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High Precision Current Stabilizers with Induction Levitation Effect

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Abstract
The present article discusses the characteristic features of the characteristics of precision controlled high-precision current stabilizers using the effect of induction levitation. The stability and shape of the load current determines the reliability, accuracy, efficiency, service life of automation devices, test equipment and electroplating baths. Determining the output characteristics, establishing analytical relationships between the initial data and the output parameters of the stabilizer is one of the stages of the algorithm for solving the problems of designing the parameters of an AC stabilizer with induction levitation of the moving part. This, in turn, contributes to the development of a mathematical model consisting of a system of equations of electric, magnetic, mechanical and thermal stabilizer circuits, the joint solution of which allows you to establish analytical relationships between the initial data and parameters such as working stroke, weight, winding and core sections, copper losses.
Key words: precision, high-precision, current stabilizer, effect, induction levitation, controlled, source, dependence, levitation winding, characteristic, load

Introduction
Reliability, accuracy, efficiency and service life of automation devices, information-measuring equipment, test equipment and galvanic baths are largely determined by the stability and shape of the load current. In most cases, the sources of power for various devices and installations are power networks, and the constancy of voltage in such networks is usually not observed, and there are always short-term and slow voltage fluctuations. Such voltage fluctuations in many cases are unacceptable, as they lead to disruption of the normal operation of the equipment. For example, for complex measuring and verification equipment, for testing medical equipment and galvanic baths, the necessary condition for ensuring a given accuracy is the stability of the load current (G.S, 2022c). The task of stabilizing the current and voltage at the load is characterized by parametric and controlled stabilizers, the principle of operation of which is based on the use of various physical phenomena (G.S, 2022a). For example, the operation of most of these stabilizers is based on the use of a non-linear volt - ampere characteristic of various elements used in stabilizer circuits. The movable anchor, being subjected to the action of the weight force $P_в$ and the force of attraction F_e, automatically finds the equilibrium position $F_e=P_в$ (the point of intersection of the traction characteristic F_e (x) and the horizontal direct weight force $P_в$) (Kerimzade G.S., 2020).

Formulation of the Problem
When the armature is moved, the inductance of the winding and its resistance change. In this case, the steady state value of the current is defined as:

$$I = \sqrt{\frac{2P_в}{\frac{dL}{dx}}} \quad (1)$$

The derivative inductance L with respect to the displacement of the core x is a constant value only for a narrow range of displacements $x = x_2 - x_1$. Therefore, the current stabilizes in a small range of supply voltage changes (6-8)%. How these stabilizers work based on the principle of magnetic suspension of ferromagnetic cores (Hasibuan & others, 2011b) (Syafrudin & Hasibuan, n.d.). A controlled electrodynamic stabilizer allows you to smoothly adjust the value of the stabilized current (G.S, 2022b). The stabilizer has an elongated magnetic circuit, on which a fixed and a moving AC coil are located. The moving coil is mounted on a mobile device (trolley) and can move freely along the magnetic circuit (G.S., 2022). Another type of controlled stabilizers are stabilizers with induction levitation windings, which are much simpler than existing ones in design, provide high stabilization accuracy when the supply voltage changes over a wide range, allow you to simultaneously obtain several nominal values of the stabilized current, the shape of the stabilized current curves is close to a sinusoid if the supply voltage sinusoidally (fig.1). The main disadvantages of these stabilizers are the possibility of their operation in the vertical position of the magnetic circuit and in the absence of vibration and shaking (Y. R. Abdullayev et al., 2015) (Y. Abdullayev et al., 2009) .

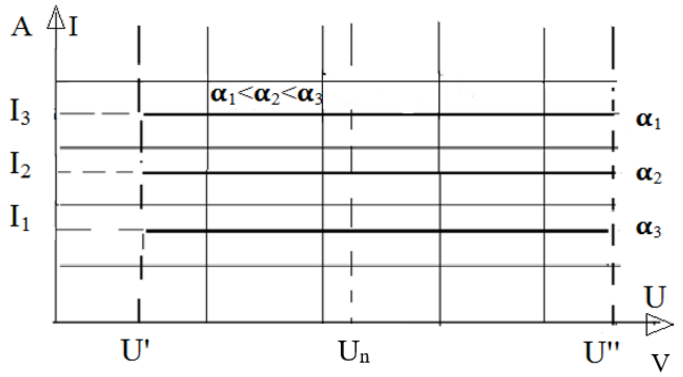

Figure 1. Volt-ampere characteristic of an electrodynamic stabilizer

Solutıon Methods

AC stabilizers with inductive levitation of the moving part are divided into two groups: stabilizers with levitation short-circuit winding and stabilizers with levitation excitation winding (Xue et al., 2021) (Gieras, 2008). To obtain several nominal values of the stabilized current, the windings are made from a number of sections. If it is necessary to obtain direct current at the loads, the alternating current is rectified by the bridge (Spooner & Williamson, 1996) (Simo Fotso et al., 2019). According to their design features, they are divided into stabilizers with a straight and stepped magnetic circuit (Simo Fotso et al., 2019) (Esbensen et al., 2002). To reduce the height of the excitation winding and improve its cooling, the winding can be divided into two equal parts located on the extreme rods (Esbensen et al., 2002) (Gieras et al., 2011) (Boldea, 2015). The separated windings are connected to each other in series - counter. The inductive resistance of the winding in this case is two times less than when it is entirely located on the middle rod:

$$x_1 = \omega^2\left[0.5\omega W_1^2\lambda\left(\frac{0.5h_1}{3}+x_M\right)\right] \tag{2}$$

Winding current:

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

If the winding is located on the middle rod:

$$\begin{gathered} x_1 = \omega W_1^2\lambda\left(\frac{h_1}{3}+x_M\right) \\ I_1 = \frac{U_1}{I_1} = \frac{U_1}{\omega W_1^2\lambda\left(h_1+x_M\right)} \end{gathered} \tag{4}$$

One of the stages of the algorithm for solving the problems of designing the parameters of an AC stabilizer with inductive levitation of the moving part is the determination of output characteristics, the establishment of analytical relationships between the initial data and the output parameters of the stabilizer. Design, which includes the fluctuation and magnitude of the mains voltage $\Delta U_c = U_{cmax}-U_{cmin}$, U_{nom} and load current I_{load}. The stabilizer must be designed for the rated load current I_{load} and for the rated voltage U_n, at which the levitation coordinate corresponds to the initial position of the levitation winding. Design criteria: allowable overheating of the windings τ_{d1} and τ_{d2}, allowable voltage increment at the terminals of the supply winding ΔU_1 and allowable increment of the stabilized current at the load ΔI_n [1-5]. The basis of design is the establishment of analytical relationships between the initial data and geometric dimensions. This requires the development of a mathematical model consisting of a system of equations of electric, magnetic, mechanical and thermal stabilizer circuits, the joint solution of which allows you to establish analytical relationships between the initial data and the working stroke x_M, the weight force $P_в$, the sections of the windings S_o and the core S_c, copper losses P_M. The initial values for calculating an AC stabilizer with inductive levitation of the moving part are the range of mains voltage change ΔU_c, load currents I_{load1}, I_{load2}, …I_{loadn}, mains frequency ω, load resistance R_{load} or load power P_{load}, as well as the stroke of the moving part x_M or minimum levitation coordinate value h_{min}.

$$h = \frac{k_u U_1}{\omega W_1\sqrt{2P_в}\,\lambda} - \frac{h_1}{3n_\lambda} \tag{5}$$

$$I_1 = \frac{k_u U_1}{\omega W_1^2 \lambda \left(h + \frac{\lambda_1}{3n_\lambda} \right)}; I_2 = b_2 I_1 \frac{W_1}{W_2}$$

$$F_1 = I_1 W_1; F_2 = I_2 W_{21}; F_e = \frac{1}{2} (IW)^2 \lambda = P_в \tag{6}$$

$$B_M = \frac{k_u U_1 \sqrt{2}}{\omega W_1 k_{3c} S_c}; \tau_2 = \frac{I_2^2 r_2}{k_T S_{cool}^2}$$

The ratio of the voltage at the terminals of the excitation winding U_1 to the inductive reactance of this winding x_1 is a constant parameter equal to the stabilized current I_1:

$$\frac{kU_1}{x_1} = \frac{k_u U_1}{\omega W_1^2 \lambda \left(h + \frac{\lambda_1}{3n_\lambda} \right)} = I_1 = const \tag{7}$$

The levitation coordinate h is a linear function of the voltage U_1:

$$h = \frac{k_u U_1}{\omega W_1^2 \lambda I_1} - \frac{h_1}{3n_\lambda} \tag{8}$$

The maximum and minimum values of the levitation coordinate will be determined by the voltages U_{1max} and U_{1min}, respectively. Maximum stroke LW:

$$x_M = h_{max} - h_{min} = \frac{k_u \Delta U_1}{\omega W_1^2 \lambda I_1} = \frac{k_u \Delta U_1}{\omega W_1 \lambda F_1} = \frac{k_u \Delta U_1}{\omega W_1 \sqrt{2 P_в \lambda}} \tag{9}$$

The specific magnetic conductivity of the working air gap can be determined by the formula:

$$\lambda = 2\mu_0 \left[\frac{b}{c} + 2.92 \ln \left(1 + \frac{\pi a}{2b} \right) \right] \tag{10}$$

To ensure the uniformity of the magnetic field of the working air gap, the following ratios are recommended:

$$m_c = \frac{b}{c} = 2 \div 6, m_a = \frac{b}{c} = 2 \div 6 \tag{11}$$

Table 1 shows the calculated values of the specific magnetic conductivity λ and the buckling coefficient $\sigma_в$.

Table 1. Calculated values λ and $\sigma_в$

в/c	в/a	2.0	2.5	3.0	4.0	5.0	6.0
2.0	$\sigma_в$	1.85	1.72	1.61	1.48	1.38	1.34
	λ	6.73	6.98	7.44	8.00	8.64	9.30
2.5	$\sigma_в$	1.68	1.57	1.49	1.39	1.32	1.27
	λ	7.97	8.30	8.73	9.36	9.86	10.55
3.0	$\sigma_в$	1.56	1.47	1.40	1.32	1.26	1.22
	λ	9.30	9.60	10.00	10.64	11.20	11.86
4.0	$\sigma_в$	1.42	1.36	1.31	1.24	1.20	1.17
	λ	11.75	12.06	12.4	13.10	13.60	14.20
5.0	$\sigma_в$	1.34	1.29	1.25	1.19	1.16	1.13
	λ	14.24	14.60	15.00	15.7	16.2	16.83
6.0	$\sigma_в$	1.28	1.24	1.2	1.16	1.13	1.11
	λ	16.8	17.00	17.60	18.16	18.76	19.40

According to the dependence $\Delta U_1 / x_M = f(I_1)$ for different values of the weight force (fig.2), with an increase in the nominal values of the current I_1, the ratio decreases, if the weight force of the levitation winding is constant. This is the case for multi-rated AC stabilizers, where with the switching of sections of the fixed winding, the current I_1 changes, and the weight force remains constant. The coefficient k_n takes into account the voltage drop U_R on the load R_{load}. Figure 3 shows the dependence $K_{load}=f(P_{load})$ for different values of load resistance R_{load} (Hasibuan & others, 2011a).

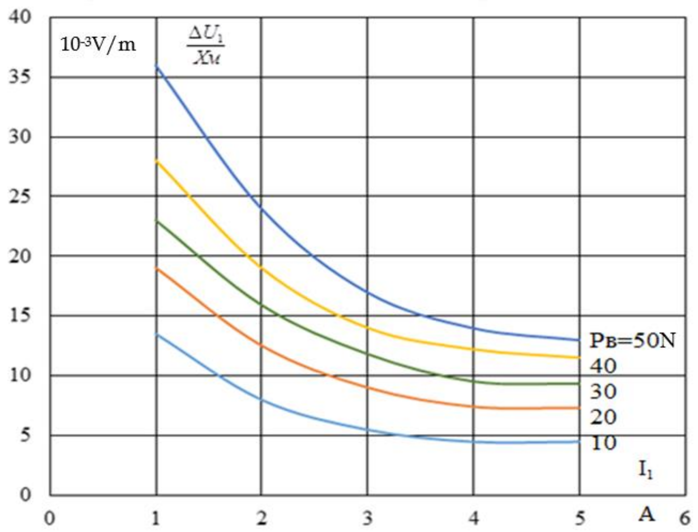

Figure 2. Dependence $\frac{\Delta U_1}{X_M} = f(I_1)$ for different values of the weight force $P_в$.

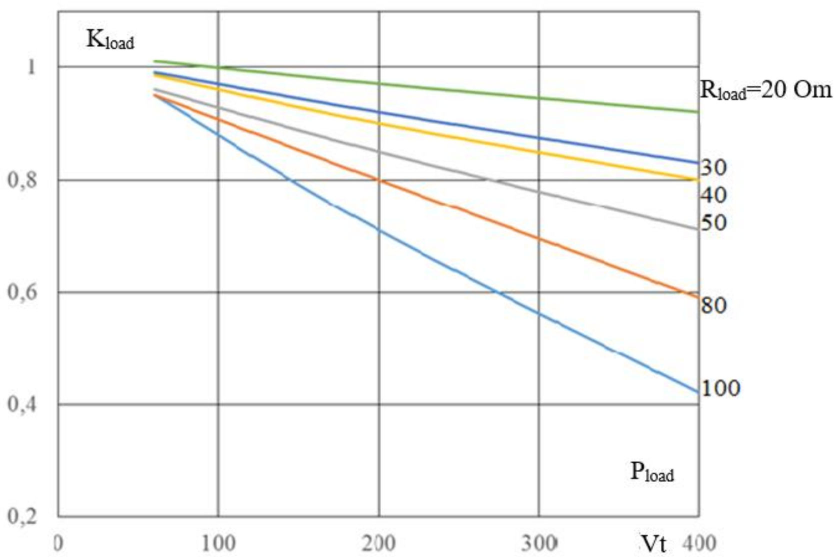

Figure 3. Dependence K_{load}=f(P_{load}) for different values of R_{load}

Another important characteristic is the dependence of the weight force of the induction levitation winding (ILW) $P_в$ on the current I_1 (fig.4) for various values of the stroke x_M, according to which the weight force increases with increasing current, and with an increase in the stroke x_M it falls. For supplying electroplating baths and test benches, for automated control of calibration parameters of measuring instruments, etc. precision current stabilizers are used as a power source (Kurniawan et al., 2023) (Manishe et al., 2021) .

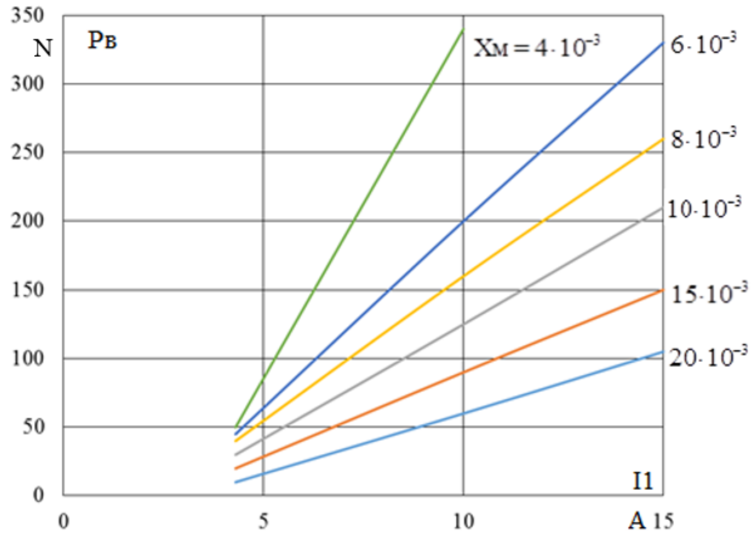

Figure 4. Dependence of the weight force $P_в$ on the current I_1

Analytical expressions for a number of basic dependencies have been obtained that characterize the ability of current stabilizers with a levitation winding to satisfy their functions as an element of the general circuit of the device: dependence of the voltage increment at the excitation winding terminals on mains voltage fluctuations; dependence of the maximum stroke of the LW on the voltage increments (supply winding) of the EW; dependence of the course of the LW, input, output and overall powers on the initial data for design; dependence of the load current on the ambient temperature and the temperature rise of the windings; dependence of the main dimensions on power, electromagnetic load and winding overheating temperature; dependence of the increment of induction in the core on fluctuations in the mains voltage, load power and rated power of the stabilizer (Gieras et al., 2011) (Nisworo et al., 2022). The main criteria for designing a current stabilizer are: allowable overheating τ, allowable voltage drop U_1, allowable stroke x_m of the levitation winding, allowable ratio of the height of the windings (or magnetic circuit) to their thickness (or width of the magnetic circuit) and the accuracy of current stabilization for a given range of changes in mains voltage $\Delta U = U_{max} - U_{min}$. As a generalized model, the design of a stabilizer with maximum symmetry and homogeneity of the magnetic system is considered (Boldea, 2015) (Kurniawan et al., 2022).

For this purpose, a mathematical model has been developed that allows, based on the solution of the equations of the levitation coordinate, mechanical forces, winding MMF and winding excess temperature, to establish the most important analytical relationships between the initial design data and the main parameters of the stabilizer. The developed technique was used for a three-limit stabilizer for stands and galvanic baths as an adjustable source of stabilized current at 7,8,9 A. The current stabilization error of the prototype current stabilizer was 0.1% when the mains voltage fluctuated in the range (160 ÷ 250) V.

Conclusions

The current states of power sources for galvanic baths are analyzed. The features of operation and varieties of electroplating baths, their fields of application are considered, the requirements for modeling the optimal temperature control of electroplating baths are established. Analytical expressions are obtained for a number of basic dependencies that characterize the ability of current stabilizers with a levitation winding. A calculation of a three-section AC stabilizer for powering galvanic baths is made, a method for calculating a current stabilizer for testing equipment and galvanic baths is given, a computer study of the current stabilizer coupling equation using the program (EXEL) is carried out.

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