International Journal on
"Technical and Physical Problems of Engineering"
(IJTPE)
Published by International Organization of IOTPE

ISSN 2077-3528
IJTPE Journal
www.iotpe.com
ijtpe@iotpe.com

June 2023 | Issue 55 | Volume 15 | Number 2 | Pages 274-280

MATHEMATICAL MODEL FOR CALCULATION OF ELECTRICAL DEVICES BASED ON INDUCTION LEVITATORS

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Abstract- The article deals with the optimization of levitation elements and the solution of design issues, taking into account the peculiarities of the operating modes of electrical devices for various purposes based on induction levitators, as well as taking into account the restrictions imposed on the proportions of overall dimensions. The calculations are based on the basic laws for electrical, magnetic, thermal and mechanical circuits of electrical devices, to develop accurate calculation methods and comparisons of theoretical and practical results.

The purpose of the calculations is the calculation, optimization, processing of methods for solving design issues and expanding the scope of electrical devices for various purposes based on an induction levitator. The obtained analytical expressions for the parameters can be used to calculate electrical devices for various purposes based on an induction levitator.

Keywords: Electrical Device, Mathematical Model, Induction Levitator, Optimization, Calculation, Magnetic Circuit, Excitation Winding, Levitation Winding, Levitation Coefficient.

1. INTRODUCTION

Induction levitators (IL) are a key element of the tracking system for vertical wind generators, power and displacement meters, control supports and seals, multi-rated stabilizers alternating current, remote transmission of force to variables and mechanisms [1, 3]. The usual design of the IL includes: a stepped magnetic circuit (SM); fixed electromagnetic excitation winding (EW); levitation windings (LW). On the basis of this IL, compiled in different directions of electrical devices, additional windings (output and compensation windings) are located in the magnetic circuit. LE consist of a short-circuited copper winding or a short-circuited aluminum frame. Thus, the induction levitator (Figure 1) consists of a vertically located closed magnetic circuit 1, levitation winding (LW) 2 (or a short-circuited coil made of aluminum) and a fixed excitation winding (EW) 3, which is located on a stepped section of the magnetic circuit. The stepped section is an open slot of rectangular cross section and is designed to reduce the height h_1 and increase the thickness c_1 of the excitation winding. In this case, the total height of the magnetic system H is less than in the case of a direct magnetic wire. The excitation winding is connected to a source of control voltage U_y, the value of which automatically changes from $U_{\min}$ to $U_{\max}$.

Alternating currents I_1 and I_2 flow in the windings, as a result of the interaction of which a lifting electrodynamic force F_e is created. Under the action of this force F_e, the levitation winding of the LW moves upward to a distance h, where the gravity force of the P_T is compensated by the force F_e. In this case, the currents reach their established value and the levitation winding keeps the movable working mechanism of the WM in a vertical position. The IL designs are simple, and the relationship between the parameters is complex, since they simultaneously contain electrical, magnetic, thermal and mechanical parameters. As a result, the calculation, design and optimization of IL parameters are associated with the fulfillment of a number of conditions, for example, the principle of proportionality [4, 5]. In addition, the high sensitivity of the parameters of changes in the magnitude of the specific magnetic conductivity of the working air gap λ, as well as the stepping of the magnetic circuit, complicate the solution of problems of theory and design of IL.

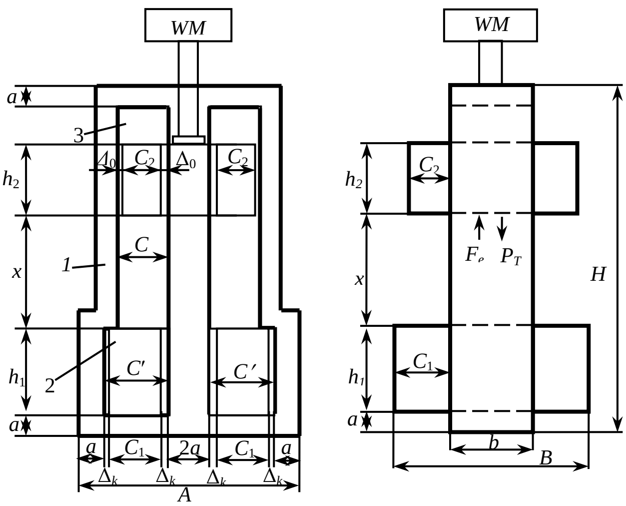

Figure 1. Design diagram of a single-phase induction levitator

2. STATEMENT OF THE PROBLEM AND MATHEMATICAL MODEL OF IL

The tasks of the levitation winding and the induction levitator include the working stroke of the main parameters of the support, the levitation coordinate, the mathematical description of the dependence of the levitation winding on electromagnetic and thermal quantities. When constructing a mathematical model, the following features of the levitation winding and induction levitator are taken into account.

The steady-state values of the currents in the windings I_1 and I_2 do not depend on the control voltage of the excitation winding control U_y, since there is a linear relationship between the inductance of the excitation winding L_1 and the movement of the levitation winding x, and the specific magnetic conductivity of the working air gap λ does not depend on the height of the magnetic circuit window. By physical modeling of the magnetic field in the working air gap, it was found that under the conditions $m_a=b/a=2\div6$; $m_c=b/c=2\div6$, this field is homogeneous [2, 5]. Taking this into account, the magnetic conductivity of the working air gap λ does not change along it.

The currents in the windings depend only on the gravity of the levitation winding P_T and the specific magnetic conductivity of the working air gap λ [1, 7]. With a large value of the gravity force, the MMF of the windings $F_1=I_1W_1$; $F_2=I_2W_2$ with an increase in the gravity force P_T and a decrease in conductivity λ increase.

In the steady state, the overheating temperatures of the windings τ_1 and τ_2 are also constant parameters due to the stability of the current values in the windings. The values of temperatures τ_1 and τ_2 is determined by the active power losses P_1 and P_2 in the windings, the heat transfer coefficients of the windings k_m, as well as the cooling area of the windings S_{cool1} and S_{cool2}. The cooling area of windings with a frame is mainly determined by the side surfaces of the windings.

As is known, with changes in the control voltage U_y at the terminals of the excitation winding from $U_{\min}$ to $U_{\max}$, the value of the magnetic induction B_M in the steel of the magnetic wire increases from $B_{\min}$ to $B_{\max}$. The range of changes in magnetic induction corresponds $\Delta B=B_{\min}-B_{\max}$ to the linear section of the magnetization curve of a given grade of electrical steel. Therefore, the steel sections are not saturated and the magnetic resistance of the steel sections is much less than the magnetic resistance of the air sections through which the magnetic flux passes. In this case, there are no higher harmonics of currents and magnetic fluxes.

An increase in the working air gap is associated with the need to increase the thickness of the levitation winding c_2. Therefore, the electromagnetic coupling b_2 between the excitation and levitation windings is less in an induction levitator than the electromagnetic coupling between the transformer windings. It is accepted that for a two-winding transformer $b_2 \approx 0.999$, and for an induction levitator $b_2 \approx 0.97\div0.98$ [2, 8].

The thickness of the working air gap in many designs of induction levitators is $c>15$ mm. Given that the depth of penetration of an electromagnetic wave at the industrial frequency of a solid aluminum screen does [6] not exceed 13 mm, then the implementation of a levitation winding of copper wires in an induction levitator is a necessary requirement.

Copper wire has the lowest specific electrical resistance ($\rho_{20}=1.72\times10^{-8}$ Omm), and its density γ is relatively higher than for aluminum ($\gamma_м=8.9\times10^3$ kg/m^3, $\gamma_a=2.7\times10^3$ kg/m^3). The resistance ρ_{20} for aluminum is greater compared to copper ($\rho_{20}=2.8\times10^{-8}$ Omm). According to the Fourier and Wiedemann-Franz laws [10], a copper levitation winding cools and heats up faster than aluminum winding [9].

In addition to the lifting force F_e, the levitation winding is subjected to centering forces F_c, which prevent friction between the winding and the core of the magnetic circuit [7, 11].

The ratio of overall dimensions H/A and B/A (Figure 1) is mainly determined by the ratios $n_{e2}=h_2/c_2$; $n_{e1}=h_1/c_1$. As the coefficients n_{e2} and n_{e1} decrease, the height H of the magnetic system also decreases. To reduce the height H, first of all, it is necessary to reduce the working stroke of the levitation winding. In this case, the value of the working stroke x_p is often given in the assignment for calculation and design [9, 10]. Taking into account the above characteristics of an induction levitator with a levitation winding, the mathematical model includes the following:

Newton's equation for the established overheating temperature of the levitation winding and the excitation winding [9]:

$$\tau_2 = \frac{I_2^2 r_2}{k_T S_{cool2}}; \tau_1 = \frac{I_1^2 (r_1 + r_{np})}{k_T S_{cool1}} \tag{1}$$

Expression of the lifting electrodynamic force F_e and gravity P_T [10]:

$$F_e = \frac{1}{2}(I_1 W_1)^2 \lambda ; P_T = k_n l_{cp2} S_{02} \tag{2}$$

The equation for the balance of forces acting on the levitation winding:

$$F_e = P_T \tag{3}$$

Winding MMF balance equation [10]:

$$F_2 = b_2 F_1 = b_2 \sqrt{\frac{2P_T}{\lambda}} \tag{4}$$

Expression for the maximum value of the controlled voltage:

$$U_{\max} = \frac{\omega k_c}{k_u \sqrt{2}} B_m S_c W_1 \tag{5}$$

Expression for currents and current densities in windings [9-10]:

$$I_1 = \frac{k_u U_{\max}}{\omega W_1^2 \lambda (h_0 + X_{\max})}; I_2 = b_2 I_1 \frac{W_2}{W_1} \tag{6}$$

$$j_1 = \frac{F_1}{k_{31} S_{o1}}; j_2 = \frac{F_2}{k_{32} S_{o2}} \tag{7}$$

In Equations (1)-(7) coefficient $k_n=k_k g \gamma_2 k_{32}$ is the specific weight of the wire material γ_2, the fill factor k_{32} of the levitation winding and the acceleration g; k_{31} and k_{32} is coefficients of filling with materials of wires of the excitation winding and levitation winding; k_T is heat transfer coefficient from the side surfaces of the windings; k_c is filling factor of steel magneto tope water; k_u is coefficient that takes into account the voltage drop of the active resistance of the excitation winding; h_0 is generalized size of windings; r_1 is reduced active resistance of the levitation winding; $x_{\max}$ is the maximum stroke of the levitation winding; l_{cp2} and S_{02} are the average length of the coil and the cross-sectional area of the levitation winding; W_1 and W_2 are the number of turns of the *EW* and *LW*, respectively. The remaining designations are generally known.

3. DEFINITION OF INDUCTANCES

The winding currents are determined through the inductance of the field winding. The inductance of the excitation winding depends on the displacement of the levitation winding x. To determine the inductances, it is necessary to consider the diagrams of the distribution of the magnetic flux in the magnetic circuit (Figure 2), where the total magnetic flux Φ is divided into the following types [8]:

1. The stray flux Φ_1 that occurs around the conductors of the excitation winding and does not pass through the working air gap from c [6]. The leakage current Φ_{1s} corresponds to the leakage inductance:

$$L_{1s}=\frac{\Phi_{1s}}{I_1}=W_1^2\lambda\frac{h_2}{3}$$

where, Ψ_{1S} is flux linkage:

$$\Psi_{1s}=\int_0^{h_1}\frac{W_1}{h_1}dy_1 d\Phi_{1s}=\frac{I_1W_1}{h_1^2}\lambda_s\int_0^{h_1}y_1^2dy_1=\frac{h_1}{3}I_1W_1^2\lambda_s$$

2. The scattering flux Φ_{sh}, which passes through the section corresponding to the minimum levitation coordinate $h_{\min}$. The leakage inductance due to these flows is defined as [5, 6]:

$$L_{sh}=\frac{\Phi_{sh}}{I_1}=\frac{1}{I_1}\int_0^{h_{\min}}W_1(I_1W_1)\lambda dx=\lambda W_1^2h_{\min}$$

3. The flow Φ_x corresponds to the working stroke x. With the movement of the levitation winding, the inductance changes [7]:

$$L_x=\frac{\Phi_x}{I_1}=\frac{1}{I_1}\int_0^x W_1(I_1W_1)\lambda dx=\lambda W_1^2x$$

4. The flux Φ_{2s} corresponds to the leakage inductance of the levitation winding:

$$L_{2s}=\frac{\Phi_{2s}}{I_2}=W_2^2\lambda\frac{h_2}{3}$$

$$\Phi_{2s}=\frac{I_2W_2}{h_2^2}\lambda_s\int_0^{h_2}y_2^2dy_2=\frac{h_1}{3}I_2W_2^2\lambda$$

The resulting inductance of the excitation winding is determined as a function of displacement x of the levitation winding [6, 7]:

$$L_1=L_{1s}+L_{sh}+L_x+L'_{2s}=W_1^2\lambda(h_0+h_{\min}+x)$$

where, $L'_{2s}=k^2L_{2s}=W_1^2\lambda\frac{h_2}{3}$; $h_0=\frac{h_1}{3n_\lambda}+\frac{h_2}{3}$.

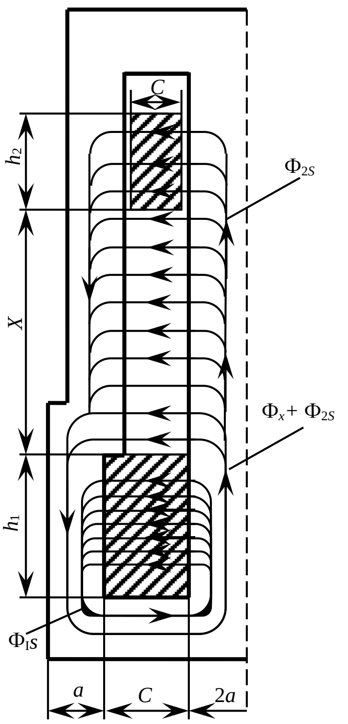

Figure 2. Distribution of magnetic fluxes along the height of the magnetic circuit

The minimum and maximum values of the inductance correspond to the voltages $U_{\min}$ and $U_{\max}$ [4]:

$$L_{\min}=W_1^2\lambda H_{\min}\ ;\ L_{\max}=W_1^2\lambda H_{\max}$$

where,

$$H_{\max}=H_{\min}+x_p\ ;\ H_{\min}=h_0+h_{\min}$$

The minimum value of the voltage $U_y=U_{\min}$ corresponds to the minimum value of the levitation coordinate $h_{\min}$, and the maximum value of the voltage $U_y=U_{\max}$ corresponds to the maximum value of the levitation coordinate $h_{\max}$. Therefore, the working stroke is defined as [1-3]:

$$x_p=H_{\max}-H_{\min}=h_{\max}-h_{\min}$$

and the maximum move:

$$x_{\max}=h_{\max}=h_{\min}+x_p$$

4. REPRESENTATION OF THE PARAMETERS OF THE MAGNETIC SYSTEM IN TERMS OF DIMENSIONLESS QUANTITIES

Analytical expressions of parameters are greatly simplified if they are expressed in dimensionless quantities, determined by known and given parameters for the calculation. The average coil length is defined as Figure 1 [5, 6]:

$$l_{cp2}=2\left[2a+2\left(\Delta_0+\Delta_k\right)+c_2\right]+2\left[b+2\left(\Delta_0+\Delta_k\right)+c_2\right]$$

$$\Pi_c+4c=\Pi_c+4c_2n_{02}=2c_2k_k+4c_2n_{02}=2c_2k_0$$

Let us determine the perimeter of the middle core of the magnetic core Π_c, the thickness of the gap c and the coefficient n_{02}:

$$\Pi_c = 2(2a+b) = 2c_2 k_k;\ c = c_2 n_{02};\ n_{02} = 1 + \frac{2}{c_2}(\Delta_0 + \Delta_k)$$

$$k_k = \frac{n_{02}}{m_a}(2m_c + m_a m_c);\ k_0 = k_k + 2n_{02} = n_{02}\frac{n_1}{m_a}$$

where,

$$n_1 = 2m_a + 2m_c + m_a m_c \tag{8}$$

Lateral heat transfer surface of the levitation winding [4]:

$$S_{ox2} = S_{b2} = h_2(l_{cp2} + 4c_2) = 2n_{e2}c_2^2 \times (2 + k_0) \tag{9}$$

Cross sections of the levitation winding and the middle rod of the magnetic core [4]:

$$S_{02} = c_2 h_2 = n_{e2}c_2^2; S_c = 2ab = k_3 n_{02}^2 c_2^2 \tag{10}$$

According to Equations (1-10) we determine the geometric factor of the levitation winding:

$$\Gamma_2 = \frac{S_{02}S_{cool2}}{l_{cp2}} = \frac{n_{e2}c_2^3}{k_s}$$

where,

$$k_s = \frac{k_0}{2+k_0} = \frac{n_1}{n_1 + \frac{2}{n_{02}}m_a} \tag{11}$$

In Tables 1 and 2 [7, 8, 10] the numerical values of the coefficients k_0 and k_s are given, which depend on the quantities (dimensionless) of the magnetic wire m_a and m_c (or specific magnetic conductivity λ). The scheme of changing these coefficients will be used to estimate the parameters of the magnetic system [8, 9]. According to (4), gravity is expressed as:

$$P_T = k_n S_{02} l_{cp2} \tag{12}$$

where,

$$k_n = n_k \gamma g K_{32} = 1.1 \times 8.9 \times 10^3 \times 9.81 \times 0.6 = 550 \times 10^2$$

The coefficient n_k takes into account the gravity of additional elements mechanically associated with the levitation winding (for example, the strength element and the frame of the levitation winding).

Table 1. Values of coefficient k_0 [2, 4]

m_c \ m_a	1	2	3	4	5	6
1	5.5	4.4	4.033	3.85	3.74	3.66
2	8.8	6.6	5.866	5.5	5.28	5.133
3	12.1	8.8	7.7	7.15	6.82	6.6
4	15.4	11	9.533	8.8	8.36	8.066
5	18.7	13.2	11.366	10.45	9.9	9.533
6	22	15.4	13.2	12.1	11.44	11

Table 2. Values of coefficient k_s [2, 4]

m_c \ m_a	1	2	3	4	5	6
1	0.733	0.687	0.668	0.658	0.652	0.647
2	0.814	0.767	0.746	0.733	0.725	0.720
3	0.858	0.815	0.794	0.781	0.733	0.767
4	0.885	0.846	0.826	0.814	0.807	0.801
5	0.903	0.868	0.850	0.839	0.832	0.826
6	0.917	0.885	0.868	0.858	0.851	0.846

The active power and overheating temperature of the levitation winding are determined from the expression:

$$P_2 = I_2^2 r_2 = F_2^2 \frac{2k_0\rho_2}{k_{32}c_2 n_{e2}}$$

The overheating temperature of the levitation winding according to (1) and (11) is defined as:

$$\tau_2 = \frac{F_2^2\rho_2}{k_T \Gamma_2} = \frac{\Delta_{OK}}{\alpha_0 - \alpha_M}$$

where marked:

$$n_T = \frac{k_T k_{32}}{\rho_{20}} = \frac{13 \times 0.6}{1.72 \times 10^{-8}} = 453.488 \times 10^6$$

$$\alpha = \alpha_M = 0.0043\frac{1}{0_C};\ \rho_2 = \rho_{20}(\Delta_{OK} + \alpha\tau_2)$$

$$\rho_2 = 1.72 \times 10^{-8}(1.0645 + 0.0043\tau_2)$$

$$\Delta_{\text{ok}} = 1 + \alpha_M(\theta_{OK} - 20)$$

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

Thus, to determine the temperature τ_2, it is enough to determine the value of α_0. According to Equations (3), (4) and (11) for F_1 and c_2 we get:

$$F_1 = \sqrt{\frac{4k_n}{\lambda}c_2^3 k_0 n_{e2}};\ c_2 = 3\sqrt{\frac{k_u I_1 \Delta U}{4k_n \omega x_p k_0 n_{e2}}}$$

Using Equation (5) one can find the number of excitations turns [2]:

$$W_1 = \frac{k_u U\sqrt{2}}{\omega k_c B_M S_c} = \frac{k_2}{S_c} = \frac{k_2}{k_3 n_{02}^2 c_2^2}$$

Then we have:

$$F_1 = I_1 W_1 = I_1\frac{k_2}{S_c} = \frac{k_1}{S_c} = \frac{k_1}{k_3 n_{02}^2 c_2^2}$$

$$F_2 = b_2 F_1 = b_2 I_1 \frac{k_2}{S_c} = b_2\frac{I_1}{S_c} = \frac{b_2 k_1}{k_3 n_{02}^2 c_2^2}$$

where, k_1 and k_2 are constant values known from the task for calculating the control induction winding:

$$k_1 = k_2 I_1;\ k_2 \frac{k_u U_{\max}\sqrt{2}}{\omega k_c B_M}$$

The excitation winding current and coefficient depend on the quality factor and are determined from the expressions:

$$I_1 = \frac{U_1}{\sqrt{R_1^2 + x_1^2}} = \frac{U_1}{x_1\sqrt{1+\frac{1}{Q_1^2}}} = \frac{k_u U_1}{x_1}$$

$$k_u = \left(\sqrt{1+\frac{1}{Q_1^2}}\right)^{-1};\ Q_1 = \frac{x_1}{R_1}$$

Coefficient k_u of voltage drop U_a on actives resistance to electromagnetic excitation. In calculations it is possible to accept: k_U=0.95÷0.98; k_c=0.92÷0.96; B_M=1.5÷1.8 Tl.

5. DETERMINATION OF THE MAGNETIZING FORCES OF THE WINDINGS

The magnetizing forces of the winding depend on $F_1=I_1W_1$; $F_2=b_2I_1W_1$ the temperature of their overheating (τ_1, τ_2), working gap λ, dimensions of the magnetic circuit

(a, b and c) and on the specified parameters used in the design specification. Let us determine the dependencies for F_1 and F_2. To do this, we use the formulas of the mathematical model (1)-(6) and compose a system of equations for the levitation winding [7, 8]:

$$\tau_2 = \frac{F_2^2 r_2}{k_T S_{cool2} W_2^2}; r_2 = \frac{\rho_2 l_{cp2} W_2^2}{k_{32} S_{02}}$$

$$F_2 = b_2 F_1 = b_2 \sqrt{\frac{2P_T}{\lambda}}; P_T = k_n S_{02} l_{cp2}$$

$$U_{\max} = \frac{\omega k_c}{k_u \sqrt{2}} B_M S_c W_1$$

From the mathematical model for the levitation coefficient, we obtain [9]:

$$n_{e2} = n_0 \left(\frac{\rho_2}{\tau_2}\right) m_{20}\ ,\ n_0 = \frac{4b_2^2}{k_T} n_k g \gamma$$

$$\frac{\rho_2}{\tau_2} = \frac{\rho_{20}}{\tau_2}(1.063 + 0.0043\tau_2)$$

$$m^* = \frac{n_{02} n_1^2}{m_a (n_1 + 2\frac{m_a}{n_{02}})}\ ,\ m_{20} = \frac{m^*}{\lambda} = \frac{k_0 k_s}{\lambda}$$

In the initial calculation, it is convenient to use the numerical values of the dimensionless quantity n_{e2} given in Table 3 [2, 9-11]. An analysis of the patterns of change in n_{e2} from the coefficient's m_a and m_c allows you to choose the necessary values of the coefficients m_a, m_c, n_{e2} at different values of the overheating temperature τ_2.

6. THE SEQUENCE OF CALCULATION OF THE INDUCTION LEVITATOR

The expression $n_{e2} = n_0 \left(\frac{\rho_2}{\tau_2}\right) m_{20}$ is derived from the conditions of levitation and takes into account the temperature of overheating, but does not take into account the given course of the levitation winding x_p. Therefore, the dimensions of the levitation winding c_2 must satisfy not only the conditions of levitation and the given temperature values τ_2, but also the given course of x_p. In the initial calculations, the dimension measurement with known values of the coefficient n_{e2} and conductivity λ (or m_a, m_c) can be performed in the following order (Table 3) [6-9]:

$$F_1 = \sqrt{\frac{k_u \Delta U I_1}{\omega \lambda x_p}};\ W_1 = \frac{F_1}{I_1}$$

$$k_2 = \frac{k_u U_{\max} \sqrt{2}}{\omega k_c B_M}$$

$$S_c = \frac{k_2}{W_1}; c = \sqrt{\frac{m_a}{2m_c^2} S_c}; c_2 = \frac{c}{n_{02}}$$

Let to define the dimensions a, b and c_2:

$$b = m_c a;\ a = \frac{b}{m_a};\ c_2 = \sqrt[7]{c_0^2}\ ,$$

where,

$$c_0 = \frac{a_0}{b_0 n_{e2}};\ a_0 = \frac{b_2 k_2 I_1}{k_3 n_{02}^2}$$

$$\tau_2' = \sqrt{\frac{k_T k_{32}}{\frac{\rho_2}{\tau_2}}};\ \ b_0 = \frac{\tau_2'}{\sqrt{k_s}}$$

then we define:

$$F_2 = \frac{a_0}{c_2^3};\ F_1 = \frac{F_2}{b_2};\ W_1 = \frac{F_1}{I_1}$$

$$h_2 = n_{e2} c_2;\ c = n_{02} c_2;\ S_{02} = c_2 h_2$$

Table 3. The value of n_{e2} at various values of the superheat temperature τ_2 [1, 2, 10]

m_c \ m_a	2	3	4	5	6	τ_2 °C
2	5.159	4.832	4.807	4.766	4.756	80
	4.727	4.487	4.404	4.367	4.352	90
	4.378	4.156	4.080	4.045	4.031	100
	4.097	3.889	3.817	3.785	3.772	110
3	5.592	5.376	4.877	4.777	4.676	80
	5.124	4.926	4.464	4.374	4.284	90
	4.747	4.563	4.135	4.052	3.968	100
	4.441	4.270	3.870	3.791	3.713	110
4	5.818	5.246	4.934	4.762	4.643	80
	5.327	4.802	4.517	4.359	4.524	90
	4.934	4.448	4.184	4.038	3.941	100
	4.617	4.162	3.915	3..778	3.687	110
5	6.018	5.348	4.987	4.784	4.643	80
	5.515	5.899	4.569	4.382	4.254	90
	5.108	4.538	4.232	4.059	3.941	100
	4.780	4.247	3.960	3.798	3.687	110
6	6.167	5.426	5.031	4.803	4.647	80
	5.650	4.974	4.607	4.397	4.254	90
	5.233	4.608	4.267	4.073	3.941	100
	4.897	4.311	3.993	3.811	3.687	110

The dependence of the dimensionless quantity n_{e2} on the specific magnetic conductivity λ is obvious from Table 3. With a decrease in λ, the coefficient n_{e2} decreases, since with an increase in m_a, the value of λ and n_{e2} decrease, and with an increase in m_c, an increase in λ and n_{e2} occurs [9-13]. Because of this, the thickness c_2 and F_1 change. In order to describe the dimensions of the excitation winding, we use the following formulas:

$$k_{12} = \frac{m_1}{2} + \sqrt{\left(\frac{m_1}{2}\right)^2 + m_1 m_2}$$

where,

$$k_{12} = \frac{h_1}{h_2};\ \tau_{12} = \frac{\tau_1}{\tau_2}$$

$$M_1 = \frac{\rho_{12}}{b_2^2} = \frac{1}{0.96};\ \rho_{12} = \frac{\rho_1}{\rho_2}$$

$$m_1 = \frac{1}{\tau_{12}(E_1 + E_0 n_c)};\ m_2 = M_1 \left(B_0 + \frac{B_1}{n_c}\right)$$

$$E_0 = \frac{4cn_0'}{\Pi_c + 4cn_0'};\ E_1 = 1 - E_0$$

$$B_0 = \frac{4c}{\Pi_c + 4c};\ B_1 = 1 - B$$

$$n_0' = \frac{1+n_{01}}{n_{01}} \approx 1.909;\ n_{01} = \frac{c'}{c_1} \approx 1.1$$

Next, we define: gap thickness c' and winding c_1: $c'=cn_c$, $c_1=c'/n_{01}$; height and section of the excitation winding: $h_1=k_{12}h_2$, $S_{01}=h_1c_1$; the average length of the turn and the cooling area of the excitation winding: $l_{cp1}=\Pi_c+4c'$, $S_{cool1}=h_1(l_{cp1}+4c_1)$;

odds n_{e1} and k_p: $n_{e1} = \frac{h_1}{c_1}$; $k_p = \tau_{12}k_{12}(E_1 + E_0 n_c)$;

active powers: $P_1 = (k_p - 1)P_2$; $P = P_1 + P_2$;

superheat temperature τ_1: $\tau_1 = \frac{P}{k_T S_{cool1}}$.

From the obtained analytical expressions of the parameters, it follows that the levitation constant n_{e2} is a generalized indicator, since it establishes the relationship between the geometric dimensions, overheating temperatures τ_1 and τ_2, as well as the parameters and characteristics of the materials specified in the technical design assignments [2, 9, 10]. The use of the levitation constant n_{e2} in calculations leads to a significant improvement in the solutions of the tasks set. The value of n_{e2} is a constant value for the optimal values of the parameters, and the value of n_{e2} for the levitation winding is greater than for the levitation element. For this reason, the thickness of the working gap for an induction levitator operating in the current mode is greater than for an induction levitator operating in the force mode. To reduce the height of the induction levitator, it is necessary to reduce the force coefficient n_p and increase the overheating temperature τ_2 [7, 9-11].

7. CONCLUSIONS

On the basis of a comparative analysis, it was found that the calculation, optimization and methods for designing electrical devices for various purposes, built on the basis of induction levitators, are not at the required level, and therefore the scope of these devices rats is limited. Methods have been developed that take into account the operation of induction levitators in various modes, varieties of characteristics and restrictions on the ratio of overall dimensions in design assignments. On the basis of a comparative analysis of operating modes and varieties of input and output parameters for these devices, two generalized modes (current and effort modes) were determined. Since the characteristics of induction levitators are determined using their electrical, magnetic, thermal and mechanical parameters, therefore, these parameters are included in their mathematical models, composed of a number of equations, from the joint solution of which the analysis was obtained analytic expressions of the parameters of induction levitators. In order to simplify the solution of the problem, the main parameters and geometric dimensions are expressed in terms of dimensionless quantities and in terms of the parameters specified in the design assignments.

REFERENCES

[1] N.M. Piriyeva, "Design of Electric Devices with Induction Levitation Elements", International Journal on Technical and Physical Problems of Engineering (IJTPE), Issue 50, Vol. 14, No. 1, pp. 124-129, March 2022.

[2] Y.R. Abdullayev, G.S. Kerimzade, G.V. Mammadova, N.M. Piriyeva, "Design Issues of Electromechanical Converters with Levitation Elements", Electromechanical Scientific and Technical Journal, Vol. 61, No. 2. pp. 47-52, Moscow, Russia, 2018.

[3] G.V. Mamedova, G.S. Kerimzade, N.M. Piriyeva, "Electromagnetic Calculation of Tension Devices for Winding Wires of Small Cross Sections", International Journal on Technical and Physical Problems of Engineering (IJTPE), Issue 53, Vol. 14, No. 4, pp. 80-85, December 2022.

[4] Y.R. Abdullayev, G.S. Kerimzade, G.V. Mammadova, N.M. Piriyeva, "Generalized Indicators of Electromagnetic Devices with Levitation Elements", Priborostroenie Journal, Vol. 60, No. 5, pp. 17-23, Saint Petersburg, Russia, 2017.

[5] Y.R. Abdullayev, N.M. Piriyeva, O.O. Kerimzade, "Calculation of Excitation Winding of the Stepped Inductional Levitator", The 11th International Conference on Technical and Physical Problems of Electrical Engineering (ICTPE), pp. 342-346, Bucharest, Romania, 10-12 September 2015.

[6] Y.R. Abdullayev, G.S. Kerimzade, G.V. Mammadova, N.M. Piriyeva, O.O. Kerimzade, "Calculation and Analysis of the Work of the Tracking System of Devices for Stabilizing the Tension of Wires of Small Cross-Sections", Izvestiya VTUZov, No. 3, pp. 59-68, Baku, Azerbaijan, 2018.

[7] Y.R. Abdullayev, G.S. Kerimzade, G.V. Mammadova, "Tracking System for Stabilizing the Tension of Wires of Small Cross-Sections", Izvestiya VTUZov, No. 5, pp. 39-46, Baku, Azerbaijan, 2021.

[8] O.O. Karimzada, Y.R. Adullayev, "Electromagnetic Calculation of The Tracking System with Levitation Screens", The 61th International Scientific Conference on Power and Electrical Engineering of Riga Technical University (RTUCON), pp. 1-4, 2020.

[9] N.M. Piriyeva, "Fundamentals of the Theory and Calculation of the Induction Levitator of Electrical Devices", Journal Electricity, No. 7, pp. 68-75, Moscow, Russia, 2022.

[10] G.S. Kerimzade, "Analytical Connections of the Parameters and Sizes of the Precision Stabilizer of Alternating Current Using the Effect of Inductive Levitation", International Journal on Technical and Physical Problems of Engineering (IJTPE), Issue 52, Vol. 14, No. 3, pp. 175-184, September 2022.

[11] G.S. Kerimzade, "Analysis of the Methodology for Calculation Current Stabilizer with Induction Levitation", International Journal on technical and Physical Problems of Engineering (IJTPE), Issue 53, Vol. 14, No. 4, pp. 170-174, December 2022.

[12] G.S. Kerimzade, "Analytical Expressions of the Relationship to the Calculation of the AC Stabilizer with Induction Levitation", International Journal on Technical

and Physical Problems of Engineering (IJTPE), Issue 54, Vol. 15, No. 1, March 2023.
[13] Y.R. Abdullayev, G.S. Kerimzade, G.V. Mammadova, N.M. Piriyeva, "Design of Electric Devices with Induction Levitation Elements", Russian Electrical Engineering, No. 86, Vol. 5, pp. 252-257, 2015.

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