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ISSUES OF DESIGN OF ELECTRICAL DEVICES WITH LEVITATION ELEMENTS

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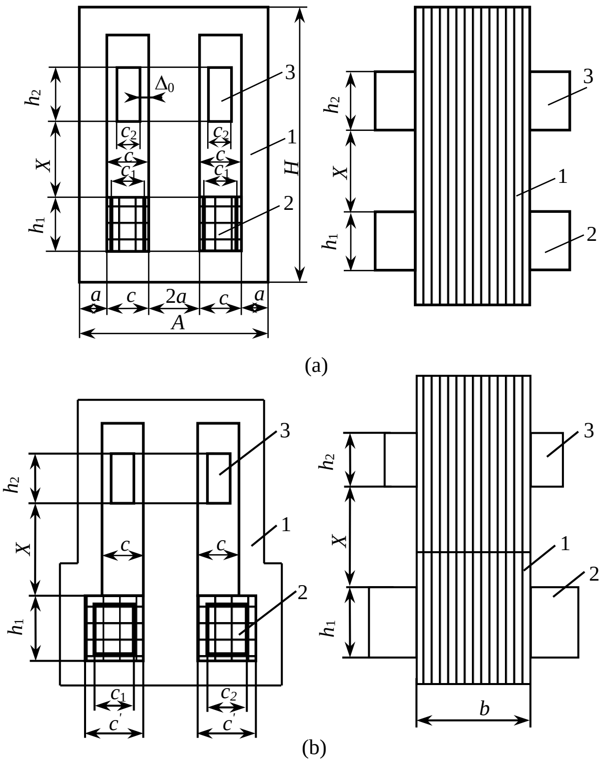
Abstract- In the presented article, the issues of designing electrical devices with levitation elements (LE) are considered. With a purpose to develop a method for the generalized design of an induction levitator, design indicators are determined and analytical locutions are given for the main calculated parameters of the current mode and power of electrical appliance of different LE, an analysis is made to solve design problems. The analysis of all analytical expressions received by us is made. To solve the problems of designing electrical devices with induction LE, their numerical values are determined, general design indicators are established. Simple analytical expressions for these indicators are obtained in terms of dimensionless quantities. Electrotechnical devices with a levitation element are widely used in the automation of production processes due to their simple design, high accuracy and reliability. In the processes of automation of technological processes, automatic control of the positions of the moving parts of the working mechanisms is often required with the help of an external force and an alternating current voltage. In these cases, it also becomes necessary to measure the external force, stabilize the current on a variable load and obtain several nominal values of the current on the load. Despite the simplicity of the design of induction levitators (IL), they are more effectively involved in solving these problems, under the action of the efficiency of the induction levitator, there are no friction forces, the working stroke of the moving part is automatically controlled and additional elements not required.

Keywords: Elements of Levitation (LE), Elements of Levitation, Electrical Device, Design, Task, Mode, Current, Force, Power, Indicators, Dimensionless Quantities, Levitator.

1. INTRODUCTION

The solution of the main issues with the theoretical foundations, calculation and application of electrical devices with levitation elements based on induction levitators, is reflected in scientific articles and monographs [1-13]. The purpose and characteristics of these devices are different, the solution of design problems is carried out by different methods. They are simple in structure and have high stability and performance accuracy. Figure 1 shows the direct (a) and stepped (b) magnetic systems with levitation elements [1-4]. These devices include a magnetic circuit 1, an excitation winding 2 and a levitation element 3. The excitation winding (EW) is made of several sections and is connected in series to the AC voltage source U_1. The levitation element is made of aluminum in the form of a short-circuited solid frame or a short-circuited winding of copper wires (Figure 2a, 2b and 2c, respectively) [1].



(a)

(b)

Figure 1. Magnetic systems with levitation elements

The magnetic core is assembled from Ш-shaped electrical plates. Devices with levitation elements operate in current and effort modes. Physical processes in these modes are different [6-13].

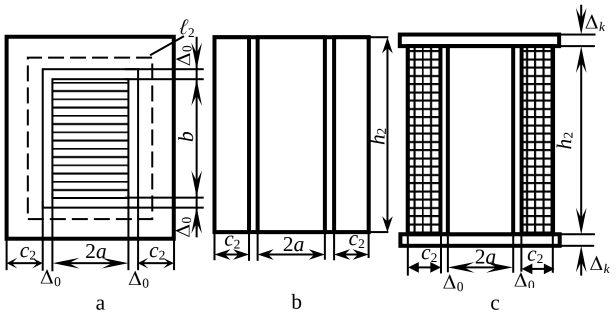


Figure 2. Types of levitation element

The development of a generalized calculation method includes parameters in the mathematical model that characterize these modes. In this case, it is necessary to take into account the parameters that characterize these modes: levitation coordinate h, vertical working stroke x_p, lifting electromagnetic force F_e, external force acting on the levitation element in the vertical direction P_b, gravity P_T, thermal resistance τ_2, electromagnetic rigidity c_e and pressure P_e.

The set data of the currents of the EW and the levitation element (EL) in the current mode are determined by Equations (1), (2) [2]:

$$I_1 = \frac{U_1 \pm \Delta U}{\omega(L_1 \pm \Delta L)} = \text{const}; \; I_2 = kI_1 = \frac{W_1}{W_2} = \text{const} \tag{1}$$

$$I_1 = \frac{1}{W_1}\sqrt{\frac{2P_T}{\lambda}} = \text{const} \tag{2}$$

where, $U_1=U_{nom}$ are the value of the nominal voltage at the ends of the EW; $\Delta U=U_{\min}\div U_{\max}$ is voltage change interval; ΔL is the magnitude of the change in the inductance of the EW; L_1 is the value of the inductance corresponding to U_{nom} voltage of the EW; W_1 and W_2 is number of turns; $\omega=2\pi f – U_1$ is voltage angular frequency; P_T is gravity of the levitation element; k is the coefficient of electrical coupling between the excitation and levitation windings ($k\approx0.98$); λ is unit magnetic conductance of the working air gap [1-5].

In AC regulators with $U_1=U_{nom}$ the levitation element is in the middle position on the middle bar of the magnetic circuit. When the voltage is changed by $\pm\Delta U$, it changes its position by $L_e\pm\Delta x$, as a result of which the levitation height h and the inductance of the EW change by $\Delta h=\pm\Delta x$ and $\pm\Delta L$, respectively. In this case, the dependence $L_1(U_1)$ is a linear function. In current mode, when the voltage at $\Delta U=U_{\min}\div U_{\max}$ the EW terminals changes in the range, the working stroke changes in the range $\Delta x_p=x_{\min}\div x_{\max}$. In this case, the currents in the EW and LE remain constant ($I_1=const$, $I_2=const$). In the force mode, the voltage at the EW $U_1=const$ terminals and the external force P_x applied to the levitation element changes within $\Delta P=P_{\min}\div P_{\max}$ the limits. In this case, the currents in the windings change within $I_{1\min}\div I_{1\max}$ and $I_{2\min}\div I_{2\max}$ the limits and. Due to changes in the values of currents, a change in the overheating temperature of the windings (τ_1 and τ_2) occurs, x_p and the inductance L_1 of the EW also changes. In current mode, ampere-turns are determined by the working stroke x_p and voltage increase ΔU [6-7]:

$$F_1 = \sqrt{\frac{k_u I_1 \Delta U}{\omega\lambda x_p}} \tag{3}$$

According to this equation, for the levitation element, you can write [9]:

$$F_2 = b_2 F_1 = b_2\sqrt{\frac{k_u I_1 \Delta U}{\omega\lambda x_p}} \tag{4}$$

The values of the parameters involved here I_1, ΔU,ω and x_p are known from the design specifications. The analytical expression for the unit magnetic conductance λ of the working air gap is known [1, 9]. For the unit magnetic conductance λ of two working air gaps:

$$\lambda = 2\mu_0\left[m_c + 2.92\log\left(1+\frac{\pi}{m_a}\right)\right] \tag{5}$$

where, $m_a=b/a$; $m_c=b/c$; $m_c=2\div6$; b is core thickness.

For the working air gap, we accept [2, 4]: $\lambda=(6\div20)\times10^{-6}$ Hn/m. In the power mode, the voltage at the ends of the EW is maintained constant at $U_1=U_{nom}$, and the external force P_b acting on the levitation element changes in the range $P_{\min}\div P_{\max}$. In this case, the currents change [1-2]:

$$I_1 = \frac{1}{W_1}\sqrt{\frac{2(P_T+P_b)}{\lambda}}; \; I_2 = kI_1\frac{W_1}{W_2} \tag{6}$$

It can be seen from this that for $P_b=P_{\max}$ is accepted $I_1=I_{\min}$, since $x=x_{\min}$ and $L_1=L_{\max}$. When is $P_b=P_{\max}$ accepted $I_1=I_{\max}$; $x=x_{\max}$ and $L_1=L_{\max}$. Therefore, when solving the design problem in the power mode, the current $I_1=I_{\max}$ and force $P_b=P_{\max}$ must be known, or the current I_1 required for is $P_b=P_{\max}$ set during design. In this case, the ampere-turns of the EW are determined as follows [3]:

$$F_1 = I_1W_1 = \sqrt{\frac{2}{\lambda}(P_T+P_{\max})} = F_{1\max} \tag{7}$$

2. LIFTING ELECTROMAGNETIC FORCE

The main characteristics of electrical devices with levitation elements are determined by the lifting electromagnetic force P_e. For example, in power converters and electromagnetic compressors, an increase in lift allows you to expand the range $\Delta P=P_{\min}\div P_{\max}$ and increase the compressive strength. This force is determined by the Equation (8) [9-11]:

$$P_e = \frac{1}{2}\lambda(I_1W_1)^2 \tag{8}$$

At F_1=2000A and $\lambda=11.387\times10^{-6}$ Hn/m., P_e=22.7N. With large values of the parameters F_1 and λ, the size of the EW can undesirably increase. On the other hand, the EW forces depend on the levitation height $h=x$ [5]:

$$F_1 = \frac{k_u U_1}{\omega W_1 \lambda(h_0+x)} \tag{9}$$

where, $h_0 = \frac{h_1}{3n_\lambda} + \frac{h_2}{3}$.

In the last expression $n_\lambda=\lambda/\lambda_s=1.1\div1.8$; h_1 and h_2 are the height of the EW and the levitation element; λ and λ_s are special magnetic conductivities of the working and step air gaps (c and c'), respectively; h_0 is equivalent winding height. From Equations (8) and (9) we obtain the dependences of the lifting force on the levitation coordinate, respectively [6]:

$$n_\lambda = \frac{\lambda}{\lambda_s} = 1.1 \div 1.8;\ P_e = \alpha_F \left(h_0 + x\right)^{-2}$$

where, α_F is constant parameter:

$$\alpha_F = \frac{1}{2\lambda}\left(\frac{k_u U_1}{\omega W_1}\right)^2 \tag{10}$$

when, an external force P_b acts on the levitation element:

$$P_T + P_b = P_e = \frac{\alpha_F}{\left(h_0 + x\right)^2} \tag{11}$$

In this case, the levitation coordinate is determined as follows [2]:

$$x = \sqrt{\frac{\alpha_F}{P_T + P_b}} - h_0 \tag{12}$$

If there is no outside influence [1]:

$$x = \sqrt{\frac{\alpha_F}{P_T}} - h_0 \tag{13}$$

The maximum value of the lifting electromagnetic force:

$$P_{e\max} = \frac{\alpha_F}{h_0^2} = P_T + P_{\max} \tag{14}$$

The overall dimensions and accuracy of electro-mechanical converters with levitation elements depend on the levitation coordinate x and the moving part x_p. These parameters are determined by the values of the external force P_b acting on the levitation element. In current mode, the levitation coordinate is defined as [8]:

$$x = \frac{k_u U_1}{\omega W_1 \sqrt{2\lambda P_T}} - h_0 \tag{15}$$

The levitation coordinate is determined for $U_1 = U_{\min}$ and $U_1 = U_{\max}$:

$$x_{\min} = \frac{k_u U_{\min}}{\omega W_1 \sqrt{2\lambda P_T}} - h_0$$

$$x_{\max} = \frac{k_u U_{\max}}{\omega W_1 \sqrt{2\lambda P_T}} - h_0 \tag{16}$$

For current and force modes, the stroke is defined as:

$$x_p = x_{\max} - x_{\min} = \frac{k_u \Delta U}{\omega W_1 \sqrt{2\lambda P_T}}$$

$$x_p = \frac{k_u U_1}{\omega W_1 \sqrt{2\lambda P_T}}\left(1 - \frac{1}{\sqrt{n_p}}\right) \tag{17}$$

where, $n_p = 1 + \frac{P_b}{P_T}$.

In current mode, the value is given I_1, and in power mode $P_T = P_{\max}$, at $P_T = P_{\max}$ and $x_T = x_{\max}$, the current $I_1 = I_{1\max}$ is equal to [1]:

$$I_{1\max} = \frac{k_u U_{nom}}{\omega W_1^2 \left(h_0 + x_{\min}\right)} \tag{18}$$

Between the maximum value of the current $I_{\max}$ and the cross section of the middle rod S_c of the magnetic circuit, there is the following dependence [2, 4]:

$$S_c = 2ab = \frac{k_u U_{nom}\sqrt{2}}{\omega k_c B_M W_1} = \frac{I_{1\max} W_1}{k_c B_M}\left(h_0 + x_{\min}\right)\sqrt{2}$$

where,

$$U_1 = \sqrt{2} U_{nom};\ \frac{k_u U_{nom}}{\omega W_1} = I_{1\max} W_1 \left(h_0 + x_{\min}\right)$$

$k_c = 0.92 \div 0.96$; $B_M = 1.5 \div 1.8$ Tl.

In this case, the ampere-turns of the EW are determined as follows [1-3]:

$$F_{1\max} = I_{1\max} W_1 = \frac{k_c B_M S_c}{\left(h_0 + x_{\min}\right)\sqrt{2}}$$

3. ELECTROMAGNETIC RIGIDITY AND LOAD CAPACITY

To increase the vertical resistance of the levitation element, the established mode needs to increase the electromagnetic stiffness c_e. Electromagnetic rigidity is determined by the displacement of the lifting force [7]:

$$c_e = \frac{dP_{e\alpha}}{dx} = -\frac{2\alpha_F}{\left(h_0 + x\right)^3}$$

By definition of the coefficient α_F (10), it can be noted that the electromagnetic stiffness is directly proportional to the square of the power supply voltage and inversely proportional to the square of the number of turns of the EW; at high values of the angular frequency, the electromagnetic rigidity decreases sharply; with an increase in the height of the EW and the levitation element, the electromagnetic rigidity decreases sharply; electromagnetic rigidity is very high at small values of the working stroke and its value decreases as the working stroke increases [3-7]. Depending on the course of the moving part, the magnitude of the electromagnetic rigidity in the developed structures can be in the range $(8.3 \div 15) \times 10^2$ N/m.

The property of compensation of an external force $P_{\max}$, which is many times greater than the gravity of the LE, is called the lifting force [1-2]:

$$k_{gr.} = \frac{P_{x\max}}{P_T} = n_p - 1 = \left(\frac{I_{\max}}{I_{\min}}\right)^2 - 1 = 6.25 - 1 = 5.25$$

where, $\frac{I_{\max}}{I_{\min}} \approx 2.5;\ P_{\max} = 5.25 P_\alpha$.

The maximum load capacity depends on the temperature of the heating element of the levitation τ_d [5, 6]:

$$k_{gr.} = \frac{\tau_T}{\tau_{TO} A_1 b_2^2} = \tau_{TO} A_1 b_2^2 \left[\frac{\left(\alpha + \Delta_{ok}\right)}{\tau_d}\right]^{-1} - 1$$

$$n_p = \frac{P_T + P_в}{P_T} = \frac{P_{e\max}}{P_T} = \frac{\alpha_F}{P_\alpha \left(h_0 + h_{\min}\right)^2}$$

Then, $P_{x\max} = \frac{\alpha_F}{P_\alpha \left(h_0 + h_{\min}\right)^2}\left[1 - \tau_{TO} A_1 b_2^2 \left(\alpha + \frac{\Delta_{ok}}{\tau_d}\right)\right]$.

From the last expression we have:

$$k_{gr.} = \frac{\alpha_F}{\left(h_0 + x_{\min}\right)^2}\left[1 - \tau_{TO} A_1 b_2^2 \left(\alpha + \frac{\Delta_{ok}}{\tau_d}\right)\right]$$

4. THERMAL RESISTANCE

When the optical fiber is connected to a power source, currents flow through the EW and the levitation element that significantly exceed the nominal values. In this case, the losses of the levitation element increase, the heat transfer increases slightly, and all the energy of the element goes to heat it. According to the law of convective heat transfer, the temperature increase of the levitation element is determined by the Equations (3, 4, 5, 9):

$$\frac{d\tau}{dt} = \frac{I_2^2 r_2}{mc} = \frac{2r_2}{cg}\left(\frac{P_T}{m}\right)$$

where, g=9.8 N/m; c and m are the heat capacity coefficient of the material and the mass of the levitation element. According to the condition $P_e=ma$, from Equation (8) we get:

$$\frac{\left(\frac{d\tau}{dt}\right)}{\alpha} = \frac{2r_2}{cg}$$

According to the last expression, according to the given measurements, the ratio of the rate of increase in the temperature of the levitation element $d\tau/dt$ to the acceleration of the action of the electromagnetic force P_e is a constant value and depends only on its ohmic resistance r_2. The established temperature rise of the levitation element is determined by its permissible value τ_d [1-3]:

$$\tau_{gr.} = \frac{I_2^2 r_2}{k_T S_2} = \frac{\Delta_{ok}\tau_T}{1-\alpha\tau_T} = \frac{\tau_d}{\Delta_{ok} + \alpha\tau_d}$$

The allowable temperature value depends τ_d on the type of material and insulation class. The coefficient Δ_{ok} for aluminum takes into account the temperature of the environment:

$$\Delta_{ok} = 1 + \alpha\left(\theta_{ok} - \theta_{20}\right) = 1 + 0.0042(35-20) = 1.063$$

For copper:

$$\Delta_{ok} = 1 + 0.0043(35-20) = 1.0645$$

The temperature τ_T included in Equation (4) is determined by the geometric dimensions of the levitation element [10-11]:

$$\tau_T = \tau_{TO}\frac{k_i^2}{n_{e2}} b_2^2 = \tau_{TO} A_1 b_2^2$$

where,

$$\tau_{TO} = \frac{g\gamma k_i}{k_T \mu_0};\ A_1 = \frac{k_i^2}{1+n_{e2}}$$

$$n_{e2} = \frac{\tau_{TO}}{\tau_T}\left(k_i^2 b_2^2 n_p\right) - 1;\ k_i = \sqrt{\frac{\mu_0 b_2}{c_2\lambda}}$$

It follows from this expression that in order to reduce the temperature of the heating element of the levitation, it is necessary to increase the dimensionless value n_{e2} (while maintaining the condition $S_2=c_2h_2$=const). The dimensionless value $n_{e2}=h_2/c_2$ depends on the geometric dimensions of the magnetic wire, the physical and technical characteristics of the levitation element and the increase in the overheating temperature τ_2. As is known [3-5]:

$$n_{e2} = n_0 m_{20}\left(\frac{\rho_2}{\tau_2}\right)$$

where,

$$n_0 = \frac{4b_2^2}{k_T} g\gamma n_k$$

$$m_{20} = \frac{1.1\left(2m_a + 2m_c + 2m_a m_c\right)^2}{m_a(2m_a + 2m_c + m_a m_c + 1.818m_a)\lambda}$$

where, n_k is dimensionless coefficient that takes into account the mass of additional parts connected to the levitation element. Accordingly, for a levitation element made of aluminum and copper:

$$\left(\frac{\rho_2}{\tau_2}\right)_{\text{alu.}} = \frac{2.8\times10^{-8}}{\tau_2}(1.063 + 0.0042\tau_2)$$

$$n_0 = \frac{4}{18}\times0.98^2\times9.81\times2.7\times10^3 = 7.823\times10^3$$

$$\left(\frac{\rho_2}{\tau_2}\right)_{\text{copper}} = \frac{1.72\times10^{-8}}{\tau_2}(1.0645 + 0.0043\tau_2)$$

$$n_0 = \frac{4}{13}\times0.98^2\times9.81\times8.9\times10^3 = 25.789\times10^3$$

The value n_0 is calculated for n_k =1. Under the action of an external force, it is taken n_k instead of n_p=2÷5 [6].

5. CONCLUSIONS

The parameters of current and effort modes form the basis for the progress of a generalized method for project electrical devices with various levitation elements. Determination of analytical expressions for design indicators for various purposes of devices with levitation elements and their application in solving design problems is the purpose of this work. For this purpose, constructive parameters were determined and analytical expressions were obtained for the working stroke of the moving part, the lifting electromagnetic force, electro-magnetic rigidity and thermal resistance.

An increase in the height of the windings and a decrease in their thickness lead to a decrease in the average length of the conductors and the temperature of overheating of the windings (at a constant value of the cross-sectional area of the windings). These changes increase the quality factor and increase the efficiency of the induction levitator. To increase the electromagnetic efficiency and quality factor of the induction levitator, it is necessary to increase the specific magnetic conductivity of the working air gaps, where the levitation winding moves.

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