltages into symmetrical components is considered relative to sinusoidal currents and voltages. Non-symmetric non-sinusoidal currents and voltages should first be decomposed into higher harmonic ones and then the symmetrical components that come from the main and higher harmonics should be considered. At the same time, different transformer parameters correspond to each system of currents and voltages in an asymmetric non-sinusoidal operating mode [6].

Since there are no rotating parts in the transformer, the total resistance of the forward sequence to the currents of the higher harmonics Z_{1v} (where, v shows the harmonic order) is assumed to be equal to the resistance of their reverse sequence [5]:

$$Z_{1v} = Z_{2v} \tag{5}$$

Based on this, for decomposed into forward and reverse sequences of the fundamental harmonic voltages, it is possible to use a generally accepted system of transformer deceleration, taking into account magnetic losses [11, 12, 13]. If the transformer operates at an asymmetric sinusoidal mains voltage, then, as indicated above, it is necessary to consider the action of each harmonic separately. Then the transformer resistances to the currents of higher harmonics in general will be as Equation (6) [6]:

$$\left.\begin{aligned} Z_{1v} &= R_{1v} + jX_{1v} \\ Z_{2v} &= R_{2v} + jX_{2v} \\ Z_{rv} &= R_{rv} + jX_{rv} \\ Z_{mv} &= R_{mv} + jX_{mv} \end{aligned}\right\} \tag{6}$$

In an inversely proportional relationship between the flow and frequency, it is possible not to take into account the magnetizing current in the delay circuit for higher voltage harmonics, i.e., $Z_{mv} = \infty$ (without the magnetizing branch) should be taken into account.

3. DETERMINATION OF PARAMETERS INCLUDED IN THE VOLTAGE APPLIED TO THE TRANSFORMER

One of the main parameters of transformers is the active resistance R, which is a measure of the conversion of electrical energy into heat [1, 8, 11]. It is known that the losses in the transformer windings from the periodic component of the load current in normal and abnormal operating modes are equal to I^2R, where the active resistance R is the total resistance determined during the passage of the periodic current and proportional to the sum of ohmic losses in the windings and additional short-circuit losses [4]:

$$R = R_1 + r_d \tag{7}$$

where, the r_d determines the losses in the conductors of the primary and secondary windings from displacement current losses in structural elements (tank, pressure plates, tightening bolts, etc.). Then for additional short-circuit losses from 5th-order currents without taking into account losses in tightening studs and other elements of the structure due to their smallness, we can write the Equation (8) [6]:

$$P_{DV} = I_v^2 \left(P_{b1} v'' + P_{\delta 1} v''' + P_{y1} v^p + P_{p\lambda} v^q \right) \tag{8}$$

where, P_{b1}, $P_{\delta 1}$, P_{y1}, $P_{p\lambda}$ are losses from current displacement in windings, tightening beams, yoke beams and pressing plates, respectively.

Experimental studies [3] show that the physical processes in the tank walls, yoke beams, pressing plates and other massive steel elements when the magnetic field changes are similar. Therefore, the dependences of losses in the tank walls and in other details of the structure on current and frequency will be similar, i.e., it is possible to take $m \approx p \approx q$=1.02+1.18. The value of the degree of n depends on numerous factors and for practical purposes its definition is given in [4].

Voltage harmonics in transformers cause an increase in hysteresis losses and losses associated with eddy currents in steel, as well as losses in windings. The service life of the insulation is also reduced. An increase in losses in the windings is most important in a converter transformer, since the presence of a filter, usually attached to the AC (alternating current) side, does not reduce the harmonics of the current in the transformer. Therefore, it is required to install a large transformer power. Local overheating of the transformer tank is also observed.

The negative aspect of the effect of harmonics on powerful transformers consists in the circulation of a tripled zero-sequence current in windings connected in a triangle. This can lead to their overload [15]. If we assume that the dependencies of losses in the tank walls and in other details of the structure on current and frequency are equal $\left(v'' = v''' = v^p = v^q = v^k\right)$, then Equation (8) can be written as [5]:

$$P_{Du} = I_v^2 \times P_{D1} \times v^k \quad (9)$$

where,

$$P_{D1} = P_{b1} + P_{\delta 1} + P_{y1} + P_{p\lambda} \quad (10)$$

Represents additional short-circuit losses from the main frequency current. The exponent of the degree of k in Equation (9), depending on the location of the structural elements, the size of the winding wire, the structure of the windings varies widely and its exact determination analytically is very difficult. Taking into account the percentages of the individual components of P_{D1} and based on the experimental data for practical calculations, we can recommend the following values [1, 3]:

- ✓ K≈1.02÷1.05 - for low-power transformers;
- ✓ K≈1.05÷1.12 - for medium power transformers;
- ✓ K≈1.12÷1.20 - for high-power transformers.

Accordingly, the resistance determined by additional losses from currents of higher harmonic components will be:

$$r_{Dv} = r_{D1} \times v^k \quad (11)$$

The active resistance of the short circuit of the current transformer of higher harmonics is defined as:

$$R_{kv} = R + r_{D1} \times v^k \quad (12)$$

To determine the inductive resistance of a transformer to currents of higher harmonics of the X_{kv}, it is necessary to calculate the scattering fluxes that occur when currents with a frequency vf_1 flow through the transformer windings. The scattering field that causes the X_{km} is created by the magneto motive force of the primary winding and the MDS of the secondary winding equal to it in magnitude. With neglect of the idling speed, as well as the magnetic resistance of the magnetic circuit, the inductive resistance of the transformer short circuit is determined by the Equation [5]:

$$X_k = \frac{7.9 f_1 W^2 \pi D p + r_{D1} \times v^k}{I_S} \times 10^{-8} \quad (13)$$

where, D is the average diameter of the channel between the windings; p is the coefficient, determined by the size of the gap between the windings, the maximum size (thickness) of the primary and secondary windings, is equal to p=0.93÷0.95.

As can be seen from the Equation (13), the inductive resistance of the transformer X is determined mainly by the geometric dimensions of the windings, which makes it possible to easily determine its values for higher harmonic components. If Equation (13) are written as $X_{k1} = C_1 f_1$, then for higher harmonic components without taking into account the nonlinearity of ferromagnetic elements [15]:

$$X_{kv} = C_1 f_v = v \times f_1 C_1 = X_{k1} v \quad (14)$$

taking into account the nonlinearity:

$$X_{kv} = X_{k1} v^d \quad (15)$$

where, C_1 is a constant coefficient determined by the geometric dimensions of the transformer windings; d is an exponent; for practical purposes of calculation, it is assumed to be equal to one.

The total resistance of a short circuit with a current of the v^{th} order can be determined by Equation (16) [6]:

$$Z_{rv} = \sqrt{R_{rv}^2 + X_{kv}^2} \quad (16)$$

By increasing frequency, difference between R_{kv} and X_{kv} increases, i.e., $R_{kv} = X_{kv}$ and the total short-circuit resistance:

$$Z_{kv} \approx X_{kv} = X_{kv1}, \;\; v \neq 1 \quad (17)$$

If there is a zero wire in the network, i.e., when zero-sequence currents flow, it is necessary to represent the resistance to zero-sequence currents Z_{sc}, $R_{sc}=X_{sc}$. The voltage asymmetry presents in the network and, consequently, the asymmetry and non-sinusoidal currents require the determination of the zero-sequence resistance of both the main harmonic of the current and the higher harmonics. Phase load asymmetry is created not only by the first harmonic, but also by the higher harmonics. Decomposition of each from higher harmonics to symmetrical components leads to the justification of the existence of all three symmetrical components for each harmonic.

The active resistance of zero-sequence currents of oil transformers in comparison with the resistance of the windings to direct current increases due to losses in the magnetic circuit, tank and structural elements of the recess part. The active resistance of zero-sequence currents of the R_{sc} is commensurate with the inductive one and can be determined with sufficient accuracy from [5]:

$$R_{sc} = r_{k1} + r_0$$

where, r_{k1} is the active resistance of the magnetizing winding, which is determined by the catalog value of short-circuit losses; r_0 is the reduced resistance due to losses in the transformer tank. The active resistance to currents of the zero-sequence of higher harmonics, respectively, is defined as Equation (18) [5]:

$$R_{scv} = r_{k1v} + r_{0v} \quad (18)$$

Losses in the transformer tank, taking into account the Equation [5], can be determined by:

$$P_{scv} = I_v^2 \times P_{o\delta 1} \times v^m \quad (19)$$

Accordingly, we find the resistance caused by losses:

$$R_{scv} \approx r_{0v} + r_{0v1} \times v^m \quad (20)$$

The inductive resistance of the zero sequence of the transformer:

$$X_{scv} = x_{0s} + x_{0\mu} \quad (21)$$

where, x_{0S} is the inductive resistance of the transformer winding due to scattering flows from zero-sequence currents; $x_{0\mu}$ is the inductive resistance of magnetization by zero-sequence current. The magnetic flows of the zero sequence are closed through the structural parts of the transformer recess, the air space between the magnetic circuit and the tank, the walls, the bottom and partially the tank lid.

4. ANALYSIS OF INDUCTIVE RESISTANCE OF ZERO SEQUENCE OF THREE-PHASE OIL TRANSFORMERS

The derivation formula from [5, 6, 7] for determining the inductive resistance of a zero sequence of transformers without taking into account $x_{0\mu}$ has the form [15]:

$$X_{sc} = \frac{4_{f1}\omega^2 t_a}{b}\left(h + \frac{L_a}{b}\right) \times 10^{-8} \quad (22)$$

where, L_a is the average perimeter of the flow, b is distance between magnetic circuit and transformer tank $h = \frac{h_1 + h_2}{2}$

where, h_1 is the distance between the winding and the bottom of the tank, h_2 is the distance between the winding and the axis of the magnetic core rod, measured along the surface of the rod [15].

The constructive distances and the frequency of the current included in Equation (22) determine mainly the inductive resistance of the zero sequence. Then, for the fundamental harmonic, Equation (22) can be written as follows:

$$X_{sc1} = C_2 f_1$$

The inductive resistance of the zero sequence of the transformer to currents of higher harmonics, without taking into account the nonlinearity of ferromagnetic elements, can be determined by Equation of the X_{sc1}:

$$X_{sc1} = C_2 f_v = C_2 f_1 v = X_{sc1} \times v \quad (23)$$

Taking into account the nonlinearity:

$$X_{scv} = X_{sc1} \times v^e$$

where, e is the exponent, for practical calculation circuits is assumed to be equal to one.

The total resistance to currents of the zero sequence of higher harmonic components is [7]:

$$Z_{sc} = \sqrt{R_{sc}^2 + X_{sc}^2} \quad (24)$$

Taking into account the fact that $r_{k1} = r_{sc}$ (for higher harmonic components, the increase in r_{k1} relative to r_{sc} is very small), frequency exaggerations:

$$Z_{scv} = \sqrt{R_{scv}^2 v^{2m} + X_{sc1}^2 v^2} \quad (25.a)$$

If we take the average value for m to be 1.1, then,

$$Z_{scv} = v\sqrt{R_{sc1}^2 v^{2.2} + X_{sc1}^2} \approx Z_{sc1} \quad (25.b)$$

Usually, in high-power transformers,

$$\begin{aligned} &R_{scv} \ll X_{scv} \\ &Z_{scv} \approx X_{scv} = X_{sc1} \times v\ ,\ v \neq 1 \end{aligned} \quad (25.c)$$

$$I_{1v} \approx a_{1v}\ ,\ I_{11} v^{-1} \quad (26)$$

$$I_{2v} \approx a_{1v}\ ,\ I_{21} v^{-1} \quad (27)$$

$$I_{scv} \approx a_{scv}\ ,\ I_{sc1} v^{-1} \quad (28)$$

The effective value of the currents can be determined from the Equation [2, 5, 6]:

$$I_k = \sqrt{I_{11}^2 + I_{12}^2 + I_{13}^2 + \ldots + I_{1n}^2} = I_{11}\sqrt{\sum_{v=1}^{n} a_{2v}^2 v^{-2}}$$

Accordingly, $I_n = I_{21}\sqrt{\sum_{v=1}^{n} a_{2v}^2 v^{-2}}$, $I_{sv} = I_{sv1}\sqrt{\sum_{v=1}^{n} a_{svv}^2 v^{-2}}$, the effective value of the short-circuit current [5]:

$$I_k = \sqrt{I_1^2 + I_2^2 + I_{sv}^2} \quad (29)$$

It should be borne in mind that with the asymmetry of the current in phases and non-sinusoidal shape e. g, the value of the permissible relative current of the fundamental frequency will be determined for the busiest phase. Short circuit losses from non-sinusoidal current can be determined as the sum of losses from currents of higher harmonic components and fundamental frequency. The definition of these losses is carried out by Equations (8), (9), (10) and (19) and does not present any difficulty. Based on these data, it is possible to calculate the dependence of energy losses for all voltage frequencies. The power factor in the short-circuit mode for the higher harmonic components will be defined as the ratio of the active resistance to the total short-circuit resistance, i.e. [6]:

$$\cos\varphi_{kv} = \frac{R_{kv}}{Z_{kv}}$$

If we express the ratio of resistances in terms of the short-circuit power factor for the fundamental harmonic, then we will have [5]:

$$\cos\varphi_{kv} = \cos\varphi_{kv1} = \frac{Z_{k1}R_{kv}}{Z_{kv}R_{k1}}$$

Given a small change in relation $\frac{R_{kv}}{R_{k1}}$ with increasing frequency, as well as Equation (17), we obtain an approximate relation for determining $\cos\varphi_{kv}$ [5]:

$$\cos\varphi_{kv} = \cos\varphi_{kv1}\frac{Z_{k1}}{X_{kv}v}$$

The approximation is achieved by taking $\frac{R_{kv}}{R_{k1}}$ in the numerator $Z_{kv}=X_k v$ which is in the denominator. The calculation shows that such an approximation gives an error of up to 7% for the most pronounced 5th harmonic of the voltage.

5. ANALYSIS OF TRANSIENTS IN TRANSFORMER WINDINGS

One of the most important tasks is the timely detection of emerging defects in the windings and initial damage to the transformer, which will help to repair the transformer before an accident occurs, causing its failure [1, 2]. Therefore, there is a need to create a model of a power transformer for further calculation of the elements of the replacement circuit in order to diagnose it by the method of low-voltage pulses. For this purpose, the method of low-voltage nanosecond pulses is most acceptable, which is based on a pulse generator that creates pulses with a nanosecond front and a duration of several hundred nanoseconds. Such an impulse is applied to one of the windings of the power transformer**.** The pulse is applied to one of the windings of the power transformer. The flowchart of this method is shown in Figure 1 [16].

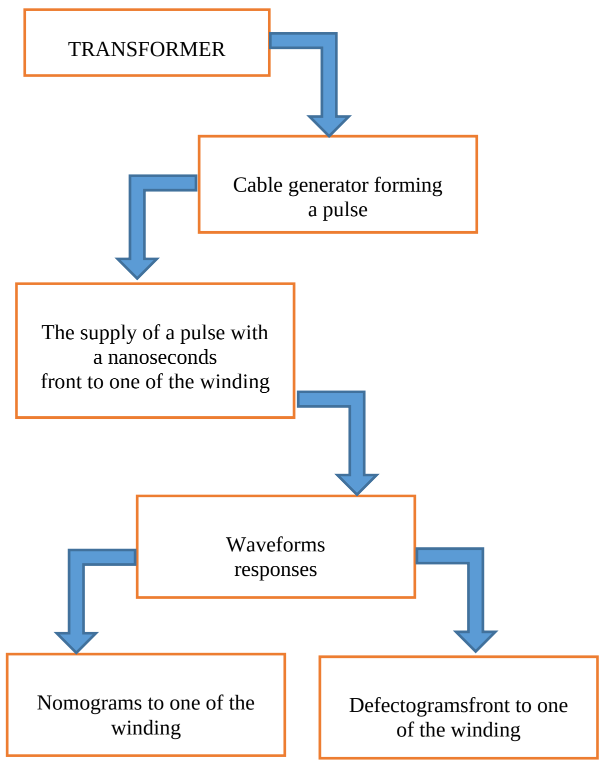

Figure 1. The method of low-voltage nanosecond pulses

During the operation of power transformers, various damages inevitably occur that can disrupt the normal operation of the equipment. With some defects, the units can continue functioning, while others lead to their complete shutdown. In any case, prompt repairs are necessary, which will avoid a serious accident and lead to even more complex damage. It is important not only to determine the nature of the defect, but also the causes of its appearance.

Among the causes of defects in the windings of a power transformer, the main one is the electrodynamic effect of short-circuit currents, leading to the displacement of the turns in the windings [2]. With varying degrees of deformations, the capacitances and sometimes the inductance of a link consisting of a number of elements change, where L is the inductance of the scattering of the winding, taking into account the deformed elements. The consequence of this is the deviation of the natural oscillation frequencies, leading to a change in the oscillogram of pulse currents and voltages [3]. The spectrum of the influencing nanosecond pulse contains high-frequency components, which means that when such a pulse is exposed to one of the transformer windings, high-frequency currents begin to flow in it, where the current distribution density is concentrated at the surface of the conductor.

Figure 2 shows an electrical diagram for replacing the winding of a power transformer. When constructing a replacement scheme, it is necessary to take into account a number of important factors:

- ➢ The acting pulse has a short duration, the length of the test pulse is about 400-500 nanoseconds, so the electrical circuit of the replacement should be distributed.
- ➢ Since the acting pulse contains a high-frequency filling, therefore, it is necessary to take into account the dependence of the elements of the substitution circuit on frequency.
- ➢ When calculating transients using a substitution scheme, it is advisable to use the principle of frequency overlap.

In accordance with the principle of superposition, the calculation can be carried out for each harmonic separately. Moreover, taking into account the fact that an ordinary inductive coil at sufficiently high frequencies is a line with distributed parameters. Transformer windings should be considered as circuits with distributed parameters when they are exposed to pulsed currents and voltages, when the time interval of changes in currents and voltages is comparable to the time of the passage of waves along the winding wire.

Therefore, in addition to inductors, inter-turn capacitances and capacitances on the device body (on the ground) must be present in the replacement circuit. Since the frequency increases with the growth of harmonics, the current through the capacitances can be many times higher than the currents through the coils of the coil. In this case, entire coil as a whole will provide capacitive, rather than inductive, resistance to the passage of alternating current (quantitative changes have passed into qualitative ones), which must be taken into account when drawing up model.

The created SPS model (MATLAB/ Simpowersystems) of the replacement circuits of one inductor and a subcircuit simulating one winding are shown in Figure 2 [16]. A subcircuit simulating a chain model of a transformer winding when exposed to different frequencies is shown in Figure 3 [16].

The transformer winding model includes series-connected subcircuits, i.e., the model consists of a set of subcircuits. Each subcircuit models one turn of the transformer winding, the parameters of which for each harmonic of the signal change in accordance with the calculated in previous studies [16, 17]. It is convenient to calculate one branch by the method of state variables, as which we take values that uniquely determine the state of the circuit, i.e., obeying the laws of switching; i_L is inductance current, u_{C1}, u_{C2} are voltage at capacitances, respectively. Then the equation of variables are [16]:

$$\begin{pmatrix} \dfrac{di_L(t,\omega)}{dt} \\ \dfrac{dU_{C1}(t,\omega)}{dt} \\ \dfrac{dU_{C2}(t,\omega)}{dt} \end{pmatrix} = \begin{pmatrix} -\dfrac{R1(\omega)}{L(\omega)} & \dfrac{1}{L(\omega)} & 0 \\ -\dfrac{1}{C1} & -\dfrac{1}{C1(R2+r)} & -\dfrac{1}{C1(R2+r)} \\ 0 & -\dfrac{1}{C2(R2+r)} & -\dfrac{1}{C2(R2+r)} \end{pmatrix} \times$$

$$\times \begin{pmatrix} i_L(t,\omega) \\ U_{C1}(t,\omega) \\ U_{C2}(t,\omega) \end{pmatrix} + \begin{pmatrix} 0 \\ \dfrac{E(t,\omega)}{C1(R2+r)} \\ \dfrac{E(t,\omega)}{C2(R2+r)} \end{pmatrix}$$

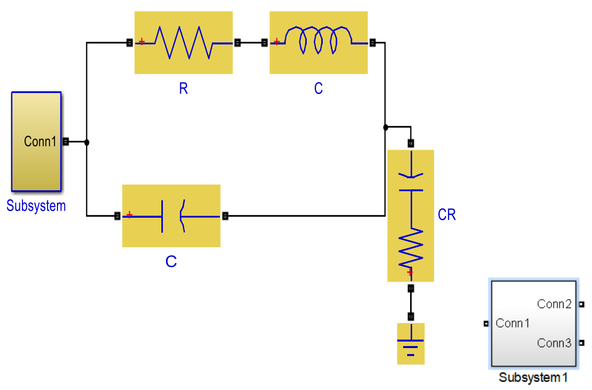

Figure 2. SPS model of the replacement circuits of one inductor and a subcircuit simulating one winding

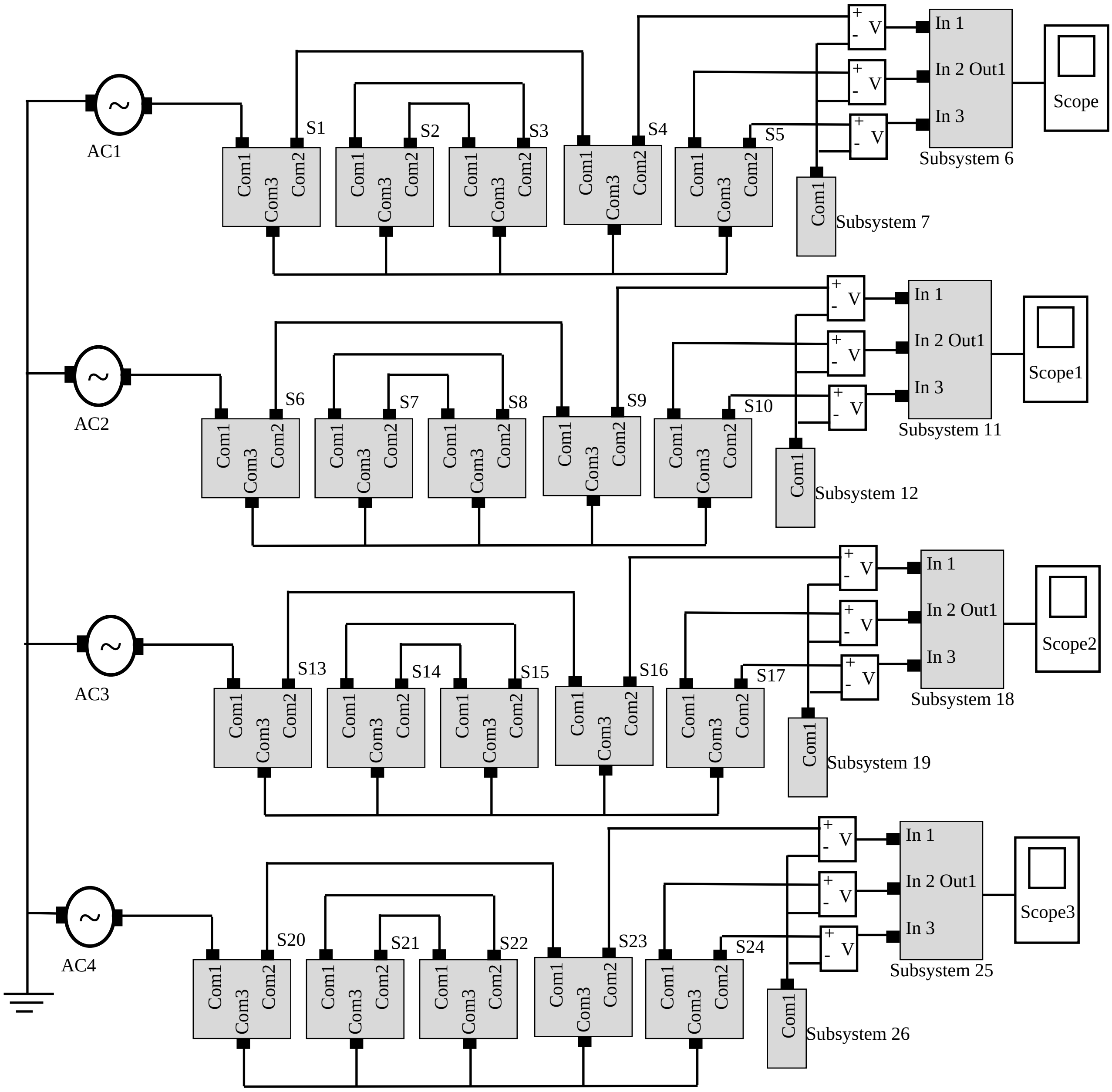

Figure 3. Subcircuit simulating a chain model of a transformer winding

Having obtained the required dependencies of the inductance and resistance of the windings on the frequency, it is necessary to calculate the transients acting in the transformer windings. Since the input pulse was represented as a sum of harmonics, calculations were made taking into account the overlay method. First, the voltages and currents for each harmonic were calculated. After that, the results of the calculations of the currents and voltages of each harmonic were summed up and the resulting currents and voltages were obtained when a probing pulse was applied (Figure 4) [17].

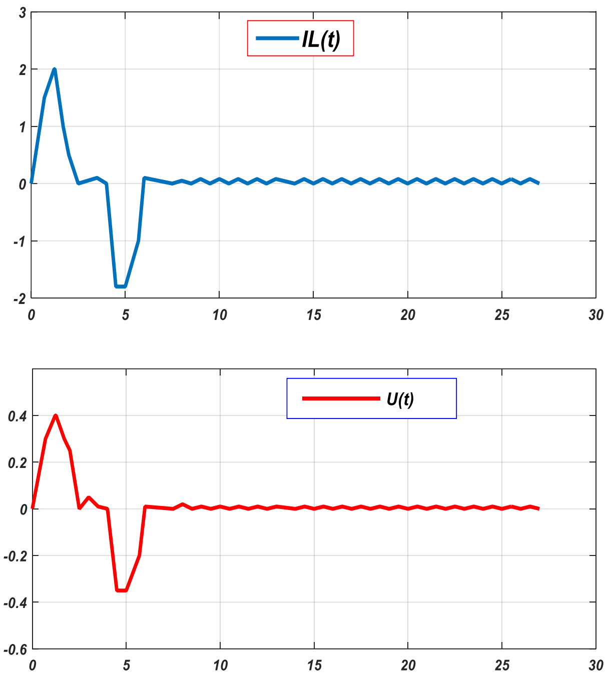

Figure 4. Simulation graphs of inductive current $IL(t)$ and active resistance voltage $U(t)$ of the winding wire of a power transformer

Thus, experimental data obtained at constant load are quickly processed, the amplitude-frequency characteristics of the winding are compared with the normogram in the form of a signal difference and the mechanical condition of the windings of the transformers under study is judged. The speed of processing and comparison of characteristics is significantly increased when studying transformers by the method of nanosecond pulses.

6. CONCLUSION

The characteristics of a short circuit of a three-phase transformer with asymmetry and non-sinusoidal voltage were studied using the method of mathematical modeling overlay. The forward, reverse and zero sequence currents are determined for all higher harmonic components defined by with the help of energy losses in the windings and structural elements of the transformer, taking into account the amplitude of the voltages of the higher harmonics in relation to the main harmonic. The power factor for the higher harmonic components in the short-circuit mode is determined through the short-circuit power factor for the main harmonic and short-circuit parameters.

The method of detecting emerging defects in the windings and initial damage to the transformer is considered. The flowchart of the method of low-voltage nanosecond pulses, a model of a power transformer for calculating the elements of a replacement circuit for the purpose of its diagnosis by low-voltage pulses and Subcircuit simulating a chain model of a transformer winding are analyzed. The compiled model determines the currents and voltages of the transformer windings with sufficient accuracy. Such a model can be used to simulate winding defects and diagnose the transformer.

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