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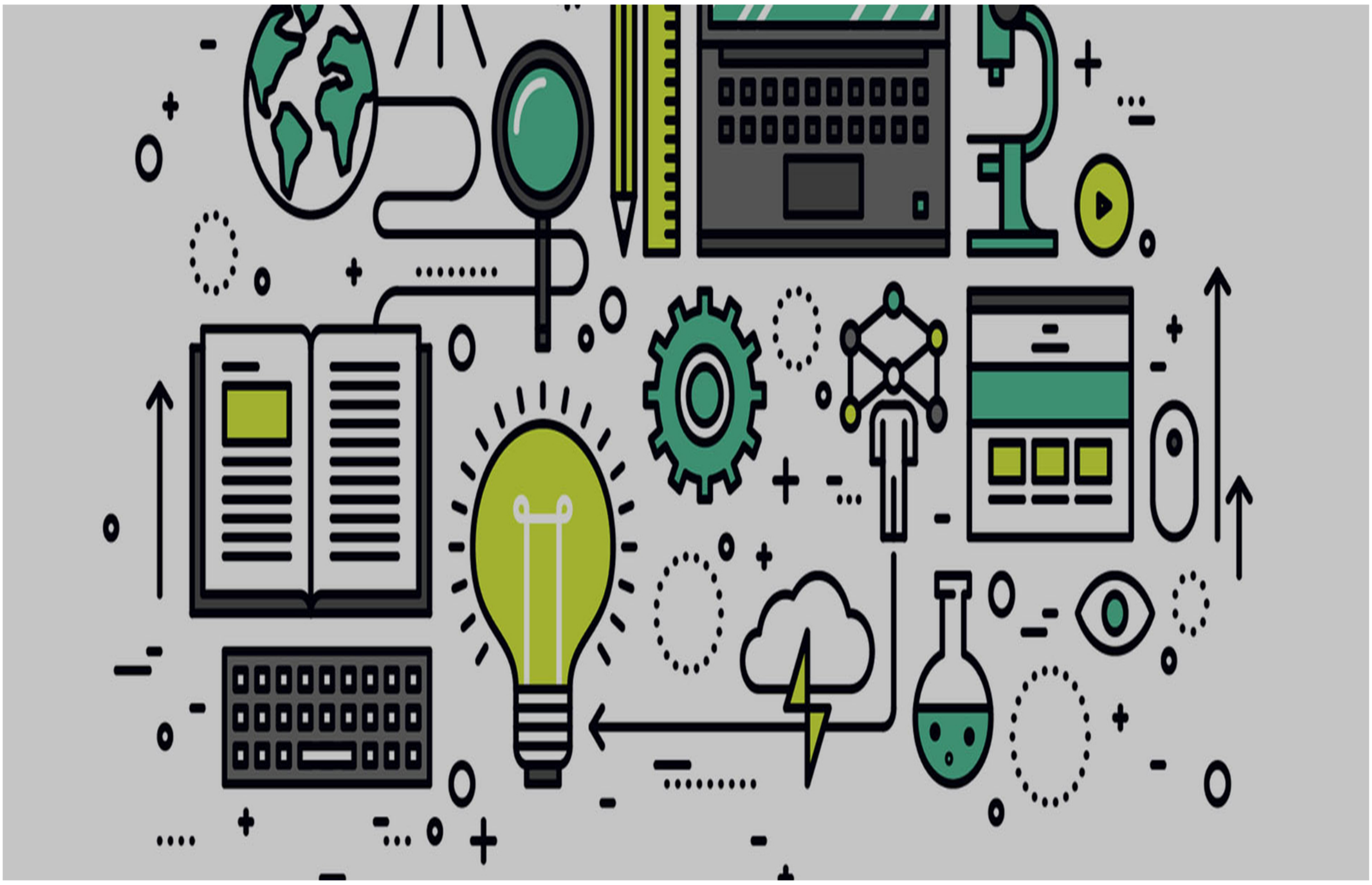

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Using of the parametric nonlinear LC-circuits in stabilized converters of the number of phases

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Abstract.-In the article is considered using of nonlinear circuits of an autoparametric nature with inductive and capacitive elements for obtaining the necessary phase shifts in single-phase-three-phase converters. Obtained amplitude-phase relations between the stresses of windings located on different rods of a three-kernel core. Shown the conditions under which it is possible to stabilize the stresses of the artificial phases of the converter, as well as the phase shifts between them.

Keywords-converters of the number of phases, non-linear ferromagnetic core, a capacitor, an artificial phase, amplitude ratios, phase ratios.

Introduction

Artificial phase number converters are widely used in automation devices, computer technology, when powering devices of electronic equipment and communications. The most common devices of this type are three-phase-single-phase converters (so-called symmetrical devices) and single-phase-three-phase converters that are used in single-phase circuits to power three-phase consumers. Usually single-phase-three-phase converters are manufactured using transformers [1, 2, 3, 4], electronic and mixed circuits [5, 6], inductive-capacitive phase-shifting linear elements [7, 8] and nonlinear inductive-capacitive elements [9, 10, 11, 12].

The disadvantage of such schemes is the lack of stabilization or the value of the obtained phase voltages or the value of phase shifts between the voltages of artificial phases, which requires the use of separate voltage stabilizers and restricts the use of converters to power real devices. Individual converters stabilize either the phase voltage or the phase shifts between them [12], but there are no devices that would simultaneously stabilize both the voltage and phase shifts.

Statement Of A Problem

The effect of stabilizing the stresses of artificial phases and phase shifts between them is possible in parametric circuits with nonlinear inductive and capacitive elements. The diagram of one of these circuits is shown in Fig. 1, a.

For simplicity of explaining the effects, let's assume that all the regime parameters of the circuit (magnetic flows, voltages, etc.) are expressed by sinusoidal functions, which means that the connections between them can be described using vectors.

In this circuit, the windings W_1 of the first ferroresonance oscillating circuit (FOC1), formed by the winding W_1 and the capacitor C_1 connected in parallel, and the second ferroresonance oscillating circuit (FOC2), formed by the winding W_2 and the capacitor C_2, have such winding directions that provide a consistent direction of the magnetic flows $\overline{\Phi}_1$ and $\overline{\Phi}_2$ the extreme rods of the nonlinear magnetic circuit. In the circuit under consideration, under certain operating conditions, the effects of stabilization of magnetic flows are observed $\overline{\Phi}_1$ and $\overline{\Phi}_2$, as a result, the circuit can stabilize the voltage $\overline{U}_1$ and $\overline{U}_2$. When applying an AC voltage $\overline{U}$ to the input circuit and exciting ferroresonance vibrations in it, the flows $\overline{\Phi}_1$ and $\overline{\Phi}_2$ tend to saturate the extreme rods of the magnetic circuit and shift in phase at an angle ψ that depends on the parameters of the magnetic circuit, the number of turns of the windings W_1 and W_2 and the capacitance of the capacitor C_1 and C_2 in FOC1 and FOC2. If the windings W_1 and W_2 were perfect and had no active resistance, the angle ψ would be equal 180°. But as imperfect winding and in parallel, each of them connected to the condenser, the angle ψ will be less 180°, and by adjusting values of capacitors C_1 and C_2 to obtain a value 120° that corresponds to the phase shift between voltages of three-phase system.

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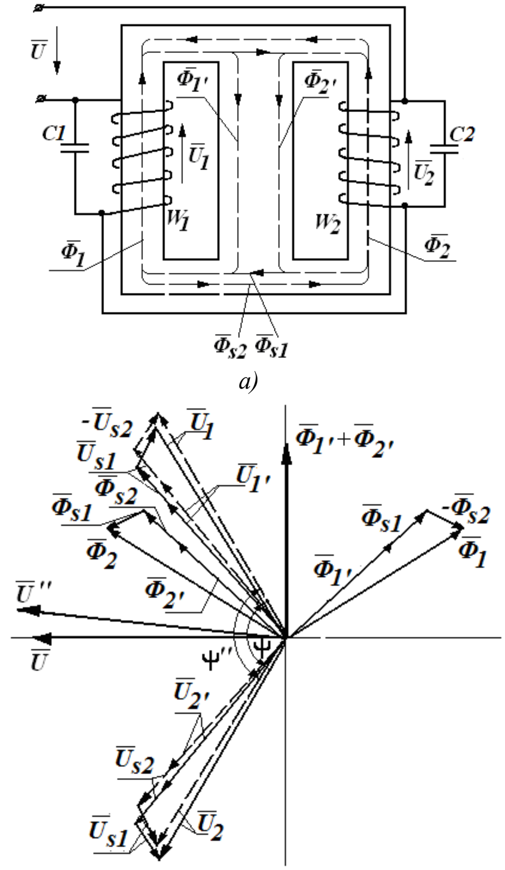

a) *b)*

Fig. 1. Circuit diagram of parametric nature with nonlinear inductive and capacitive elements (*a*) and vector diagram (*b*).

As can be seen from Fig. 1, the flow $\overline{\Phi}_1$ of the left rod is divided into two components: the main one $\overline{\Phi}'_1$, which closes through the middle rod, and the penetrating one $\overline{\Phi}_{s1}$, which closes through the right rod and is directed towards the flow $\overline{\Phi}_2$ of this rod. Similarly, the flow $\overline{\Phi}_2$ of the right rod is also divided into the main part $\overline{\Phi}'_2$ that closes through the middle rod and the penetrating part $\overline{\Phi}_{s2}$ that closes through the left rod of the magnetic core and is directed towards the flow $\overline{\Phi}_1$ of this rod.

Since the components $\overline{\Phi}_{s1}$ and $\overline{\Phi}_{s2}$ pass along the extreme rods and magnetize the material of the magnetic core in an unfavorable direction for magnetization, they $\overline{U}_{s1}$ and $\overline{U}_{s2}$ thevoltage components induced by them in the windings W_1, W_2 will be significantly less than the main parts of the flows $\overline{\Phi}'_1$, $\overline{\Phi}'_2$ and respectively the voltage induced by them $\overline{U}'_1$ and $\overline{U}'_2$. In accordance with Fig.1, and for the left rod of the magnetic circuit and the winding W_1, the expressions are valid

$$\overline{\Phi}_1 = \overline{\Phi}_1' + \overline{\Phi}_{s1} - \overline{\Phi}_{s2}\,;\ \overline{U}_1 = \overline{U}_1' + \overline{U}_{s1} - \overline{U}_{s2}, \quad (1)$$

and for the right rod and winding W_2 – expressions

$$\overline{\Phi}_2 = \overline{\Phi}_2' + \overline{\Phi}_{s2} - \overline{\Phi}_{s1}\,;\ \overline{U}_2 = \overline{U}_2' + \overline{U}_{s2} - \overline{U}_{s1}. \quad (2)$$

Based on (1) and (2), you can build a vector diagram that reflects the qualitative picture of the process. This vector diagram is shown in Fig. 1, *b*. When the input voltage is increased $\overline{U}$ to $\overline{U}''$, the currents in the windings W_1 and W_2 increase, and in the winding W_1 more significantly than in the winding W_2 due to non-simultaneous saturation of the saturation of the extreme rods of the magnetic circuit (provided that C_2 is greater than C_1). This causes an uneven change in the magnetic resistances of the rods, which entails a relatively smaller increase $\overline{\Phi}_{s1}$ (and, respectively $\overline{U}_{s1}$) than the increase $\overline{\Phi}_{s2}$ (and, respectively $\overline{U}_{s2}$), which causes the angle to increase ψ to ψ''. But these changes in the modes have almost no effect on the voltage $\overline{U}_1$ and on the $\overline{U}_2$ (Fig. 2 construction of solid lines corresponds to the initial state, and dotted lines-after increasing the input voltage). It is of interest to create a mathematical model of the device in order to identify the conditions and boundaries of the existence of ferroresonance vibrations, at which the output voltages and phase shifts in the phase number converter are stabilized.

The Concept Of The Problem Decision

The mathematical model of the basic circuit of the phase number converter is shown in Fig. 2, where: S_1, S_2, S_3 – cross-section areas of the left, right and middle strands of the magnetic core, respectively; L_1, L_2, L_3 - average lengths of magnetic lines of the magnetic core; $\varphi_1, \varphi_2, \varphi_3$ - instantaneous values of magnetic flows, respectively, in the left, right and middle rods of the magnetic core; g_1, g_2 - active conductivities of the primary windings W_1 and W_2; W_1, W_2 - the number of turns of the primary windings; i_1, i_2 - instantaneous current values in the primary windings; ig_1, ig_2 - instantaneous current values in the conductivities of the primary windings; C_1, C_2 – capacitors, connected in parallel with the primary windings W_1 and W_2; i_{c1}, i_{c2} - is the instantaneous current in the capacitors; $i = I_m \sin(\omega t + \psi_i)$ – the instantaneous value of the supply current; $u = U_m \sin(\omega t + \psi_u)$ - is the instantaneous value of the supply voltage; W_3, W_4, W_5 – number of turns of the secondary winding of the transducer; Z_1, Z_2, Z_3 – resistance phase of three-phase load of the consumer; U_{1m}, U_{2m}, U_{3m} – voltage of artificial phases.

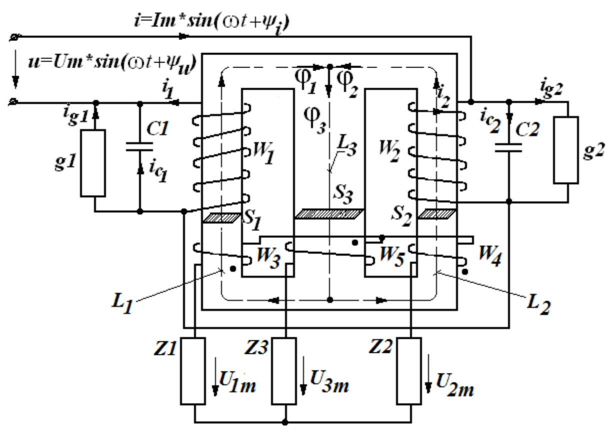

Fig. 2. Mathematical model of the basic circuit of the phase number converter

To simplify the analysis, while maintaining qualitative and approximate quantitative ratios, we will make a number of assumptions:

– the hysteresis loop of the magnetic core material can be described, for example, using the methods given in [13, 14, 15]. However, due to its narrowness, it can be replaced with a magnetization curve approximated by a power function $H = k \cdot b^9$ of the form that fairly accurately reflects the course of the magnetization curve for cold-rolled electrical steel [16, 17];

- active losses for hysteresis, remagnetization, and eddy currents are considered constant, independent of the mode, and are accounted for by conductivities g_1, g_2 [18, 19];

- windings scattering inductions, which have little effect on the nature of electromagnetic processes in the circuit, are not taken into account [20];

- the own capacity of the windings is not taken into account due to their extreme smallness [21];

– only the first harmonics of inductions, voltages, and currents are taken into account in the calculations.

The mode of operation of the stabilizer can be described by a system of equations for instantaneous values of electric and magnetic quantities

$$\left\{ \begin{array}{l} \varphi_1 + \varphi_2 - \varphi_3 = 0 \\ i_1 W_1 = \varphi_1 \dfrac{L_1}{S_1 \mu_1} + \varphi_3 \dfrac{L_3}{S_3 \mu_3} \\ i_2 W_2 = \varphi_2 \dfrac{L_2}{S_2 \mu_2} + \varphi_3 \dfrac{L_3}{S_3 \mu_3} \end{array} \right\}, \quad (3)$$

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where μ_1, μ_2, μ_3 - is the dynamic magnetic permeability of the corresponding magnetic core rods. Taking into account the accepted approximation $H = k \cdot b^9$ and expressing magnetic flows in terms of instantaneous values of inductions we obtain

$$\begin{Bmatrix} b_1S_1 + b_2S_2 - b_3S_3 = 0 \\ kL_1b_1^9 + kL_3b_3^9 - i_1W_1 = 0 \\ kL_2b_2^9 + kL_3b_3^9 - i_2W_2 = 0 \end{Bmatrix}, \qquad (4)$$

where b_1, b_2, b_3 - are the instantaneous values of the inductions in the corresponding rods of the magnetic core.

Let's simplify the resulting system by substituting the value b_3^9 from the second expression into the third expression using b_1 and b_2

$$\begin{Bmatrix} b_1S_1 + b_2S_2 - b_3S_3 = 0 \\ b_1^9 = \dfrac{kL_2 \cdot b_2^9 - i_2W_2 + i_1W_1}{kL_1} \end{Bmatrix}. \qquad (5)$$

At certain ratios of the circuit parameters, values *U* and frequency *f* in the considered circuit, the current ferroresonance is possible, the magnetic and electric parts of the circuit are described by a system of equations for instantaneous values of electric and magnetic values

$$\begin{Bmatrix} b_1S_1 + b_2S_2 - b_3S_3 = 0;\ b_1^9 = \dfrac{kL_2b_2^9 - i_2W_2 + i_1W_1}{kL_1} \\ u = W_1S_1\dfrac{db_1}{dt} + W_2S_2\dfrac{db_2}{dt}; \quad i = i_2 + i_{C2} + i_{g2} \\ i = i_1 + i_{C1} + i_{g1} \end{Bmatrix}, \qquad (6)$$

where the instantaneous values of the currents in the branches of the chain can be found from the expressions

$i_2 = \dfrac{kL_2b_2^9}{W_2}$ (7); $i_{C1} = W_1CS_1 \cdot \dfrac{d_2b_1}{dt^2}$ (8); $i_{C2} = W_2CS_2 \cdot \dfrac{d_2b_2}{dt^2}$ (9); $i_{g2} = W_2g_2S_2 \cdot \dfrac{db_2}{dt}$ (10); $i_1 = \dfrac{kL_1b_1^9}{W_1}$ (11); $i_{g1} = W_1g_1S_1 \cdot \dfrac{db_1}{dt}$ (12).

From the expressions for currents in (6), we express and with (12), substituting them in the expression for induction in (6), we get

$$b_1^9 = \frac{kL_2b_2^9 - \left(\dfrac{kL_1b_1^9}{W_1} + W_1g_1S_1 \cdot \dfrac{db_1}{dt} - W_2CS_2 \cdot \dfrac{d_2b}{dt^2} - W_2g_2S_2 \cdot \dfrac{db_2}{dt}\right) \cdot W_2}{kL_1} + . (13)$$

$$+ \frac{\left(\dfrac{kL_2b_2^9}{W_2} + W_2L_2S_2 \cdot \dfrac{d_2b_2}{dt^2} + W_2g_2S_2 \cdot \dfrac{db_2}{dt} - W_1g_1S_1 \cdot \dfrac{db_1}{dt}\right) \cdot W_1}{kL_1}$$

Solution (13) is assumed as

$$b_1 = B_{1m} \sin \omega t; b_2 = B_{2m} \sin(\omega t - \psi). \qquad (14)$$

Substituting (14) in (13), we perform the differentiation operation, as well as replacing the degrees of harmonic functions with the sum of harmonics of the first degree and taking into account only the main harmonic after the transformation we get

$$\begin{aligned} &0{,}5 \cdot B_{1m}^9 \sin \omega t = 0{,}5 \cdot \frac{L_1}{L_2} \cdot B_{2m}^9 \sin(\omega t - \psi) - 0{,}5 \cdot \frac{W_2}{W_1} B_{1m}^9 \sin \omega t - \\ &- \frac{W_2W_1 \cdot g_1S_1\omega}{kL_1} B_{1m} \cos \omega t - \frac{W_2^2C \cdot S_2\omega^2}{kL_1} B_{2m} \sin(\omega t - \psi) + \\ &+ \frac{W_2^2 g_2 \cdot S_2\omega}{kL_1} B_{2m} \cos(\omega t - \psi) + \frac{0{,}5 \cdot W_1L_2}{W_2L_1} B_{2m}^9 \sin(\omega t - \psi) - \\ &- \frac{W_1W_2 \cdot CS_2\omega^2}{kL_1} B_{2m} \sin(\omega t - \psi) + \frac{W_1W_2 \cdot g_2S_2}{kL_1} B_{2m} \cos(\omega t - \psi) - \\ &- \frac{W_1^2 g_1 \cdot S_1\omega}{kL_1} B_{1m} \cos \omega t \end{aligned} . \qquad (15)$$

Divide the right and left parts (15) into $CS_2 \cdot \omega^2 W_2 B\delta$ and group similar terms, we get

$$\left(0{,}5 \cdot \frac{B\delta^9}{CS_2 \cdot \omega^2 W_2 \cdot B\delta} + 0{,}5 \cdot \frac{B\delta^9}{W_1 S_2 \cdot \omega^2 C \cdot B\delta}\right) \cdot \frac{B_{1m}^9}{B\delta^9} \sin \omega t =$$
$$= \left(0{,}5 \frac{L_2}{L_1} + 0{,}5 \frac{W_1 L_2}{W_2 L_1}\right) \cdot \frac{B\delta^9}{CS_2 \cdot \omega^2 W_2 \cdot B\delta} \cdot \frac{B_{2m}^9}{B\delta^9} \sin(\omega t - \psi) -$$
$$-\left(\frac{W_1 g_1 \cdot S_1}{kL_1 \cdot CS_2 \omega} + \frac{W_1 g_2}{kL_1 \cdot W_2 C \cdot S_2 \omega}\right) \cdot \frac{B_{1m}}{B\delta} cos \omega t -$$
$$-\left(\frac{W_2}{kL_1} + \frac{W_1}{kL_1}\right) \cdot \frac{B_{2v}}{B\delta} \sin(\omega t - \psi) + \left(\frac{W_2 g_2}{kL_1 \cdot C\omega} +\right.$$
$$+ \frac{W_1 g_2}{k \cdot LCS_2 \cdot \omega^2 W_2 \cdot B\delta_1 W_2 \cdot CS_2 \omega} \cdot \frac{B_{1m}}{B\delta} \cos(\omega t - \psi) \quad . \tag{16}$$

Enter the basic values and denote the coefficients:

$$B\delta = 1T\pi; I_{\delta} = CS_2 \cdot \omega^2 W_2 B\delta; \tau = \omega t; X_{1m} = B_{1m} / B\delta; X_{2m} = B_{2m} / B\delta; \quad \alpha = 0{,}5 \cdot \frac{B\delta^9}{CS_2 \cdot \omega^2 B\delta}\left(\frac{1}{W_2} + \frac{1}{W_2}\right);$$

$$\beta = 0{,}5 \cdot \frac{L_2 B\delta^9}{L_1 C \cdot S_2 \omega^2 \cdot W_2 B\delta} \cdot \left(1 + \frac{W_1}{W_2}\right);$$

$$\gamma = \frac{W_1 g_1 \cdot S_1}{kL_1 \cdot CS_2 \omega}\left(1 + \frac{W_1}{W_2}\right); \ \delta = \frac{W_1 + W_2}{kL_1}; \ \xi = \frac{g_2}{kL_1 \cdot C\omega}(W_1 + W_2). \tag{17}$$

Substituting (17) in (16) after the transformations we get

$$\alpha \cdot X_{1m}^9 \sin(\tau + \gamma) \cdot X_{1m} \cos \tau =$$
$$= (\beta \cdot X_{2m}^9 - \delta X_{2m}) \sin(\tau - \psi) + \quad . \tag{18}$$
$$+ \xi \cdot X_{2m} \cos(\tau - \psi)$$

We transform (18) by the harmonic balance method, replacing the sums and differences of the harmonic functions with their products and equating the coefficients for $\sin \tau$ and $\cos \tau$. Obtained system

$$\left\{\begin{aligned} \alpha X_{1m}^9 &= (\beta X_{2m}^9 - \delta X_{2m}) \cdot \cos\psi + \xi X_{2m} \sin\psi \\ \gamma X_{1m} &= -(\beta X_{2m}^9 - \delta X_{2m}) \cdot \sin\psi + \xi X_{2m} \cos\psi \end{aligned}\right\} . \tag{19}$$

We square the left and right parts of the equations of the system (19) and summing them, we find a dependence that connects the values of relative amplitudes of magnetic inductions X_{1m} and X_{2m} in the extreme rods of the magnetic circuit

$$(\alpha \cdot X_{1m}^9)^2 + (\gamma \cdot X_{1m})^2 = (\beta \cdot X_{2m}^9 - \delta \cdot X_{2m})^2 + $$
$$+ (\xi \cdot X_{2m})^2 \quad . \tag{20}$$

Denote $A = \beta X_{2m}^9 - \delta X_{2m}$; $B = \alpha X_{1m}^9$; $C = \xi X_{2m}$; $D = \gamma X_{1m}$.(21)

Taking into account (21), the system (19) is described as

$$\left\{\begin{aligned} B &= A\cos\psi + C\sin\psi \\ D &= A\sin\psi + C\cos\psi \end{aligned}\right\} . \tag{22}$$

Multiplying the equations of the system (22) by *D* and *B*, respectively, and equating the left parts of the equations, we find the angle of phase shift between the inductions in the rods FOC1 and FOC2

$$\psi = \frac{CB - AD}{AB + CD} . \tag{23}$$

To find the relationship between the relative values of the magnetic inductions of the extreme and middle rods from (6), we express the instantaneous value of the induction in the middle rod

$$b_3 = \frac{b_1 S_1 + b_2 S_2}{S_3}$$

Given the solution $b_3 = B_{3m} \sin(\omega t - \psi_3)$ and considering (13), we get

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$$B_{3m}\sin(\omega t-\psi_3)=\frac{S1}{S3}B_{1m}\sin\omega t+\frac{S_2}{S_3}\cdot B_{2m}\sin(\omega t-\psi)\,. \qquad (24)$$

Divide the left and right parts (24) into $I_б$ and entering the notation

$$\mu=\frac{1}{CS_2\cdot\omega^2W_2};\ \theta=\frac{S_1}{S_3S_2\cdot C\omega^2\cdot W_2};\ \rho=\frac{1}{CS_3\cdot\omega^2W_2};\ X_{3m}=\frac{B_{3m}}{Bб}\ (25),$$

and also taking into account (21) we get

$$\begin{aligned}&\mu\cdot X_{3m}\sin(\tau-\psi_3)=\theta\cdot X_{1m}\sin\tau+\\&+\rho\cdot X_{2m}\sin(\tau-\psi)\end{aligned}\,. \qquad (26)$$

Transform (26) by the harmonic balance method, we will have

$$\left\{\begin{aligned}&\mu\cdot X_{3m}\cos\psi_3=\theta\cdot X_{1m}+\rho\cdot X_{2m}\cos\psi\\&-\mu\cdot X_{3m}\sin\psi_3=-\rho\cdot X_{2m}\sin\psi\end{aligned}\right\}. \qquad (27)$$

Let's square the right and left parts of the equations of the system (27) and sum them up to get $(\mu\cdot X_{3m})^2=(\theta\cdot X_{1m}+\rho\cdot X_{2m}\cos\psi)^2+(\rho\cdot X_{2m}\sin\psi)^2$, where is the desired relationship between X_{1m}, X_{2m} and X_{3m}.

$$X_{3m}=\frac{\sqrt{(\theta\cdot X_{1m}+\rho\cdot X_{2m}\cos\psi)^2+(\rho\cdot X_{2m}\sin\psi)^2}}{\mu}\,. \qquad (28)$$

The angle between the induction vectors in the left and middle rods of the magnetic core is found from (27), and we divide the lower equation of the system by the upper one

$$\psi_3=arctg\frac{\rho\cdot X_{2m}\sin\psi}{\theta\cdot X_{1m}+\rho\cdot X_{2m}\cos\psi}\,. \qquad (29)$$

Let's find the dependence that connects the parameters X_{1m}, X_{2m} and the current i in the unbranched part of the circuit. It follows from expressions (6) and (7) – (11) that

$$\begin{aligned}&i=i_2+i_{C2}+i_{g2}=\frac{kL_2\cdot b_2^9}{W_2}+W_2C\cdot S_2\frac{d_2b_2}{dt^2}+\\&+W_2g_2\cdot S_2\frac{db_2}{dt}\end{aligned}\,. \qquad (30)$$

Considering only the first harmonic and substituting in (30) solutions (14) we get

$$\begin{aligned}&I_m\sin(\omega t+\psi_i)=0{,}5\frac{kL_2\cdot B_{2m}^9}{W_2}\cdot\sin(\omega t-\psi)-\\&-W_2C\cdot S_2\omega^2B_{2m}\sin(\omega t-\psi)+\\&+W_2g_2\cdot S_2\omega\cdot B_{2m}\cos(\omega t-\psi)\end{aligned}\,. \qquad (31)$$

Divide the right and left parts (31) into $I_б=CS_2\cdot\omega^2W_2Bб$ and enter the notation $Y_m=\frac{I_m}{I_б}$; $\lambda=0{,}5\cdot\frac{kL_2\cdot Bб^9}{CS_2\cdot\omega^2W_2^2\cdot Bб}$; $\upsilon=\frac{g_2}{\omega C}$, and also taking into account the notation (21) we will have

$$\begin{aligned}&Y_m\sin(\tau+\psi_i)=\lambda\cdot X_{2m}^9\sin(\tau-\psi)-\\&-X_{2m}\sin(\tau-\psi)+\upsilon\cdot X_{2m}\cos(\tau-\psi)\end{aligned}\,. \qquad (32)$$

Transform (32) by the harmonic balance method and group such terms, we get

$$\left\{\begin{aligned}&Y_m\cos\psi_i=(\lambda\cdot X_{2m}^9-X_{2m})\cos\psi+\upsilon\cdot X_{2m}\sin\psi\\&Y_m\sin\psi_i=-(\lambda\cdot X_{2m}^9-X_{2m})\sin\psi+\upsilon\cdot X_{2m}\cos\psi\end{aligned}\right\}. \qquad (33)$$

Let's square the right and left parts of the equations of the system (33), sum up the obtained expressions and solve with respect to Y_m find the desired relationship between the relative values of the amplitudes of the supply current and the induction of X_{2m}

$$Y_m=\sqrt{(\lambda\cdot X_{2m}^9-X_{2m})^2+(\upsilon\cdot X_{2m})^2}\,. \qquad (34)$$

Find the angle ψ_i between Y_m and X_{2m}, for which we divide in (33) the lower expression by the upper one, we get

$$\psi_i = arctg\frac{K\cos\psi + M\sin\psi}{M\cos\psi - K\sin\psi} \quad . \qquad (35)$$

To construct the current-voltage characteristic of the circuit under study, we will find the connection of the induction X_{1m}, X_{2m} amplitudes with the value of the supply voltage *u*. In the expression for the stress from (6), we substitute solutions from (14) and perform differentiation operations to obtain

$$\begin{gathered} U_m \sin(\omega t + \psi_u) - W_1 S_1 \omega \cdot B_{1m} \cos\omega t + \\ + W_2 S_2 \omega \cdot B_{2m} \cos(\omega t - \psi) \end{gathered} \quad . \qquad (36)$$

Divide the right and left parts of the expression (36) by the base voltage $U_б = W_2\omega \cdot S_2 Bб$ and, entering the notation $Z_m = \frac{U_m}{U_б}$; $\sigma = \frac{W_1 S_1}{W_2 S_2}$, and taking into account (21), we have

$$Z_m \sin(\tau + \psi_u) = \sigma \cdot X_{1m} \cos\tau + X_{2m} \cos(\tau - \psi) . \quad (37)$$

Transform (37) by the harmonic balance method

$$\begin{Bmatrix} Z_m \sin\psi_u = \sigma \cdot X_{1m} + X_{2m} \cos\psi \\ Z_m \cos\psi_u = X_{2m} \sin\psi \end{Bmatrix} . \qquad (38)$$

By squaring the right and left parts of the equations of the system (38) and summing them, as well as solving the resulting expression with respect to Z_m, we obtain the desired relationship between the relative values of amplitudes X_{1m}, X_{2m} and Z_m

$$Z_m = \sqrt{(\sigma \cdot X_{1m} + X_{2m}\cos\psi)^2 + (X_{2m}\sin\psi)^2} . \qquad (39)$$

From (38) we find the phase shift angle between the induction vectors in the NBE rods and the supply voltage

$$\psi_u = arctg\frac{\sigma X_{1m} + X_{2m}\cos\psi}{X_{2m}\sin\psi} \quad . \qquad (40)$$

From (35) and (40), the phase shift angle between the supply voltage and supply current vectors can also be found

$$\varphi = \psi_u - \psi_i \ . \qquad (41)$$

Based on expressions (20) – (41), an algorithm for calculating the amplitude-phase relations for an experimental model with parameters with values:

$C_1 = 15$ mkF, $C_2 = 20$ mkF, $g_1 = g_2 = 0{,}0015$ Om^{-1},

$W_1 = W_2 = 400$ coil, $S = 0{,}00085$ m^2,

$L_1 = L_2 = 0{,}245$ м, $L_3 = 0{,}12$ м, $H = 16{,}5 \cdot B^9$ magnetic core made of steel E330 (3414).

Realization Of The Concept

The volt-ampere characteristic of a circuit $Z_m = f(Y_m)$ is the ratio between the input voltage amplitude and the current amplitude expressed in relative units. As can be seen from Fig. 3, it has loop-like character with a plot almost constant current, that is, the analyzed chain is similar in properties to the current source, wherein these properties are retained when you change the capacitor C_2 from 15 to 30 mkF, which according to [12] indicates the possibility of stabilization modes as the relative amplitudes of the magnetic induction and are related to these amplitudes of voltage according to the principle of operation of the circuit Bushero.

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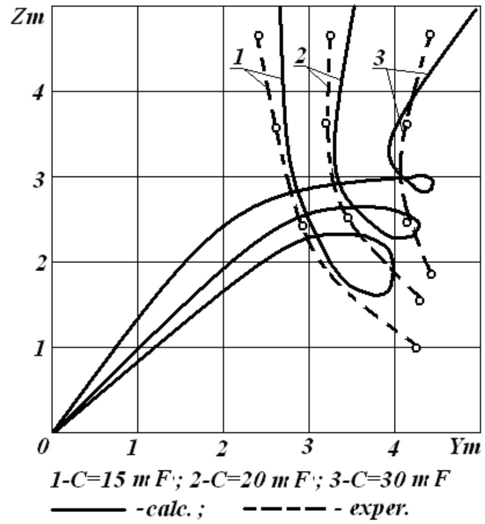

Fig.3. Volt-ampere characteristic of a circuit $Z_m = f(Y_m)$

To test the possibility of using the circuit under study as a parametric voltage stabilizer on ferroresonance circuits, we investigate the dependencies that reflect the course X_{1m}, X_{2m}, $X_{3m} = f(Z_m)$,of the stabilizer's adjustment characteristics on a certain scale $U_{1m}, U_{2m}, U_{3m} = f(U_m)$. Figure 4 shows a family of curves X_{1m}, X_{2m}, $X_{3m} = f(Z_m)$.

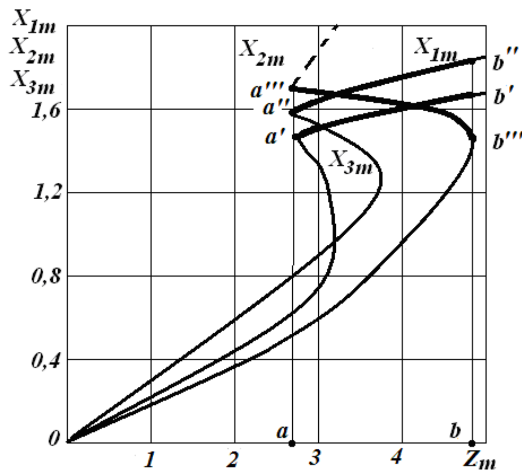

Fig.4. Curves X_{1m}, X_{2m}, $X_{3m} = f(Z_m)$.

From the curves it is seen that in the limits of existence autoparametricferroresonance oscillations (the applied voltage is inside the area bounded by points *a* and *b*) induction in the cores of the core change insignificantly: induction X_{3m} is between the points a' and b' the induction X_{1m} - between the points a'' and b'', and the induction X_{2m} - between the points a''' and b''', and this part features is on the site with an active-inductive nature of the load that is made possible by the power FOC2 from the power source [12]. A small deviation of magnetic inductions indicates the possibility of using the circuit in question as a voltage stabilizer on the resistances Z_1, Z_2, Z_3 of an artificial three-phase system, and the same voltage U_{1m}, U_{2m}, U_{3m} can be achieved by a corresponding change in the number of turns of the windings W_3, W_4 and W_5.

Using expressions (23), (29), (35), (40) and (41) we construct the dependence of the phase shifts ψ_1, ψ_2, ψ_3 of artificial phase stresses on the amplitude of the supply voltage Z_m (Fig. 5).

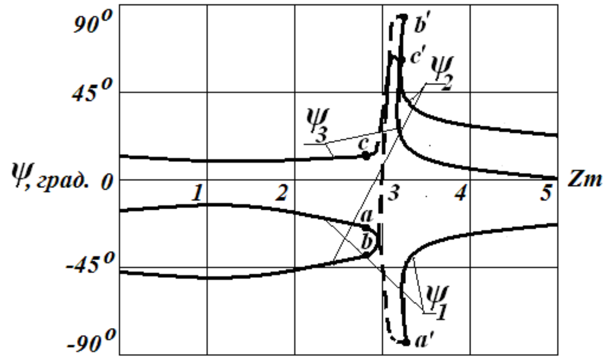

Fig. 5. Graph of the dependence of phase shifts ψ_1, ψ_2, ψ_3 of artificial phase stresses on the amplitude of the supply voltage Z_m

From Fig. 5 it can be seen that before the ferroresonance jump (from the origin to the points a, b, c), the phase shift on the extreme rods (curves ψ_1 and ψ_2) is of a capacitive nature, and the inductions in the middle rod (curve ψ_3) are of an inductive nature. After a ferroresonance jump (from points a', b', c' to the end of coordinates or to $Z_m = 5$), the curve ψ_2 has an inductive character with a phase shift of approximately $+30^0$, the curve ψ_1 is a capacitive character with a phase shift of approximately -30^0, and the phase shift ψ_3 in the middle rod approaches zero. If you swap the ends of the winding W_5 on the middle core rod, without touching the windings of the extreme rods W_3 and W_4, then a phase shift will be established between the output voltage U_{1m}, U_{2m}, U_{3m} vectors, close to 120^0 and its value will practically not change in the zone of existence of ferroresonance parametric vibrations.

Conclusion

The view of the obtained calculated and experimental characteristics of the chain allows us to draw the following conclusions:

1. In the range of existence of ferroresonance parametric oscillations, the oscillatory circuits FOC1 and FOC2 are fed in a mode close to the current source mode;
2. In the circuit, parametric stabilization of magnetic inductions from the core rods is possible when the supply voltage changes according to the principle of operation of the Bushero circuit;
3. In the zone of existence of ferroresonance parametric oscillations, it is possible to stabilize the value of the phase shift between inductions in the core rods;
4. The phenomena of stabilization of magnetic inductions in rods and the values of the phase shift between the inductions of rods can be used in the design of a single-phase voltage converter to three-phase with voltage stabilization and phase shifts of artificial phases.

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References

[1] Vorfolomeev G.N., Myatej S.V., Shurov N.I., Chemodanova O.V., Chemodanov S.S., Fleysher O.N. Obzorsxemnixresheniypreobrazovateleychislafaznatransformatorax// Sovershenstvovanietexnicheskixsredstvelektricheskogotransporta. Sborniknauchnixtrudov. Novosibrsk. – 2001 – s. 78-96.

[2] Golubev A.N., Ignatenko S.V. Characteristics optimization for a frequency converter power filter as a function of phase number// Electrical engineering. – 1999.№7. pp. 42-46.

[3] Yevdokimov S.A. Geometricheskiysposobgeneratsiisxemnixresheniypreobrazovateleychislafazdlyaviprimiteley //NauchniyvestnikNovosibirskogogosudarstvennogotexnicheskogouniversiteta. – 2008. – № 2(31). – S. 107-120.

[4] Venediktov G.L. Staticheskiyelektromagnitniypreobrazovatelchislafaz s tiristornoysistemoyavtomaticheskogosimmetrirovaniyadlyapitaniyaputeyskogoelektroinstrumenta: avtoref. diss… kand. tekn. nauk. – Leningrad: Leningr. in-t injenerov j.-d. transp. im. V.N. Obraztsova, 1984. – 23 s.

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*Corresponding Author: Ivan MikhaylovichBedritskiy, Email: lade00@bk.ru
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[5] A.s. SU1394367A1. Elektronniypreobrazovatelchislafazmnogofaznogonapryajeniya / Yermakov V.F.Byul. – 1981. - № 12- S. 136.

[6] Kosouxov F.D., Vasilev N.V., Boroshnin A.L. i dr. Dvuxprovodnaya Sistema elektroperedachitrexfaznogotoka // Elektrichestvo. – 2018. – № 10. – S. 37-44.

[7] Glushenko V.P. Opisanie, rezultatiraschetaiissledovaniyarejimovrabotinekotorixustroystv, elektricheskixtsepeyisistem, ispolzuyushixnelineynixyavleniya, reaktivnosti, soderjashixnelineyniekomponenti: avtoref. diss… d-ra.texn. nauk. – Moskva: MEI, 1997. – 40 s.

[8] A.s. SU764061A1. Preobrazovatelodnofaznogonapryajeniyavtrexfaznoe/ BichkovA.I., BladikoV.M., GorbarukV.N.Byul. - 1980.

[9] A.s. SU1741239A1. Ferromagnitniypreobrazovatelchastotiichislafazvchetireraza/ KarimovA.S., TurdiyevM.T., XudaykulovZ.R., IbragimovN.R.Byul. - 1992.

[10] Karimov A.S., Raximov G.R. Avtoparametricheskiepreobrazovatelichastotichislafazichostatiperemennogotoka. – T.: Fan, 1995. – 275 s.

[11] D Jiles, D Atherton. Theory of ferromagnetic hysteresis // Journal of Magnetism and Magnetic Materials. – 1986. N 5. - P.48-60.

[12] John H. Chan, Andrei Vladimirescu, Xiao-Chun Gao and other. Nonlinear Transformer Model for Circuit Simulation // Electron journal TRANSACTIONS ON COMPUTER-AIDED DESIGN. – 1991. VOL.10, N 4.

[13] Halilov N.A., Bedritsky I.M. To a question on approximation of curves of magnetization of electro technical steels // NEWS OF HIGH SCHOOLS OF REPUBLIC UZBEKISTAN. Engineering in Life Sciences. – 2002. – № 4. – S. 33-37.

[14] Bedritsky I.M. Sravnitelniyanalizanaliticheskixvirajeniydlyaapproksimatsiikrivixnamagnichivaniyaelektrotexnicheskixstaley // Elektrika. – 2011. - №7. – S. 38-41.

[15] PavlovskiyYu.N. Imitatsionniemodeliisistemi// M.: VTS RAN – 2000. – 144 s.

[16] Bazarov M., Bedritskiy I.M., Boltaev O.T. Estimation of an error of calculations of ferromagnetic elements from inductance of dispersion // European Journal of Technical and Natural Sciences. 2017. - №3.– P.47-49.

[17] MusurmonovR.B.Mejvitkovayaemkostnelineynoyinduktivnoykatushkiieevliyanienaraschetrejimovrabotistabilizatorov ferrorezonansnogotipa // Sb. tr. VII mejdunarodnogokokursa «Molodyej v nauke: novieargumenti». – Lipets

[18] k, 2019. – S. 119-122.