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Amplitude-phase relations in a single-phase to six-phase voltage converter on an amorphous alloy core

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Abstract. The article discusses amplitude-phase relations in a stabilized single-phase to six-phase voltage converter on a core of amorphous alloys. The converter can be used as a stabilized power source with phase conversion for powering six-phase rectifiers, in protection and automation devices for power transmission lines, as well as for powering low- and medium-power six-phase loads from a single-phase network.

Keywords: phase number converter, amorphous alloys, three-rod transformer, windings, capacitors, ferroresonance, autoparametric oscillations.

Introduction

Currently, the production, transmission and distribution of electricity is carried out by three-phase sinusoidal current systems. The advantages of a three-phase system are realized only with complete symmetry of the phase currents. However, for some consumers (electrified transport, electrical installations, welding), single and two-phase power is used. The presence of such consumers leads to asymmetry or non-sinusoidal currents of the three-phase supply network. To preserve the advantages of a three–phase system when powering such receivers, it is necessary to use intermediate devices - phase number converters. This article discusses a converter of a parametric nature from a single-phase system to a six-phase one. Such a converter can be used as a stabilized power source with phase conversion for powering six-phase rectifiers, in protection and automation devices for power transmission lines, as well as for powering low- and medium-power six-phase loads from a single-phase network. The use of cores made of amorphous alloys can significantly improve the performance of the device, due to the high value of magnetic permeability and a significant reduction in losses due to hysteresis, magnetization reversal and eddy currents [3,4,7,8].

Materials and methods

The mathematical model of this phase number converter can be implemented on the basis of an armored magnetic core [5], built using an amorphous alloy of Chinese production 1K101 or the Russian equivalent – AMAG492. To build the model, we used a core with a cross–section of $s = 41 \cdot 10^{-4}\, m^2$, the number of turns of coils $w = 350 - 400$, the length of the average magnetic line of the core $l = 0.35\, m$, saturation induction - $1.56\, Tl$, coercive force is $8\, A/m$, relative magnetic permeability at a frequency of 10 kHz is 5000.

The hypothesis of the study is that magnetization curves are supposed to be used as models of magnetization for magnetically soft amorphous alloys, since these alloys have a very narrow hysteresis loop, and the obtained amplitude-phase ratios at the moment of current resonance will allow obtaining the necessary phase shifts for the phase transformation process and stabilizing the output voltages.

During the conversion process, the following assumptions were made:

-the magnetization curve can be approximated by the function $H = k \cdot b^9$, which gives acceptable results for the amorphous alloy type AMAG492 used in the converter design [2];

-all types of active losses are considered independent of the mode and are taken into account by the conductivities g_1, g_2 [1];

-the inductions of scattering of windings [1] and the value of their own capacitance [1] are not taken into account;

-calculations of all parameters are performed using the harmonic balance method, and the values of the first harmonics of magnetic inductions, currents and voltages varying according to sinusoidal laws are taken into account.

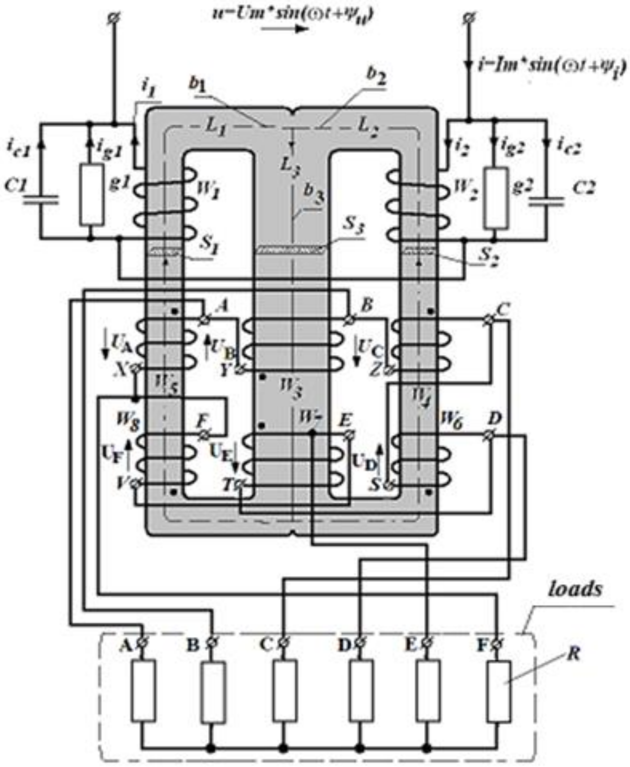

Fig.1. Diagram of a single-phase to six-phase voltage converter

For the diagram in Fig.1, the following designations are used: S_1, S_2, S_3 – cross–sectional areas of the core rods; L_1, L_2, L_3 – lengths of the magnetic lines of the core; b_1, b_2, b_3 – instantaneous values of inductions in the core rods; g_1, g_2 – active conductivities of the windings of oscillatory circuits; W_1, W_2 – the number of turns of the oscillating circuit windings; $W_3, W_4, W_5, W_6, W_7, W_8$ are the secondary windings of the converter on which the artificial transformation of the number of phases takes place; C_1, C_2 are the capacitances of the oscillating circuit capacitors; R is the load of the artificial phases; $A, B, C, D, E, F, x, y, z, s, t$ are the beginnings and ends of artificial phases, respectively; i_{c1}, i_{c2}, are instantaneous currents in capacitors; i_{g1}, i_{g2} are currents in the conductivity of oscillatory circuits; i_1, i_2 are currents in coils of oscillatory circuits; $i = I_m \cdot \sin(\omega t + \psi_i)$ is the instantaneous value of the supply current; $u = U_m \cdot \sin(\omega t + \psi_u)$ is the instantaneous value of the supply voltage; $U_A, U_B, U_C, U_D, U_E, U_F$ are the values of the phase voltages of the artificial phases.

At certain values of U and frequency f, ferroresonance of currents is possible in the circuit under consideration, while the magnetic and electrical parts of the circuit are described by a system of equations,

$$\left\{\begin{matrix} b_1 \cdot S_1 + b_2 \cdot S_2 - b_3 \cdot S_3 = 0; b_1^9 = \frac{k \cdot l_2 \cdot b_2^9 - i_2 \cdot W_2 + i_1 \cdot W_1}{k \cdot l_1} \\ u = W_1 \cdot S_1 \frac{db_1}{dt} + W_2 \cdot S_2 \frac{db_2}{dt}; i = i_2 + i_{C2} + i_{g2}; i = i_1 + i_{C1} + i_{g1} \end{matrix}\right\} \quad (1.1)$$

in which the instantaneous currents in the branches can be found by the expressions:

$i_2 = \frac{k \cdot l_2 \cdot b_2^9}{W_2}$ (1.2), $i_{C1} = W_1 \cdot C \cdot S_1 \cdot \frac{d_2 b_1}{dt^2}$ (1.3), $i_{C2} = W_2 \cdot C \cdot S_2 \cdot \frac{d_2 b_2}{dt^2}$ (1.4)

$i_{g2} = W_2 \cdot g_2 \cdot S_2 \frac{db_2}{dt}$ (1.5), $i_1 = \frac{k \cdot l_1 \cdot b_1{}^9}{W_1}$ (1.6), $i_{g1} = W_1 \cdot g_1 \cdot S_1 \cdot \frac{db_1}{dt}$. (1.7)

Given the expression

$$b_3 = \frac{b_1 s_1 + b_2 s_2}{s_3}$$

as well as expressions for currents (1.2 – 1.7), we obtain

$$(w_1 w_2 C_2 s_2 \frac{d_2 b_2}{dt^2} + w_1 w_2 g_2 s_2 \frac{db_2}{dt} + (\frac{w_1}{w_2}) k l_2 b_2^9 - w_1^2 C_1 s_1 \frac{d_2 b_1}{dt^2} - w_1^2 g_1 s_1 \frac{db_1}{dt} - w_3^2 C_1 s_1 \frac{d_2 b_1}{dt^2} =$$
$$= k l_1 b_1^9 + k l_3 (\frac{s_1}{s_3} b_1 + \frac{s_2}{s_3} b_2)^9 \quad (1.8)$$

We will look for solutions for the instantaneous values of inductions b_1 and b_2 in the form of sinusoidal functions $b_1=B_{1m}\sin\omega t$; $b_2=B_{2m}\sin(\omega t-\varphi_1)$. After substituting this solution in 1.8 and considering (1.2 – 1.7), after some transformations we obtain

$$w_1 w_2 C_2 s_2 \omega^2 B_{2m} \sin(\omega t - \phi_1) + +w_1 w_2 g_2 s_2 \omega B_{2m} \cos(\omega t - \phi_1) +$$
$$+0{,}5 w_1 k l_2 B_{2m} \sin(\omega t - \phi_1) + w_1^2 C_1 s_1 \omega^2 B_{1m} \sin \omega t -$$
$$-w_1^2 g_1 s_1 \omega B t_{1m} \cos \omega t = 0{,}5 k l_1 B_{1m}^9 \sin \omega t +$$
$$+ \frac{k l_3}{s_3^9} (s_1 B_{1m} \sin \omega t + s_2 B_{2m} \sin(\omega t - \phi_1))^9 \quad (1.9)$$

In expression (1.9), we raise the multiplier $\frac{kl_3}{s_3^9}$ to the right of the equal sign to the 9th power by the Newton binomial, replace the degrees of the sine function with the sum of harmonics to the 1st power, and assume that the terms containing even harmonics are zero, and the constant components that appear when decomposing even powers of the sine will be included in the resulting expression in the form of constant factors for terms with odd degrees of sine. Taking into account only the first harmonic, we get

$$(s_1 B_{1m} \sin \omega t + s_2 B_{2m} \sin(\omega t - \phi_1))^9 =$$
$$= \frac{126}{256} (s_1 B_{1m})^9 \sin \omega t + \frac{9 \cdot 420}{256} (s_1 B_{1m})^8 s_2 B_{2m} \sin(\omega t - \phi_1) +$$
$$+ \frac{36 \cdot 70}{64 \cdot 2} (s_1 B_{1m})^7 \sin \omega t (s_2 B_{2m})^2 + \frac{84 \cdot 3 \cdot 40}{4 \cdot 64} (s_1 B_{1m})^6 (s_2 B_{2m})^3$$
$$\sin(\omega t - \phi_1) + \frac{126 \cdot 5 \cdot 3}{8 \cdot 8} (s_1 B_{1m})^5 (s_2 B_{2m})^4 \sin \omega t +$$
$$+ \frac{126 \cdot 3 \cdot 5}{8 \cdot 8} (s_1 B_{1m})^4 (s_2 B_{2m})^5 \sin(\omega t - \phi_1) + \frac{84 \cdot 3 \cdot 40}{4 \cdot 64} (s_1 B_{1m})^3$$
$$(s_2 B_{2m})^6 \sin \omega t + \frac{36 \cdot 70}{2 \cdot 64} (s_1 B_{1m})^2 (s_2 B_{2m})^7 \sin(\omega t - \phi_1) +$$
$$+ \frac{9 \cdot 420}{256} (s_1 B_{1m})(s_2 B_{2m})^8 \sin \omega t + \frac{126}{256} (s_2 B_{2m})^9 \sin(\omega t - \phi_1) \quad (1.10)$$

We reduce such terms to (1.10) for $\sin\omega t$ and $\sin(\omega t-\varphi_1)$. We denote the resulting expressions for $\sin\omega t$ as F_{1m}^9, and for $\sin(\omega t-\varphi_1)$ as F_{2m}^9. After all these mathematical operations, we get

$$F_{1m}^9 = 0{,}5(s_1 B_{1m})^9 + 19{,}7(s_1 B_{1m})^7 (s_2 B_{2m})^2 + 29{,}5(s_1 B_{1m})^5 (s_2 B_{2m})^4 +$$
$$+39{,}4(s_1 B_{1m})^3 (s_2 B_{2m})^6 + 14{,}8(s_1 B_{1m})(s_2 B_{2m})^8 \quad (1.11)$$
$$F_{2m}^9 = 14{,}8(s_1 B_{1m})^8 (s_2 B_{2m}) + 39{,}4(s_1 B_{1m})^6 (s_2 B_{2m})^3 +$$
$$+29{,}5(s_1 B_{1m})^4 (s_2 B_{2m})^5 + 19{,}7(s_1 B_{1m})^2 (s_2 B_{2m})^7 + 0.5(s_2 B_{2m})^9 \quad (1.12)$$

The final expression looks like this:

$$(s_1 B_{1m} \sin \omega t + s_2 B_{2m} \sin(\omega t - \phi_1))^9 \approx F_{1m}^9 \sin \omega t + F_{2m}^9 \sin(\omega t - \phi_1) \quad (1.13)$$

Let's denote some coefficients

$$\alpha = w_1 w_2 C_2 s_2 \omega^2; \beta = w_1 w_2 g_2 s_2 \omega; \gamma = 0{,}5(\frac{w_1}{w_2}) k l_2;$$
$$\lambda = w_1^2 C_1 s_1 \omega^2; \xi = w_1^2 g_1 s_1 \omega; z = 0{,}5 k l_1; d = \frac{k l_3}{s_3^9}; \omega t = \tau \quad (1.14)$$

Taking into account these coefficients and the notation (1.11–1.14), expression (1.10) is written as

$$\alpha B_{2m} \sin(\tau-\phi_1)+\beta B_{2m} \cos(\tau-\phi_1)+\gamma B_{2m} \sin(\tau-\phi_1)+\lambda B_{1m} \sin\tau - \\ -\xi Bt_{1m} \cos\tau = zB_{1m}^9 \sin\tau + dF_{1m}^9 \sin\tau + dF_{2m}^9 \sin(\tau-\phi_1) \quad (1.15)$$

After reducing such terms to (1.15), replacing the sines and cosines of the angles with their products, and converting the resulting expression using the harmonic balance method, which consists in equating the coefficients to both the left and right of the equal sign, we obtain the system

$$\begin{cases}(\gamma B_{2m}^9 - dF_{2m}^9 + \alpha B_{2m}) \cos\phi_1 + \beta B_{2m} \sin\phi_1 = zB_{1m}^9 + dF_{1m}^9 - \lambda B_{1m} \\ -(\gamma B_{2m}^9 - dF_{2m}^9 + \alpha B_{2m}) \sin\phi_1 + \beta B_{2m} \cos\phi_1 = \xi B_{1m}\end{cases} \quad (1.16)$$

Squaring the expressions to the left and right of the equal sign in (1.16) after the transformations, we obtain an expression defining the relationship between the amplitudes of magnetic inductions in the left and right rods of the circuit core according to Fig.2.

$$(\gamma B_{2m}^9 - dF_{2m}^9 + \beta B_{2m})^2 + (\beta B_{2m})^2 = (zB_{1m}^9 + dF_{1m}^9 - \lambda B_{1m})^2 + (\xi B_{1m})^2. \quad (1.17)$$

The transformation of expression (1.17) makes it possible to determine the phase shift angle between the amplitudes of magnetic inductions B_{1m} and B_{2m}

$$\phi_1 = arctg\left(\frac{(\beta B_{2m})(zB_{1m}^9 + dF_{1m}^9 - \lambda B_{1m}) - (\gamma B_{2m}^9 - dF_{2m}^9 + \alpha B_{2m})(\xi B_{1m})}{(\gamma B_{2m}^9 - dF_{2m}^9 + \alpha B_{2m})(zB_{1m}^9 + dF_{1m}^9 - \lambda B_{1m}) + (\beta' B_{2m})(\xi B_{1m})}\right) \quad (1.18)$$

The amplitude of the magnetic induction in the middle core rod is found by the expression $b_3 = B_{3m}\sin(\omega t + \varphi_3)$, and taking into account the previously accepted designations, we obtain

$$B_{3m} \sin(\omega t - \phi_3) = \frac{s_1}{s_3} B_{1m} \sin\omega t + \frac{s_2}{s_3} B_{2m} \sin(\omega t - \phi_1) \quad (1.19)$$

Let's denote the relations between the areas as $\sigma_1 = \frac{s_1}{s_3}$; $\sigma_2 = \frac{s_2}{s_3}$, we will have

$$B_{3m} \sin(\tau - \phi_3) = \sigma_1 B_{1m} \sin\tau + \sigma_2 B_{2m} \sin(\tau - \phi_1) \quad (1.20)$$

After converting in (1.20) the difference of the sines of the angles into their product by the harmonic balance method, we obtain the system

$$\begin{cases}B_{3m} \cos\phi_3 = \sigma_1 B_{1m} + \sigma_2 B_{2m} \cos\phi_1 \\ B_{3m} \sin\phi_3 = \sigma_2 B_{2m} \sin\phi_1\end{cases} \quad (1.21)$$

Converting (1.21), we find the amplitude of the first harmonic of the magnetic induction in the middle core rod

$$B_{3m} = \sqrt{(\sigma_1 B_{1m} + \sigma_2 B_{2m} \cos\phi_1)^2 + (\sigma_2 B_{2m} \sin\phi_1)^2} \quad (1.22)$$

and its initial phase

$$\phi_3 = arctg\left(\frac{\sigma_2 B_{2m} \sin\phi_1}{\sigma_1 B_{1m} + \sigma_2 B_{2m} \cos\phi_1}\right) \quad (1.23)$$

The current in the unbranched part of the considered circuit is determined through the parameters of the primary circuit. The expression for the current is written as

$$I_m \sin(\omega t + \psi_i) = i_{C1} + i_{g1} + i_1 = w_1 C_1 s_1 \frac{d^2 b_1}{dt^2} + w_1 g_1 s_1 \frac{db_1}{dt} + \frac{k l_1 b_1^9}{w_1} \quad (1.24)$$

Substituting in (1.24) the solution for the magnetic induction in the first rod, after some transformations, we obtain

$$I_m \sin(\omega t + \psi_i) = -w_1 C_1 s_1 \omega^2 B_{1m} \sin\omega t + w_1 g_1 s_1 \omega B_{1m} \cos\omega t + 0{,}5\frac{k l_1}{w_1} B_{1m}^9 \sin\omega t \quad (1.25)$$

We introduce the notation of the coefficients before the sines and cosines.

$$\alpha_1 = w_1 C_1 s_1 \omega^2; \delta_1 = w_1 g_1 s_1 \omega; \gamma_1 = 0{,}5\frac{k l_1}{w_1} \quad (1.26)$$

We transform (1.25) using the harmonic balance method, replacing the sums of the arguments of the sine and cosine functions by their product and comparing the coefficients for $\sin\tau$ and $\cos\tau$ both to the left and to the right of the equal sign

$$\begin{cases}I_m \cos\psi_i = \gamma_1 B_{1m}^9 - \alpha_1 B_{1m} \\ I_m \sin\psi_i = \delta_1 B_{1m}\end{cases} \quad (1.27)$$

From where we get the expression connecting the amplitudes of induction B_{1m} and the supply current I_{1m}

$$I_m = \sqrt{(\gamma_1 B_{1m}^9 - \alpha_1 B_{1m})^2 + (\delta_1 B_{1m})^2} \quad (1.28)$$

And we also get an expression for determining the initial phase of the supply current I_{1m}.

$$\psi_i = arctg(\frac{\delta_1 B_{1m}}{\gamma_1 B_{1m}^9 - \alpha_1 B_{1m}}) \qquad (1.29)$$

The supply voltage U_m can be found according to Kirchhoff's second law, compiled for instantaneous voltage values.

$$U_m \sin(\omega t + \psi_u) = u_1 + u_2 = w_1 s_1 \frac{db_1}{dt} + w_2 s_2 \frac{db_2}{dt} \qquad (1.30)$$

Substituting the solutions in (1.30) $b_1=B_{1m}\sin\omega t$; $b_2=B_{2m}\sin(\omega t-\varphi_1)$, performing mathematical transformations and replacing the sine and cosine of the sum and difference of the arguments in the resulting expression with products $v_1=w_1 s_1 \omega$, $v_2=w_2 s_2 \omega$, $\tau=\omega t$, taking into account the notation, we have

$$U_m \sin\tau \cos\psi_u + U_m \cos\tau \sin\psi_u = \upsilon_1 B_{1m} \cos\tau + \upsilon_2 B_{2m} \cos\tau \cos\phi_1 + $$
$$+\upsilon_2 B_{2m} \sin\tau \sin\phi_1 \qquad (1.31)$$

Converting (1.31) by the harmonic balance method, we obtain the system

$$\begin{cases} U_m \cos\psi_u = \upsilon_2 B_{2m} \sin\phi_1 \\ U_m \sin\psi_u = \upsilon_1 B_{1m} + \upsilon_2 B_{2m} \cos\phi_{13} \end{cases} \qquad (1.32)$$

from which an expression can be derived relating the input voltage to the harmonics of the magnetic inductions in the core rods

$$U_m = \sqrt{(\upsilon_2 B_{2m} \sin\phi_1)^2 + (\upsilon_1 B_{1m} + \upsilon_2 B_{2m} \cos\phi_1)^2} \qquad (1.33)$$

and for the initial phase of the supply voltage

$$\psi_u = arctg(\frac{\upsilon_1 B_{1m} + \upsilon_2 B_{2m} \cos\phi_1}{\upsilon_2 B_{2m} \sin\phi_1}) \qquad (1.34)$$

the phase shift angle between the voltage and current vectors can also be determined.

$$\phi = \psi_u - \psi_i \qquad (1.35)$$

Results and Discussion

We investigate the dependencies B^*_{1m}, B^*_{2m}, $B^*_{3m}=f(U^*_m)$, reflecting on a certain scale the course of the converter's adjustment characteristics U_{1m}, U_{2m}, $U_{3m}=f(U_m)$. Figure 2 shows the family of curves B^*_{1m}, B^*_{2m}, $B^*_{3m}=f(U^*_m)$.

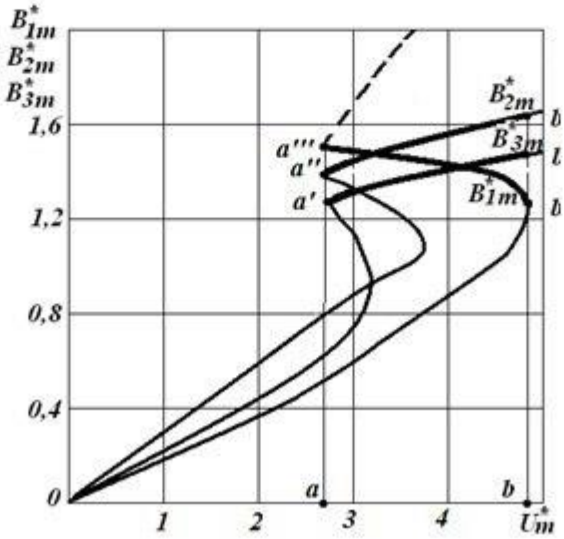

Fig. 2. Calculated adjustment characteristics of phase number converters at C_1=24 mkF, C_2=10 mkF

It can be seen from the curves that within the limits of the existence of autoparametric ferroresonance oscillations limited by points *a* and *b*, the inductions in the core rods do not change significantly: induction B^*_{3m} is located between points *a'* and *b'*, induction B^*_{1m} is between points *a''* and *b''*, and induction B^*_{2m} is between points *a'''* and *b'''*. The small deviation of the magnetic inductions indicates the possibility of using the circuit in question as a voltage stabilizer on the windings W_3-W_8.

Using expressions (1.18), (1.23), (1.29), 1.34) and (1.35) we construct the dependences of the phase shifts ψ_1, ψ_2, ψ_3 on the amplitude of the supply voltage U_m, the graphs of these dependences are shown in Fig. 3. From this figure it can be seen that before the ferroresonance jump (to points a, *b, c*) the phase shift on the extreme rods (curves ψ_1 and ψ_2) is capacitive, and in the middle rod (curve ψ_3) it is inductive. After the ferroresonance jump (from points *a'*, *b'*, *c'* to the end of the coordinates), curve ψ_2 has an inductive character with a phase shift of about *+60°*, curve ψ_1 has a capacitive character with a phase shift of about *-60°*, and the phase shift ψ_3 in the middle rod approaches zero.

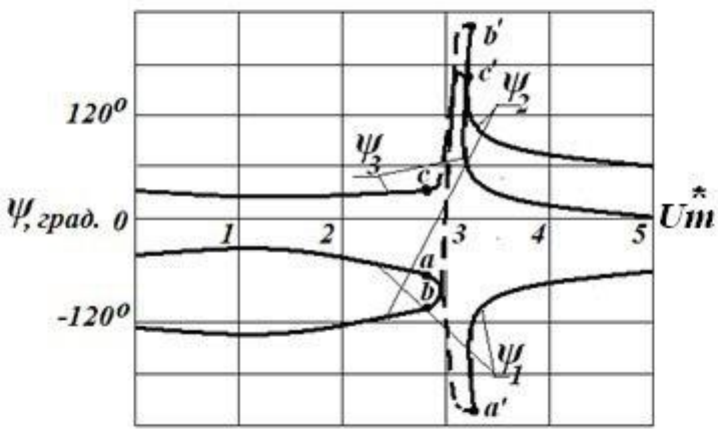

Fig. 3. The dependence of phase shifts between magnetic inductions in the rods of the magnetic circuit of phase number converters on the amplitude of the supply voltage

If the ends of the windings W_3 and W_7 are reversed on the middle core rod, a phase shift of approximately *60°* will be established between the output voltage vectors U_A, U_B, U_C, U_D, U_E and U_F and the values of the inductions and, accordingly, the voltages, as can be seen from Fig. 2, will stabilize.

The voltage characteristic of the converter $U_m^*=f(I_m^*)$, shown in Fig. 4, is the ratio between the amplitude of the input voltage and the amplitude of the current, expressed in relative units. As can be seen from Fig. 4, the current-voltage characteristic has a loop-like character with a section of almost stable current, that is, the circuit under study is close in properties to the current source, while these properties are preserved when the capacitance C_2 changes from 8 to 15 *mkF*.

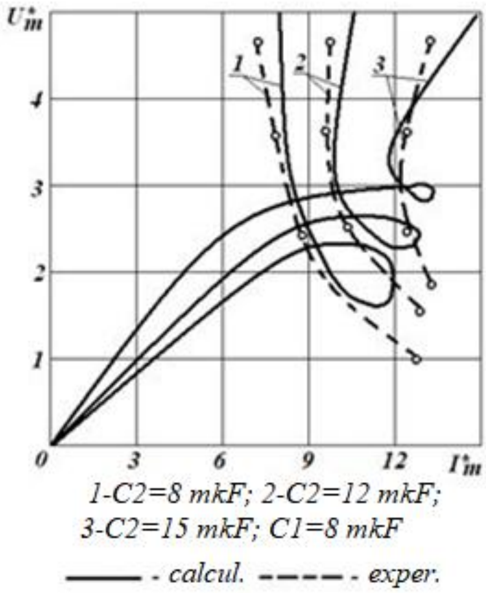

Fig. 4. Current-voltage characteristic of phase number converters at different capacitor capacitance values C_2 (C_1=*const*)

According to [1, 6], this indicates the possibility of stabilizing the modes of both the relative amplitudes of magnetic inductions $B_{1m}^*, B_{2m}^*, B_{3m}^*$ and the associated amplitudes of the phase voltages U_A, U_B, U_C, U_D, U_E and U_F of artificial phases.

Calculation

1. The type of adjustment characteristic of the converter shows that in the ferroresonance mode of currents, when the supply voltage of the induction in the rods of the amorphous magnetic core changes, they remain almost unchanged, which indicates the stabilization of the voltages on the windings located on these rods.

2. The phase shifts in the ferroresonance mode of currents remain almost unchanged and equal to approximately 60°, which allows us to conclude that it is possible to convert the number of phases with shifts between phase voltages of approximately 60°.

3. The sections of stable current of the voltage characteristic at the moment of ferroresonance of the currents indicate that the circuit in question is powered by a current source, which means that voltage stabilization is possible in the circuit in accordance with the properties of the Bouchereau circuit.

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