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ANALYTICAL CONNECTIONS OF PARAMETERS AND SIZES OF PRECISION STABILIZER OF ALTERNATING CURRENT USING EFFECT OF INDUCTIVE LEVITATION

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Abstract- One of the important tasks of power electronics is to ensure the level of constancy of the load current. Preserving the current level of current is carried out by the use of switching type controllers based on IGBT transistors and transformative circuits. Development of a current control system is the main goal for maintaining the level of load current. Current stabilizers are used for peeling electronic devices, as well as thermal stabilizers for the supply of operating temperature, loading accumulators of various types, supply of current of amplifying and converter cascades as part of integral microcircuits [1-2]. In order to achieve the technical result, the basis of the control system of the precision-and-to-stabilizer is the method of using the frequency-pulse modulation of the inverter control signal. The peculiarity of this method is to measure the value of the stabilized current in the load circuit, preserving the microcontroller in memory, straightening and smoothing output current. The measured value of a stabilized current is compared by an amplifier with the required value, and this value is determined using a digital-analysis converter installed in a microcontroller. The required sequence of pulsed frequencies for controlling the inverter is carried out by a generator, which in turn is controlled by an amplifier and thus provides regulation of the load current, high accuracy of the input voltage of the power and dynamic changes in the load.

Keywords: Current Stabilizer, Multinominal, Precision, Levitation, Load, Control System, Linen-Mopulse Modulation, Regulator, Inverter.

1. INTRODUCTION

The modern level of development of technology contributes to an increasingly wide area of use of electric devices with levitational elements for the exact stabilization of alternating current in adjustable loads, automatic control of non-electrical parameters of technological processes, etc. The design parameters and determination of optimization indicators have been analyzed, analytical expression for these indicators have been obtained. This leads to simplifying the calculations of indicators and the creation of relationships between parameters.

Electric devices with levitational elements reflect the functions of the measurement, control and stabilization of electrical and non-electrical parameters [1-4]. The main elements of these Apa are: magnetic circuit, an excitement winding from several sections connected to a variable voltage source U_1 and a levitation element. An analysis of the work [1-2] shows that electrical apparatuses with Levi-towering elements differ in characteristics, which complicates their design, therefore, the presence of generalized indicators is required that combine the basic technical characteristics and parameters. In order to determine such indicators, calculation and research methods are analyzed. Such defects include: current modes and efforts, levitation coordinate, working mobile part, lifting force, electromagnetic rigidity, etc. The resulting analytical expressions of generalized indicators make it possible to simplify the design of electrical apparatuses of various functional purposes, simple design, and working characteristics of high stability and accuracy.

2. STABILIZERS ON PRINCIPLE OF INDUCTION LEVITATION SUSPENSION

Induction suspension bodies are one of the levitation methods. The significance of such a suspension is the balancing of the electrodynamic force acting on the body with the force of gravity. The main significance of the use of induction suspension lies in the use of new high-precision AC and voltage stabilizers. Stabilizers based on the principle of induction suspension are divided into two groups:
- current stabilizers with levitation screen
- levitated voltage stabilizers with excitation winding

To obtain several nominal values of the stabilized current, the windings are divided into sections. To obtain a direct current on the load, the alternating current is rectified using a rectifier bridge. According to their design features, they are divided into stabilizers with a straight and stepped magnetic circuit [4-12]. To reduce the height of the excitation winding and improve its cooling, the winding can be divided into two parts (placement on the extreme rods). The separated windings are connected to each other in series-opposite. In this case, the winding resistance is halved than when placing the winding on the middle rod:

$$x_1 = \omega\left[\frac{1}{2}\omega W_1^2 \lambda\left(\frac{0.5h_1}{3} + X_M + \frac{h_2}{3}\right)\right] \quad (1)$$

where, h_1 and h_2 are the height of the excitation winding and the levitation screen; and λ is specific magnetic conductivity of the working air gap.
Winding current:

$$I_1 = \frac{U_1}{x_1} = \frac{U_1}{\omega W_1^2 \lambda\left(\frac{h_1}{6} + X_M + \frac{h_2}{3}\right)} \quad (2)$$

when, placing the winding on the middle rod:

$$x_1 = \omega W_1^2 \lambda\left(X_M + \frac{h_1 + h_2}{3}\right) \quad (3)$$

$$I_1 = \frac{U_1}{x_1} = \frac{U_1}{\omega W_1^2 \lambda\left(X_M + \frac{h_1 + h_2}{3}\right)} \quad (4)$$

Consider the principle of operation and the main features of the AC stabilizer.

3. CURRENT STABILIZERS WITH LEVITATION SCREEN

The stabilizer consists of a vertical Ш-shaped magnetic circuit, an excitation winding located on the lower part, a levitation screen moving along the middle rod. From the influence of gravity P_T and electrodynamic force F_E, the levitation screen changes its position in the vertical direction. The operation of the stabilizer is based on the mutual balancing of these two forces on the short-circuited winding of the levitation screen. Figure 1 shows the dependence of the electrodynamic force F_E and the screen gravity P_T on the displacement of the levitation screen or short-circuited winding. For each equilibrium position, i.e., $P_T=F_E$, short-circuited winding in levitation state. The levitation coordinate h_0 is determined by the intersection point of the force characteristic $F_E=f(h)$ and the horizontal line of gravity P_T. If the balance is disturbed, for example, with an increase in voltage U_1 with an increase in the voltage supplied at the load current to the excitation winding, the electrodynamic force F_E increases and shifts the screen up.

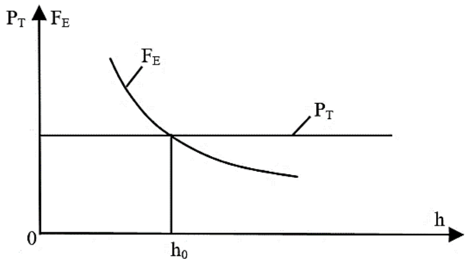

Figure 1. Dependence of F_E and P_T considering levitation coordinate h

Under the action of the inductive resistance of the excitation winding, the current decreases to the initial value. The forces F_E and P_T are rebalanced. The alternating current is stabilized in the excitation winding. Stabilization in the excitation winding causes stabilization in the levitation screen, so the load can be connected to the screen circuit.

By means of the armature, the value of the working air gap δ is regulated, and this corresponds to the initial position of the levitation screen. On the levitation screen, in addition to the electrodynamic force, radial forces also act, which are equal in value, but opposite in direction. Therefore, they are centered relative to the screen magnetic core. For current stabilizers based on the principle of induction suspension characteristic factors such as: simplicity of design and control circuit, high reliability, high stabilization accuracy (in a wide control range) $(15\div20)\times10^{-3}$%, sinusoidal form of the stabilized current, small weight and dimensions; and the disadvantages include inertia (1×10^{-1} sec.), low power factor ($\cos\varphi = (6\div7)\times10^{-1}$). For current stabilizers based on the principle of induction suspension, the presence of a movable winding (screen) is not a disadvantage and is in a free levitation position, can move without friction.

For this reason, current stabilization is high [13-17]. Structurally, the excitation winding of the levitation stabilizer consists of a Ш-shaped core, a fixed winding placed on the middle rod, and a movable winding. If the voltage U_1 is not applied to the excitation winding, then it is in the lower position. When voltage is applied, the winding moves upward under the action of the force F_E and the condition of force balance $P_T= F_E$ is fulfilled. The greater the supply voltage U_1, the greater the force F_E and the height h of the rise of the excitation winding. With an increase in voltage, the excitation current and F_E increase, the excitation winding rises, the inductive resistance decreases to a given current value.

The excitation current I_1 is stabilized with high accuracy. The advantage of stabilizers with a levitating excitation winding is that the interconnected inductive reactance and the inductive reactance of the secondary winding does not depend on the position of the excitation winding. At the terminals of the secondary winding, the no-load voltage U_{20} is determined by the winding current and mutual inductive resistance, so this voltage is also stabilized with high accuracy.

In the secondary circuit, when the resistance approaches infinity, the voltage at the terminals remains constant with high accuracy. When a load is connected to the secondary winding, a current I_2 is created and as a result, a magnetic flux is created in the secondary winding. This, in turn, inversely affects the field winding flux and creates F_E. This force acts on the excitation winding, changes its position and the condition $F_E = P_T$ is fulfilled. The field current I_1 remains unchanged and the current I_2 stabilizes. The voltage at the load in the screen circuit is determined by the product of the current I_2 and the load resistance r_{2n}. If r_{2n} = const, then the voltage, like the current, stabilizes with accuracy.

At different loads, the voltage is different, i.e., multipurpose stabilizer. The advantage of such stabilizers is similar to stabilizers with a levitation screen, but as a disadvantage it should be noted that when the load connected to the fixed winding circuit changes, voltage stabilization is fundamentally impossible. The difference between these stabilizers is that in addition to the movable and fixed windings, there is also a compensation winding and a circuit (*r-c*) is connected to its circuit (synchronous connection). The capacitance parameter is chosen in such a way that the specific resistance of the compensation winding circuit is determined by the capacitive nature. This is necessary with an instantaneous change in load resistance to compensate for the excess F_E.

4. INTERRELATIONSHIPS OF MAIN PARAMETERS OF AC STABILIZER WITH INDUCTION LEVITATION

The calculation and solution of optimization problems for an AC stabilizer with induction levitation consists of the following steps:

1. Determination of the initial parameters of the AC stabilizer.
2. Analysis of the calculation and determination of output characteristics for the criteria.
3. Determination of analytical expressions between the initial data and the output parameters of the stabilizer.
4. Development of recommendations for improving the output parameters.
5. Choice of stabilizer design.
6. Calculation of a multi-rated AC stabilizer with a levitation winding and determination of criteria for optimal parameters.

The task gives the value of the mains voltage U_c, the limit of change $\Delta U_c = U_{c\max} - U_{c\min}$ and the load current In. According to the initial position of the levitation winding, the levitation coordinate h is calculated for the rated load current I_n and voltage U_n. The calculation takes into account:

- influence of ambient temperature and normal overheating temperature;
- touch of the levitation winding to the upper yoke;
- according to the difference $\Delta U = U_{\max} - U_{\min}$ of the working stroke of the levitation winding, its minimum value;
- the maximum limit of the core induction $B_{\max}$.

To this end, the following dependencies are investigated:

- excess voltage at the terminals of the excitation winding $\Delta U_1 = U_{1\max} - U_{1\min}$, dependence of the mains voltage changes $\Delta U_c = U_{c\max} - U_{c\min}$;
- dependence of the maximum stroke X_M on the excess voltage of the excitation winding ΔU_1;
- dependence on the initial data input S, output P_n, electromagnetic forces and winding forces;
- dependence on the initial data of the X_M stroke and the current stabilization period;
- dependences τ_1 and τ_2 on overheating temperatures, load current I_n, environment θ_{ok} and windings;
- depending on the overheating temperatures of the windings of the main dimensions, power, electromagnetic loads, (inductance in the core B_c and current density in the windings j);
- dependence of the load power P_n and the total load S_n on the excess of induction in the core ΔB_c, changes in the mains voltage ΔU_c.

5. CALCULATION OF THE COURSE OF THE LEVITATION WINDING

One of the important parameters of an AC stabilizer with a levitation winding is the course of the levitation winding, since the current stabilization period is directly proportional to the course of the levitation winding. With an increase in the stroke of the levitation winding, the height of the stabilizer increases. Therefore, stroke reduction is an important task in the design of a current stabilizer. Formula for current:

$$I_1 = \frac{U_{1nom} + \Delta U_1}{x_{1s} + x_h + \Delta x} \tag{5}$$

you can write:

$$I_1 = I_{1nom} = \frac{1 + \dfrac{\Delta U_1}{U_{1nom}}}{1 + \dfrac{\Delta x}{x_{1s} + x_h}} \tag{6}$$

where, U_{nom} and I_{nom} are the nominal initial values of voltage and stabilized current for a fixed winding; $(x_{1s}+x_h)$ inductive reactance's corresponding to the nominal value of the winding voltage U_{1nom}:

$$I_{1nom} = \frac{U_{1nom}}{x_{1s} + x_h};\ x_{1s} + x_h == \omega W_1^2 \lambda \left(h_{nom} + \frac{h_1 \lambda_s}{3\lambda} \right) \tag{7}$$

The levitation coordinate h_{nom} corresponds to the nominal voltage U_{1nom}. Therefore, the winding stroke is defined as:

$$X = \frac{\Delta U_1}{\Delta U_{1nom}} \left(h_{nom} + \frac{h_1 \lambda_{1s}}{3\lambda} \right) = \frac{\Delta U_1}{I_{nom} \omega W_1^2 \lambda} \tag{8}$$

For large values of the ratio $\frac{\Delta U_1}{U_{1nom}}$, the stroke of the levitation winding can be large. To reduce the stroke of the levitation winding, the stabilizer magnetic circuit must be stepped, since in this case $\lambda_s < \lambda$ and the height of the winding h_1 is small than in a stabilizer with a direct magnetic circuit. Thus, it can be noted:

A change in the voltage at the terminals of the winding or the load resistance causes a change in the levitation coordinate of the moving part. As a result, the inductance of the stabilizer changes.

By selecting sections of the excitation winding, the stabilizer can obtain different current values at the load. The conditions of electromechanical and thermal stability of the levitation winding of the AC stabilizer are determined. Dependences of the course of the moving part on the frequency, mains voltage and load resistance are determined. Equivalent electrical and magnetic equivalent circuits take into account all losses in the stabilizer [8-16].

Attitude $\frac{\Delta U_1}{\Delta U_c}$ depends on attitude $\frac{P_n}{S_n}$. When the ratio $\frac{P_n}{S_n}$ is large, the ratio $\frac{\Delta U_1}{\Delta U_c}$ is also large. An increase in the power P_n of the current stabilizer requires an increase in the insulation of the excitation winding.

Overall power of the stabilizer P_{ov}. does not depend on the levitation coordinate or the motion of the moving part. It increases with increasing load current. To reduce the overall power, the cross sections of the winding and core must be reduced, which is associated with a decrease in electromagnetic forces. The course of the levitation winding is directly proportional to the excess voltage ΔU_1 and inversely to the nominal value of the stabilized current I_{nom}. Analytical expressions for electromagnetic force contribute to the choice of core sizes.

Increasing the power P_n of the stabilizer, the overheating temperature τ remains constant, if with an increase in size the induction $B_{\max}$ and the current density j decrease. Therefore, the dependence of the current density j and induction $B_{\max}$ on the power P_n is determined. To reduce magnetic losses in the core, according to the experimental dependences of electrical steel $\rho_R(B)$ and $\rho_x(B)$, the range of induction change $\Delta B=B_{\max}-B_{\min}$. is used. With an increase in the power of the stabilizer P_n and voltage ΔU_c, the range of induction change ΔB expands, and with an increase in power S_n, this range narrows.

6. CALCULATION OF A MULTI-RATED AC STABILIZER WITH INDUCTION LEVITATION

When designing various AC stabilizers, Ш-shaped rod magnetic circuits or sometimes symmetrical stepped ones are used as a generalized design. The most difficult task is to determine the analytical expressions between the original data and the geometric dimensions. The solution of the problem requires the development of a mathematical model of the system, consisting of the equations of electrical, magnetic, mechanical and thermal circuits of the stabilizer.

The solution of these Equations allows you to create analytical expressions between the initial data, the course of the levitation winding X_M, the gravity force P_T, the cross section of the windings (S_0, S_{02}) and the core S_c, the required power P_M. Initial data for the calculation of AC stabilizers: range of mains voltage variation ΔU_c, load currents I_{n1}, I_{n2}, ..., I_{nn}, mains voltage frequency ω, load resistance R_n (or power P_n), move of the moving part X_M.

As a result of calculations, the geometric dimensions of the core and windings, their overheating temperatures are determined. The number of stabilizer parameters to be determined is greater than the number of equations. Therefore, when calculating stabilizers from known experiments, the accepted values of electrical, electromagnetic, and design parameters are used. The main task of designing an AC stabilizer with induction levitation is to determine the analytical relationships between the geometric dimensions and the initial data. To determine these relationships, a mathematical model is used:

$$h=\frac{k_u U_1}{\omega W_1\sqrt{2P_T\lambda}}-\frac{h_1}{3n_\lambda} \tag{9}$$

$$I_1=\frac{k_u U_1}{\omega W_1^2\lambda\left(h+\frac{\lambda_1}{3n_\lambda}\right)} \tag{10}$$

$$I_2=b_2 I_1\frac{W_1}{W_2} \tag{11}$$

$$F_1=J_1K_{31}S_{01}=I_1W_1;\quad F_2=J_2K_{32}S_{02}=I_2W_2$$

$$F_E=\frac{1}{2}\left(I_1W_1\right)^2\lambda=P_T;\quad B_M=\frac{K_uU_1\sqrt{2}}{\omega W_1K_{3c}S_c} \tag{12}$$

$$\tau_1=\frac{P_{M1}+P_{M2}}{K_TS_{cool1}}=\frac{I_1^2(r_1+r_{1np})}{K_TS_{cool1}} \tag{13}$$

$$\tau_2=\frac{P_{M2}}{K_TS_{cool2}}=\frac{I_1^2r_2}{K_TS_{cool2}} \tag{14}$$

where, the ratio $n_\lambda=\lambda/\lambda_s$ is the specific magnetic conductivity of the working air gap to the specific magnetic conductivity of the scattering of the excitation winding; h_1 is the height of the excitation winding; S_{01}, S_{02} is winding cross-sections; J_1, J_2, W_1, W_2 are winding current densities and number of turns; S_c is the cross section of the middle rod of the magnetic core; K_{3s} is the filling factor of the steel core; K_T is the heat transfer coefficient; K_u is factor taking into account the voltage drop: K_{31}, K_{32} are steel fill factors; S_{cool1}, S_{cool2} are winding cooling areas; $b_2<1$ is a coefficient that takes into account the electromagnetic coupling between the windings.

These equations are the equations of the power supply voltage U_1 and frequency ω, the expression for the levitation coordinate h, the equations of the currents and the magnetomotive force (mmf) of the windings. The force balance equation characterizes the position of levitation.

We note the necessary features of the calculation and design of a multi-rated AC stabilizer with induction levitation [18-21]:

1. The load is connected in series with the excitation winding of the stabilizer. This causes the lowest voltage value at the terminals of the winding, in contrast to the mains voltage. The range of voltage variation at the winding terminals ΔU_1 may be greater than the range of mains voltage variation ΔU_c. When changing the load resistance R_n or power P_n, it is necessary to know the dependence of the voltage U_1 on the mains voltage U_c. The course of the levitation winding X_M depends on the excess voltage of the excitation winding $\Delta U_1=U_{1\max}-U_{1\min}$, then the dependencies:

$$\frac{\Delta U_1}{X_M}=f(I_1)\,;\,\Delta U_1=f(\Delta U_c) \tag{15}$$

are important characteristics of the current stabilizer. The connection between ΔU_1 and ΔU_c is determined by the parameters R_n and P_n.

2. Compared with inductive reactance, the active resistance of the field winding is very small; the flowing current is constant. Therefore, the active resistance of the winding and its overheating temperature are constant; currents (I_1 and I_2), mains voltage, frequency do not depend on the ambient temperature. The magnetomotive force (mmf) of the windings depends on the specific magnetic conductivity of the working air gap λ and the force P_T:

$$I_1W_1 = \sqrt{\frac{2P_T}{\lambda}}\ ;\ I_2W_2 = b_2\sqrt{\frac{2P_T}{\lambda}} \qquad (16)$$

where, b_2= (98÷99)×10^{-2}. The heat from the windings is transferred mainly to the environment through the surfaces of the sides, then:

$$\tau_1 = \frac{I_1^2 r}{K_T S_{side1}}\ ;\ \tau_2 = \frac{I_2^2 r_2}{K_T S_{side2}} \qquad (17)$$

where, $K = \frac{W_1}{W_2}$; $r = r_1 + b_2^2 K^2 r_2$. Usually, $\tau_1 = \tau_2 = \tau_{adm}$, therefore:

$$\frac{S_{side1}}{S_{side2}} = K_r\left(\frac{\tau_2}{\tau_1}\right) = K_r > 1\ ;\quad K_r = 1 + \frac{1}{K^2 b_2^2}\frac{r_1}{r_2} \qquad (18)$$

To fulfill the condition $\tau_1=\tau_2=\tau_{adm}$. It is necessary to provide $S_{side1}>S_{side2}$.

3. For an AC stabilizer, the ratio of the voltage at the terminals of the field winding U_1 to the inductive resistance of the winding X_1 is a constant parameter and is equal to the stabilized current I_1.

$$\frac{KU_1}{X_1} = \frac{K_u U_1}{\omega W_1^2 \lambda\left(h + \frac{h_1}{3n_\lambda}\right)} = I_1 = \text{const} \qquad (19)$$

Levitation coordinate h linear function of voltage U_1:

$$h = \frac{K_u U_1}{\omega W_1^2 \lambda I_1} - \frac{h_1}{3n_\lambda}\ ,\ n_\lambda = \frac{\lambda}{\lambda_s} \qquad (20)$$

For a given constant current value, the maximum and minimum values of the levitation coordinate are determined by the voltages $U_{1\max}$ and $U_{1\min}$:

$$h_{\max} = \frac{K_u U_{1\max}}{\omega W_1^2 \lambda I_1} - \frac{h_1}{3n_\lambda} \qquad (21)$$

$$h_{\min} = \frac{K_u U_{1\min}}{\omega W_1^2 \lambda I_1} - \frac{h_1}{3n_\lambda} \qquad (22)$$

The maximum stroke of the levitation winding is determined by the expression:

$$X_M = h_{\max} - h_{\min} = \frac{K_u \Delta U_1}{\omega W_1^2 \lambda I_1} = \frac{K_u \Delta U_1}{\omega W_1 F_1} = = \frac{K_u \Delta U_1}{\omega W_1 \sqrt{2P_T \lambda}} \qquad (23)$$

Thus, the course of the levitation winding is directly proportional to the voltage ΔU_1. But the stabilized current I_1 with the power P_T are inversely proportional.

4. The maximum value of the core induction B_M is limited by the grade of electrical steel and the currents of the three-section excitation winding are determined by the number of turns of the sections:

$$I_{11} = I_{1\min} = \frac{1}{W_{11}}\sqrt{\frac{2P_T}{\lambda}} \qquad (24)$$

$$I_{12} = I_{1cp} = \frac{1}{W_{12}}\sqrt{\frac{2P_T}{\lambda}} \qquad (25)$$

$$I_{13} = I_{1\max} = \frac{1}{W_{13}}\sqrt{\frac{2P_T}{\lambda}} \qquad (26)$$

If we take into account that the load currents $I_{n1}=I_{11}$, $I_{n2}=I_{12}$, $I_{n3}=I_{13}$ are given, then the number of turns of the sections is determined.

$$W_{11} = \frac{1}{I_{11}}\sqrt{\frac{2P_T}{\lambda}};\ W_{12} = \frac{1}{I_{12}}\sqrt{\frac{2P_T}{\lambda}};\ W_{13} = \frac{1}{I_{13}}\sqrt{\frac{2P_T}{\lambda}} \qquad (27)$$

Since for the stabilizer:

$$\sqrt{\frac{2P_T}{\lambda}} = \text{const};\ I_{11} = I_{\min};\ I_{13} = I_{\max} \qquad (28)$$

then for the number of turns you can write:

$$W_{13} = W_{\min};\ W_{11} = W_{\max};\ W_{11} > W_{12} > W_{13} \qquad (29)$$

The cross-sectional area of the core is determined by:

$$S_c = 2ab = \frac{K_u U_{1\max}\sqrt{2}}{\omega K_{3c} W_{1\min}} = 2ab = \frac{K_u U_{1\max}\sqrt{2}}{\omega K_{3c} W_{1\max} B_M}\sqrt{\frac{\lambda}{P_T}} \qquad (30)$$

According to the equations of the mmf of the windings:

$$\frac{F_1}{F_2} = \left(\frac{J_1}{J_2}\right)\left(\frac{K_{wind1}}{K_{wind2}}\right)\left(\frac{S_{01}}{S_{02}}\right) = \frac{1}{b_2} \qquad (31)$$

Winding current density ratio:

$$\frac{J_1}{J_2} = b_2\left(\frac{S_{02}}{S_{01}}\right)\left(\frac{K_{wind2}}{K_{wind1}}\right) < 1 \qquad (32)$$

where, $\frac{S_{02}}{S_{01}} < 1$; $b_2 < 1$; $K_{wind1} \approx K_{wind2}$.

As can be seen, the current density of the excitation winding J_1 is less than the current density of the levitation winding J_2. This ratio does not take into account the overheating temperature of the windings. Therefore, it is necessary to obtain a mathematical expression that takes into account this factor.

The magnetic systems of stabilizers are made up on the basis of straight and stepped magnetic circuits (Figures 2a and 2b). Usually, with a direct magnetic circuit, they are used for low-power stabilizers. In order to reduce the height h_1, it is necessary to increase its thickness c_1. Then the excitation winding cooling area $S_{cool1}=S_{side1}$ must correspond to the given overheating temperature τ_1:

$$S_{side1} = \frac{I_1^2 r}{K_T \tau_1} \qquad (33)$$

This principle also applies to the calculation of the levitation winding. The magnetic field of the working air gap for a homogeneous Ш-shaped magnetic circuit is determined by the specific magnetic conductivity of the working air gap:

$$\lambda = 2\mu_o\left[\frac{b}{c} + 2.92\ln\left(1 + \frac{2\pi a}{2b}\right)\right] \qquad (34)$$

or

$$\lambda = 2\mu_o \frac{b}{c}\sigma_b = 2\mu_o m_c \sigma_b \qquad (35)$$

where, $\sigma_b = 1 + \frac{c}{b}2.92\log\left(1 + \frac{\pi a}{2b}\right)$; $m_c = \frac{b}{c}$; $m_a = \frac{b}{a}$.

To ensure the uniformity of the magnetic field, the following ratios are proven and recommended:

$$m_c = \frac{b}{c} = 2 \div 6\ ;\ m_a = \frac{b}{a} = 2 \div 6$$

The scattering coefficient σ_b takes into account the scattering of magnetic fluxes along the cores of the magnetic circuit. Table 1 shows the calculated values of σ_b and λ. For a stepped magnetic system $\lambda_s' < \lambda_s$. For the scattering conductivity, the indicated formulas are used, but c' is taken instead of c. According to the table, knowing the values of m_a and m_c, you can determine the values of the coefficients.

Based on experimental studies: a magnetic neutral is not created

$$n_c = \frac{c'}{c} = (11 \div 13) \times 10^{-1}$$

and the system does not retain its effectiveness. Therefore, when calculating and designing a stabilizer, the development of a special technique is required.

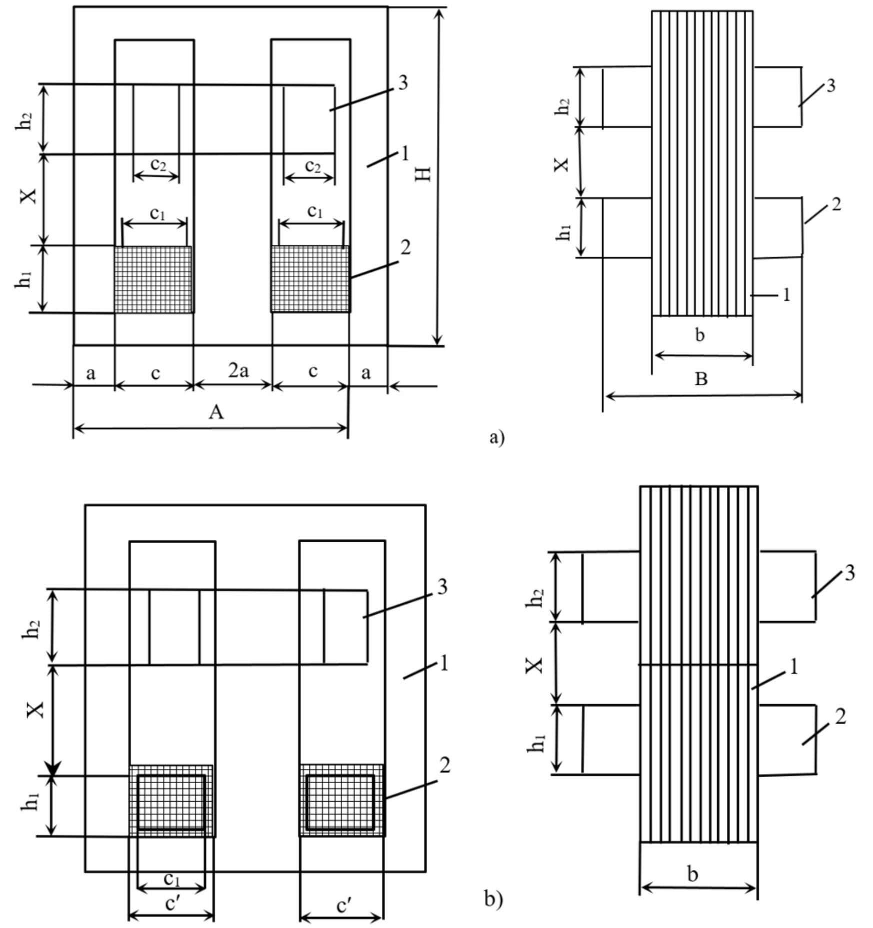

Figure 2. Magnetic system with levitation element (straight (a) and step b))

Table 1. The calculated values of the specific magnetic conductivity (λ) and the coefficient buckling (σ_b)

b/c	b/a	2	3	4	5	6
2	σ_b	1	1	1	1	1
	$\lambda \times 10^{-6}$	8	7	7	6	6
3	σ_b	1	1	1	1	1
	$\lambda \times 10^{-6}$	10	10	9	9	8
4	σ_b	1	1	1	1	1
	$\lambda \times 10^{-6}$	13	12	12	11	11
5	σ_b	1	1	1	1	1
	$\lambda \times 10^{-6}$	15	15	14	14	14
6	σ_b	1	1	1	1	1
	$\lambda \times 10^{-6}$	18	17	17	16	16

The main task of the calculation is to reduce the overall dimensions and weight. Therefore, it is necessary to increase the electromagnetic and electrical loads (magnetic induction B_M and current density in the windings J_1, J_2). However, with an increase in magnetic induction, magnetic losses in the core increase; as the current density increases, copper losses in the windings increase. In some cases, the levitation condition $P_T = F_E$ is violated. With increasing losses, the temperature rises of the core and windings can reach certain limits, since the life of the insulation depends on the overheating temperature.

With a decrease in the geometric dimensions of the windings, the cooling area decreases and a certain amount of heat increases. Therefore, for a constant temperature of the windings with a decrease in the power of the stabilizer, it is necessary to increase the calculated value of the magnetic induction and current density. At the same time, violation of the condition of levitation $P_T=F_E$ and overheating of the windings in excess of the permissible values of parameters [7-14] is not allowed.

Thus, levitation AC regulators must be rated according to the allowable superheat temperatures, but according to the nominal allowable values of induction and current density, the levitation condition must be met. To achieve this goal, first of all, it is necessary to determine the initial data, the current density, the overheating temperature of the windings, the course of the levitation winding and analytical expressions between geometric dimensions.

According to the maximum and minimum voltage values at the terminals of the excitation winding, the maximum and minimum values of the levitation coordinate are determined. Consequently:

$$X_M = h_{\max} - h_{\min} = \frac{K_u \left(U_{1\max} - U_{1\min}\right) I_1}{2\omega P_T} = \frac{K_u I_1 \Delta U_1}{2\omega P_T} \quad (36)$$

$$X_M = \frac{K_u \Delta U_1}{\omega W_1 \sqrt{2 P_T \lambda}} = \left(\frac{\Delta U_1}{U_{1\min}}\right)\left(h_{\min} + \frac{h_1}{3 n_\lambda}\right) \quad (37)$$

$$\frac{K_u}{\omega W_1 \sqrt{2 P_T \lambda}} = \frac{1}{U_{1\min}}\left(h_{\min} + \frac{h_1}{3 n_\lambda}\right) \quad (38)$$

The maximum and minimum values of the levitation coordinate:

$$h_{\max} = X_M \left(\frac{U_{1\max}}{\Delta U_1}\right); \; h_{\min} = X_M \left(\frac{U_{1\min}}{\Delta U_1}\right) \quad (39)$$

Gravity of levitation winding:

$$P_T = \frac{K_u \Delta U_1 I_1}{2\omega X_M} = \left(\frac{K_u I_1}{2\omega}\right)\left(\frac{\Delta U_1}{X_M}\right) \quad (40)$$

From here we get the ratio:

$$\frac{\Delta U_1}{X_M} = \left(\frac{2\omega}{K_u}\right)\left(\frac{P_T}{I_1}\right) \quad (41)$$

This is the ratio for the setpoints P_T and I_1 is a constant parameter. Figure 3 shows the dependence $\frac{\Delta U_1}{X_M} = f(I_1)$ for different values of gravity. This dependence shows that with an increase in the nominal values of the current I_1, the ratio $\frac{\Delta U_1}{X_M}$ decreases. This dependence is necessary for multi-rated AC stabilizers. Change in voltage at the terminals of the field winding:

$$\Delta U_1 = \frac{\Delta U_c}{K_n} \quad (42)$$

where, K_n takes into account the voltage drops across the load U_R:

$$K_n = \sqrt{1 - \frac{P_n R_n}{U_{cn}}} = \sqrt{1 - \left(\frac{U_R}{U_{cn}}\right)^2} \quad (43)$$

Figure 4 shows the dependence $K_n=f(P_n)$ for different values of R_n. The course of the levitation winding depends on the coefficient K_n. Max stroke:

$$X_M = \frac{K_u \Delta U_c}{K_n \omega W_1 \sqrt{2 P_T \lambda}} \quad (44)$$

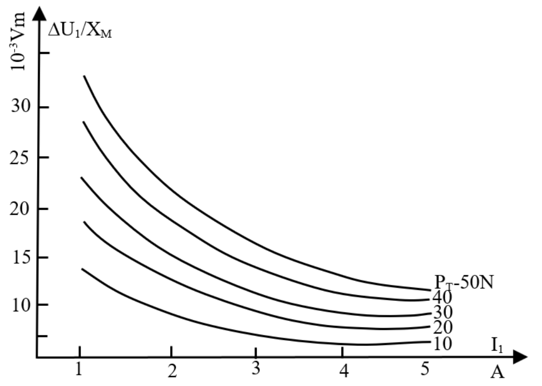

Figure 3. Dependence $\frac{\Delta U}{X_M} = f(I_1)$ (for different values of P_T)

From this it can be seen that in order to reduce the course of the levitation winding X_M, it is necessary to increase λ, P_T, the number of turns W_1. This reduces the height of the stabilizer. With an increase in the range of changes in the mains voltage ΔUc, the course of the levitation winding increases.

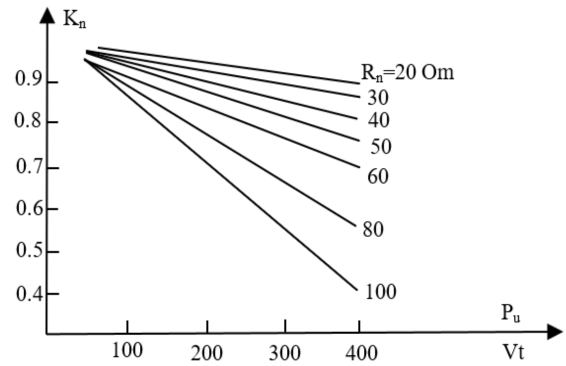

Figure 4. Dependence $K_n=f(P_n)$ (for different values of R_n)

The winding stroke is directly proportional to ΔUc, and inversely proportional to the number of turns W_1. For large values of current I_1, the number of turns W_1 is small, so the stroke of the levitation winding for $I_1=I_{1\max}$ is large. For this reason, for multi-rated AC stabilizers, gravity must be rated for the largest load current. In this case, the number of turns W_1 is small and the induction of the B_M core is maximum. The force of gravity for $I_1 = I_{1\max}$ is determined by:

$$P_T = \frac{K_u I_{1\max} \Delta U_c}{2\omega X_M K_n} \quad (45)$$

In the formula, apart from X_M, other parameters are known. X_M determines the relative travel value. To this end:

$$K_{cu} = \frac{U_{1\max}}{U_{1\min}} = \frac{K_u I_1 X_{1\max}}{K_u I_1 X_{1\min}} = 1 + 3 n_\lambda X_M^* \quad (46)$$

where, $X_M^* = \frac{X_{Mu}}{h_1}$. With $U_1=U_{1\min}$, the levitation condition must be satisfied:

$$h_{\min} \geq 0 \text{ or } \frac{K_u U_1}{\omega W_1 \sqrt{2P_T \lambda}} - \frac{h_1}{3n_\lambda} \geq 0 \quad (47)$$

The height of the excitation winding is determined, which satisfies the levitation condition $U_1 = U_{1\min}$:

$$h_1 \leq \frac{3n_\lambda K_u U_{1\min}}{\omega W_1 \sqrt{2P_T \lambda}} \quad (48)$$

$$X_M^* \geq \left(\frac{\Delta U_1}{U_{1\min}}\right)\left(\frac{h_1}{3n_\lambda}\right) \text{ or } X_M^* \geq \frac{K_{cu} - 1}{3n_\lambda} \quad (49)$$

$$\frac{\Delta U_1}{U_{1\min}} = K_{cu} - 1 = \frac{U_{1\max}}{U_1} - 1 \quad (50)$$

$$K_{cu} = \frac{U_{1\max}}{U_{1\min}} = \sqrt{\frac{U_{c\max}^2 - U_R^2}{U_{c\min}^2 - U_R^2}} \approx \frac{U_{c\max}}{U_{c\min}} \quad (51)$$

If: $\frac{U_{c\max}}{U_{c\min}} = \frac{280}{160} = 17 \times 10^{-1}$, then for straight cores (n_λ=1): $X_M^* \geq \frac{(17 \times 10^{-1}) - 1}{3 \times 1}$ or $X_M^* \geq 23 \times 10^{-2}$, For stepped cores ($n_\lambda$=13×10^{-1}): $X_M^* \geq \frac{(17 \times 10^{-1}) - 1}{3 \times (13 \times 10^{-1})}$ or $X_M^* \geq 18 \times 10^{-2}$.

Figure 5 shows the dependence $X^*_M=f(K_{cu})$ for straight and stepped cores. For stepped cores, the relative value of the levitation winding stroke is small compared to straight cores. For the range of change n_λ= (1÷14)×10^{-1} and K_{cu}= (12÷18)×10^{-1}; X_M^*= (133÷265)×10^{-3}. Then:

$$\frac{\Delta U_1}{U_{1\max}} = (36 \div 43) \times 10^{-2}$$

$$h_1 = (10 \div 100) \text{ mm}$$

$$X_M = (133 \times 10^{-2} \div 265 \times 10^{-1}) \text{ mm}$$

$$X_M = (133 \div 265) \times 10^{-3} \times h_1$$

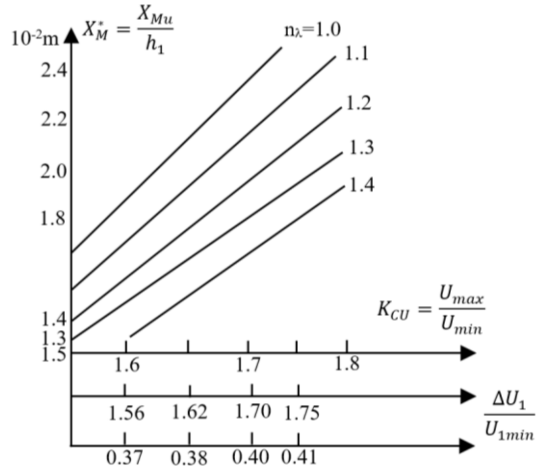

Figure 5. Dependence $X_M^* = f(K_{cu})$

Figure 6 shows the characteristic $P_T=f(I_1)$ for different X_M. With an increase in I_1, P_T increases, and with an increase in X_M, it decreases. Extending the mains voltage range ΔU_c leads to an increase in P_T. The course of the levitation winding is determined by the minimum value of the levitation coordinate: $X_M=h_{\min}(K_{cu}-1)$; $h_{\min}$= (3÷5)×10^{-3} m. Then the height of the winding:

$$h_1 = 3n_\lambda \left(\frac{X_M}{K_{cu} - 1} - h_{\min}\right) \quad (52)$$

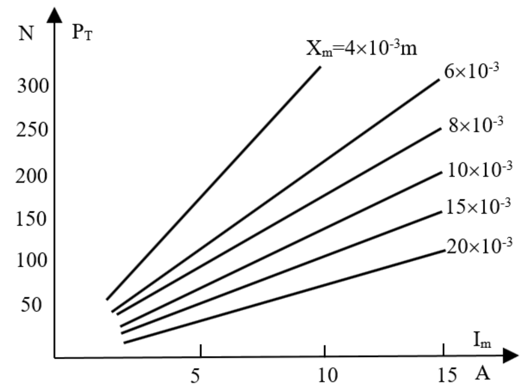

Figure 6. Dependence $P_T=f(I_1)$

The value of the coefficient n_λ is determined from the Equations:

$$n_\lambda = \frac{h_1}{3\left(\frac{I_1 U_{1\min}}{2K_u \omega P_T} - h_{\min}\right)};$$

$$X_{1\min} = \frac{U_{1\min}}{K_u I_1}; \; X_{1\min} = \omega W_1^2 \lambda \left(h_{\min} + \frac{h_1}{3n_\lambda}\right) W_1^2 = \frac{2P_T}{I_1^2 \lambda}$$

The resulting expressions allow us to determine the main parameters and geometric dimensions of the stabilizer [18-21] in the following sequence:

1. A coefficient is determined that takes into account the voltage drop and the voltage drop across the load K_n.
2. The coefficient K_{cu} is determined.
3. Coefficient n_λ and selection from Table 1 of values λ, λ_s, then m_a, m_c.
4. Determination of X_M, excitation winding height h_1.
5. Determination of the force P_T.
6. Determining the number of turns:

$$W_{1\min} = \frac{1}{I_{1\min}} \sqrt{\frac{2P_T}{\lambda}}$$

7. Determination of the minimum value of the inductive resistance of the winding $X_{1\min}$.
8. Winding height specification: $h_1 = 3n_\lambda X_{1\min} \frac{I_1^2 \lambda}{2P_T \omega}$.
9. Determination of the cross section of the core S_c: $B_{\max}$= (14÷17)×10=1 T; K_u= (95÷97)×10^{-2}; K_{3c}= (92÷96)×10^{-2}.
10. Determination of core dimensions:

$$a = \frac{S_c}{m_a}; \; b = am_a; \; c = \frac{b}{m_c}$$

11. Refinement of specific magnetic conductivity.
12. Determining the dimensions of the core and winding

$$c' = \frac{b}{m_c'}; \; c_1 = \frac{c'}{n_{01}}; n_{01} = (105 \div 110) \times 10^{-2}.$$

In most cases, as a result of calculations, the principle of proportionality of geometric dimensions is violated and the design of the stabilizer is inefficient. To ensure the principle of proportionality of dimensions, it is necessary to analyze the range of certain ratios between the cross-section of the windings and the core and the mathematical expressions of the optimal ratios.

For the maximum voltage value $U_{1\max}$, the cross-sectional area is determined:

$$S_c = A_0 \frac{\sqrt{2}}{K_{3c} B_M} \tag{53}$$

where, $A_o = \frac{K_u U_{1\max}}{\omega W_{1\min}}$; B_M is permissible maximum value of the core induction. For determining A_o:

$$h_{\max} = \frac{A_o}{\sqrt{2P_T \lambda}} - \frac{h_1}{3n_\lambda} \ ; \ h_{\min} + \frac{h_1}{3n_\lambda} = \frac{X_M}{K_{cu} - 1} \tag{54}$$

$$h_{\max} = h_{\min} + X_M$$

From mathematical expressions:

$$\frac{A_o}{\sqrt{2P_T \lambda}} = X_M \left(\frac{U_{1\max}}{\Delta U_1} \right) \tag{55}$$

From here:

$$A_o = X_M \sqrt{2P_T \lambda} \left(\frac{U_{1\max}}{\Delta U_1} \right) \tag{56}$$

For S_c, one can write that:

$$S_c = \frac{U_{1\max}}{K_{3c} B_M} \sqrt{\frac{2K_u I_1 X_M \lambda}{\omega \Delta U_1}} \tag{57}$$

With an increase in current I_1, the cross-sectional area of the core increases. At the same time, X_M and λ decrease. The decrease in specific magnetic conductivity λ is associated with a decrease in the ratio $\frac{b}{c}$. To prevent violation of the proportionality of geometric dimensions, it is necessary to determine the correct ratios between the cross-sectional areas of the core and windings. Current density in the excitation winding:

$$J_1 = \frac{I_{1\max} W_{1\min}}{K_{31} S_{01}} = \left(\frac{I_{1\max} U_{1\max}}{B_{\max} S_{01} S_c} \right) \left(\frac{K_u \sqrt{2}}{\omega K_{3c} K_{31}} \right) \tag{58}$$

From here:

$$(S_{01} \cdot S_c) = \left(\frac{K_u \sqrt{2}}{\omega K_{3c} K_{31}} \right) \left(\frac{U_{\max} I_{\max}}{J_1 B_{\max}} \right) \tag{59}$$

This formula allows you to determine the smallest value of the product ($S_{01}S_c$) for the given values $U_{1\max}$, $I_{1\max}$, $B_{\max}$, J_1, but the relationship between ($S_{01}S_c$) and λ is not visible. To determine the relationship between S_{01}, S_c, λ, the expressions are used:

$$S_c = \frac{K_u U_{1\max} \sqrt{2}}{\omega W_{1\min} B_{c\max} K_{3c}} \tag{60}$$

$$I_{1\max} W_{1\max} = J_1 K_{31} S_{01}; \ I_2 W_2 = b_2 I_{1\max} W_{1\max} = J_2 K_{32} S_{02}$$

$$I_{1\max} W_{1\max} = \frac{K_u U_{1\max}}{\omega W_{1\min} \lambda \left(X_M + h_{\min} + \frac{h_1}{3n_\lambda} \right)} = \frac{K_u \Delta U_1}{\omega W_{1\min} \lambda X_M} \tag{61}$$

$$S_1^* = \frac{S_c}{S_{01}} = A_1 J_1 \lambda \ ; \ S_2^* = \frac{S_c}{S_{02}} = A_2 J_2 \lambda \tag{62}$$

where, A_1 and A_2 are coefficients determined by the values of the parameters of the windings and the magnetic circuit:

$$A_1 = \left(\frac{K_{31}}{K_{3c}} \right) \left(\frac{X_M U_{1\max} \sqrt{2}}{B_M \Delta U_1} \right) \tag{63}$$

$$A_2 = b_2 \left(\frac{K_{32}}{K_{3c}} \right) \left(\frac{X_M U_{1\max} \sqrt{2}}{B_M \Delta U_1} \right) \tag{64}$$

To this end, the following sequence applies:

1. The X_M levitation winding stroke is received.
2. Based on X_M, the current density is determined from Table 1.
3. The specific magnetic conductivity is determined by the current density.
4. The product ($S_{01}S_c$) is determined.
5. Determined by the formula S_c.
6. S_{01} is determined by the formula $S_{01} = S_c / S^*$.
7. The ampere-winds are determined.
8. Parameters A_1 and A_2 are determined.
9. Parameters S_1^* and S_2^* are determined.
10. Cross-sectional areas are determined S_{01} and S_{02}:

$$S_{01} = \frac{S_c}{S_1^*} \ ; \ S_{02} = \frac{S_c}{S_2^*}$$

11. According to the value of λ, determined from the Table, are determined: $m_a = \frac{b}{a}$; $m_c = \frac{b}{c}$.
12. Geometric dimensions are determined:

$$2a = \frac{S_c}{m_a} \ ; \ b = a \cdot m_a ; \ c = \frac{b}{m_c}$$

The relationship between the ratio $\frac{\Delta U_1}{X_M}$ and the load current $I_n = I_1$ shows that with an increase in the nominal values of the stabilized load current, the voltage drop ΔU_1 decreases. Therefore, with an increase in the load current In, the increase in the stroke of the levitation winding is large and this causes an increase in the height of the stabilizer. To limit overtravel X_M, the gravity of the levitation winding must be calculated for the maximum load current (for a section with a small number of turns). With an increase in the mains voltage drop ΔU_c, the course of the X_M levitation winding also increases [5-11].

A mathematical expression is obtained for the relationship between the coefficient characterizing the stepped shape of the core n_λ and the ratio $X_M^* = \frac{X_M}{h_1}$. For straight cores n_λ=1, and for stepped cores: n_λ= (11÷14)× 10^{-1}m. For the optimal dimensions of the stabilizer: X_M=(133÷265)×10^{-3} m, the dependence $X_M^* = f\left(\frac{U_{\max}}{U_{\min}} \right)$ is linear and increases with increasing coefficient n_λ . Therefore, to reduce the height of the stabilizer, a stepped core is necessary. For this reason, the ratio $n_{e1} = \frac{h_1}{c_1}$ must be relatively small. A decrease in this ratio leads to the creation of a magnetic neutral and causes a decrease in lift.

7. CONCLUSIONS

The equations of functional relationships between the cross-section of the core and windings (S_c, S_0), conductivity λ, the course of X_M and current density J_1 are determined. For conductivity λ, the density of the current J and the X_M stroke, the certain changes in the changes used in the design of the sta-bicolizer of the current retain the principle of proportionality of geometric sizes.

The calculation of the precision multinominal stabilizer of alternating current is based on the equations of the magnetomotive force (mmf) of windings, currents, overheating, induction of the core and mechanical forces. When calculating and designing a precision multinominal stabilizer of alternating current, the technical assignment is determined by the direction of the analytical connection between the main parameters and the geometric dimensions. Each stage of calculation can be used for various options for a current stabilizer.

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BIOGRAPHY

Gulschen Sanan Kerimzade was born in Baku, Azerbaijan on August 9, 1967. She was the student in Electromechanical Faculty, Azerbaijan Institute of Oil and Chemistry, Baku, Azerbaijan during 1985-1990. Since 1990 to present, she has worked at department of Electromechanics". She defended her thesis on the topic of "Development of optimal multinominal high-precision stabilizations of alternating current using the effect of induction levitation" in 2004. Currently, she is an Associate Professor in Department of Electromechanics, Azerbaijan State Oil and Industry University, Baku, Azerbaijan. She is the author of 100 articles and 19 scientific-methodical lecture notes.