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DESIGN OF ELECTRIC DEVICES WITH INDUCTION LEVITATION ELEMENTS

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Abstract- The generalized method of design is developed and constructive schemes and functional depends of the main versions electric devices **(**ED) with levitation elements (LE) are systematized. Their main technical indicators are reviewed. Concepts of coefficients of an induction levitation and frequency rate of forces are for this purpose entered, their optimum values are found. It is established that at the time of connection of a winding of excitement to the power supply on a winding and a levitation element the currents much exceeding nominal rates start proceeding. Thus, losses sharply increase in a levitation element whereas the thermolysis increases slightly and all energy emitted in a levitation element goes for its heating. Depending on the geometrical sizes of a levitation element temperature of the last can reach so big size that the levitation element to melt in the start of motion, without managing to reach the established situation. Analytical expression of coefficient of an induction levitation as function of the geometrical sizes of a magnetic conductor and coefficient of frequency rate of force, physics and technology characteristics of material of a levitation element (LE) and the set overheat temperature are received. The mathematical model based on parameters of the modes of current and efforts is made. The mathematical model included the equations of magnetic, electric, mechanical and thermal chains of magnetic system. From mathematical model dimensionless sizes and the main sizes of magnetic system are determined. For LE from copper and aluminum numerical values of dimensionless sizes on the basis of which the help tables necessary for design of ED with LE are made are defined. The received analytical expressions for the main sizes consider preset values of temperature of an overheat of windings, input and output parameters and a condition of performance of uniformity of a magnetic field in a working air gap. Optimum values of the sizes of a magnetic conductor at which the perimeter of cross section of an average core gains the minimum value are defined. In this case active resistance of a winding of excitement and a levitation element will also be minimum. It leads to minimization of losses of active capacities.

Keywords: Electric Devices with Levitation Elements, Modes of Current and Efforts, Design, Step Magnetic System, Mathematical Model, The Main Sizes, Overall Dimensions of Magnetic System, Dimensionless Sizes, Minimization.

1. INTRODUCTION

Electric devices with induction levitation elements (ED with LE) combine the functions of measuring, controlling and stabilizing electrical and non-electric quantities. They belong to the low-current electrical apparatus and have simple structures, high stability and performance accuracy. The fundamentals of the theory, calculation and application of ED with LE are described in the works [1-8]. In these works, the issues of designing ED with LE with different functional purposes have not been resolved. Each type of apparatus not only must meet the requirements of design assignments, but they must be optimal both in terms of functionality and in terms of national economic costs. And this requires the systematization of structural schemes and functional dependencies of the main parameters of the existing varieties of ED with LE. Considering this and the features of the current modes and forces [1-3], a design method has been developed here. At the same time, it is taken into account that the overall dimensions of the ED with LE are mainly determined by the dimensions of the magnetic system and the restrictions on these dimensions should take into account the body resistance of the LE.

2. SYSTEMATIZATION OF DESIGN SCHEMES AND FUNCTIONAL DEPENDENCES OF ED WITH LE

The main structural elements of magnetic systems are a stepped magnetic circuit 1, an excitation winding (EW) 2 and a levitation element (LE) 3 (Figure 1).

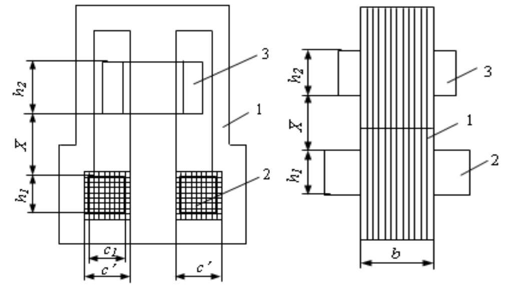
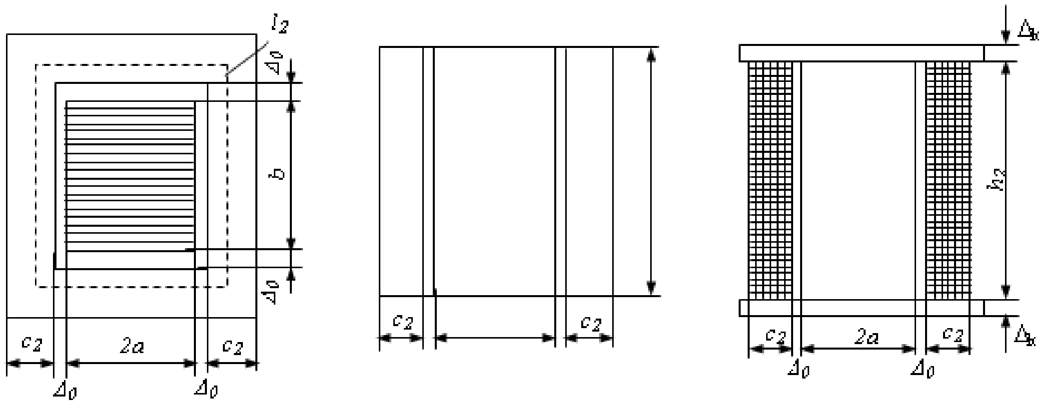


Figure 1. Stepped magnetic system with levitation elements

The EW is made of several switchable sections and is connected to the voltage source U_1. LE is made of aluminum in the form of a short-circuited solid frame or in the form of a short-circuited winding of copper wires (Figure 2). The magnetic core is assembled from W-shaped electrical plates or made of structural electrical steel in a cylindrical shape.



(a) (b) (c)

Figure 2. Schemes of continuous LE (a and b) and levitation short-circuited winding with a frame (c)

Due to the surface effect, the LE thickness c_2 is limited by the penetration depth of an electromagnetic wave in a continuous LE to 11 mm. for copper and up to 14 mm. for aluminum [1]. In the manufacture of LE from insulated copper or aluminum conductors, this restriction is removed and the thickness of the air gap can be taken more than 14 mm. With an increase in the power of the EW excitation winding, the lifting force P_e increases, the dimensions of the transverse rod a and b, as well as the thickness of the working air gap c (Figure 1).

Table 1 shows the structural diagrams of the main types of ED with LE and shows their input and output parameters. In brief, we note their purpose and main indicators:

1. The force transducer is designed to control external forces P_x. As an output signal, the current EW I_1 or the voltage drop U_2 on the active resistance, connected in series to the excitation winding circuit, is used. LE is made in the form of a rectangular aluminum frame. To expand the range of controlled efforts, P_x EW is made from several switchable sections and is connected to voltage U_1=const. The converter allows you to control the force P_x=1–30 N.
2. The displacement transducer is designed to control vertical displacements in the order of 5-50 mm. The designs of displacement and force transducers are no different from each other [2].
3. The controlled actuator is designed to automatically change the position of the operating mechanism within 5-50 mm. The actuator, in addition to the excitation winding, contains a control winding that automatically regulates the voltage U_y at the terminals of the control winding of the CW. In this case, the position of the moving part of the actuator changes smoothly. LE is made of an aluminum frame in the form of a short-circuited frame.
4. The controlled support serves for smooth control of the position of the support of the working mechanisms [5].

The output signal can be displacement x or current EW I_1. LE is made in the form of a short-circuited winding of copper conductors.

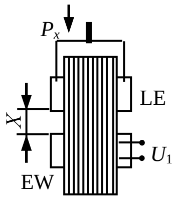
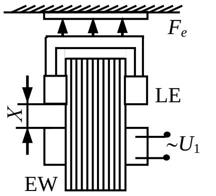
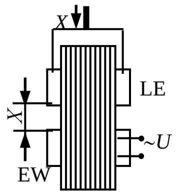
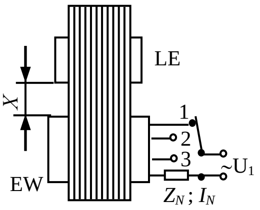
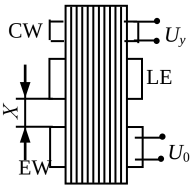
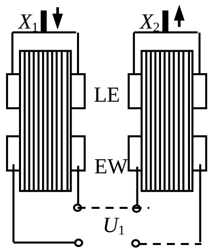
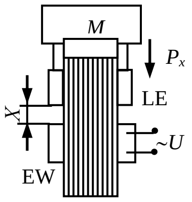
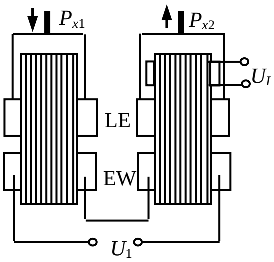
5. The sealant is used for sealing external elements with a given force P_x=P_e. LE is made of aluminum in the form of a short-circuited frame. The electromagnetic lifting force P_e for seals is controlled by the current EW I_1 or the displacement of the LE x. The seal creates a force of up to approximately 30 N [5].
6. The multi-rate alternating current stabilizer is designed to accurately stabilize the alternating current in loads connected in series with the EW sections [6]. By switching sections, a change in the magnitude of the current I_1 in the EW (or in loads) is achieved. Here, the LE is made in the form of a short-circuited winding of copper wires. When the mains voltage U_1 changes with in ΔU=160÷250 V, the current in the load remains almost constant, approximately with an accuracy of 0.05-0.08. The nominal current value is from 0.1 to 5 *A*.
7. A device for transmitting displacements over a distance allows you to transmit displacements in the order x_1=5–50 mm. with an accuracy of 0.1÷0.5 mm. The displacement x_2 received at the output of the receiver may be greater, less than or equal to the transmitted displacement x_1. This is achieved by switching sections of the EW. In some cases, the receiver is placed in a sealed environment and is consistent with the robotic system. LE is made of aluminum in the form of a short-circuited frame.
8. The stabilizer for controlling the mechanical tension of wires of small sections allows you to provide a specified value of the tension force of conductors of various sections when winding and rewinding coils. The stabilizer works as a follow-up system for the transmission of mechanical forces. LE is made of aluminum in the form of a short-circuited frame. The tension force is from 0.1 to 30 N.

3. DETERMINATION OF OPTIMAL RATIOS BETWEEN GEOMETRIC DIMENSIONS

At the time of connection of the EW to the power source, currents significantly exceeding the nominal values begin to flow through the EW and LE.

In this case, the losses in the LE sharply increase, while the heat transfer increases insignificantly, and all the energy released in the LE goes to heat it.

Table 1. Electrical devices of vertical execution with levitation elements

Name of devices and their functional dependencies	Constructive scheme	Name of devices and their functional dependencies	Constructive scheme
1. Force converter $I(P_x)$; $U_2(P_x)$		5. Sealant $I_1(X)$; $X(U_1)$	
2. Displacement transducer $I(X)$; $U_2(X)$		6. Multi Rated Stabilizer alternating current $I'_N(U_1)$; $I''_N(U_1)$; $I'''_N(U_1)$	
3. Managed executive mechanism $I(X)$; $U_2(X)$		7. Device for transmission of movements over a distance $X_2(X_1)$	
4. Managed support $X(U_1)$; $I_1(M)$		8. Stabilizer for control mechanical wire stretching $P_{x2}(P_{x1})$ $U_n(P_{x1}; P_{x2})$	

Depending on the geometric dimensions of the LE, the temperature of the latter can reach such a high value that the LE can melt at the very beginning of the movement, without having time to reach a steady state. Therefore, the minimum dimensions of the LE should be limited to. Permissible values of the LE overheating temperature τ_p is set in accordance with the insulation class of the conductor. Obviously, to reduce the overheating temperature, exceeding the specified value τ_p, it is necessary to increase the side surface of the heat transfer of the LE. This is due to the increase in the ratio $n_{e2}=h_2/c_2$ under the condition $S_{02}=c_2h_2$=const. But this can lead to an unacceptable increase in the height of the magnetic system and a deterioration in the transverse stability of the LE, since the center of gravity is shifted from the axis of the middle rod of the magnetic wire. To find the optimal ratio between the main dimensions of the LE c_2 and h_2, we determine the dependence of the dimensionless value n_{e2} on the geometric dimensions of the magnetic wire (a, b, c), the multiplicity factor of the force n_p, the physical and technical characteristics of the LE material and the specified overheating temperature τ_2.

Let's make a mathematical model based on the parameters of the current and voltage modes:

$$\tau_2 = \frac{P_2}{k_T S_T} = F_1^2 \frac{b_2^2 P_2}{k_{32} k_T}\left(\frac{l_2}{S_2 S_{T2}}\right) \tag{1}$$

$$F_1^2 = \frac{2}{\lambda}\left(P_T + P_T\right) = 2gyk_{32}n_p \frac{S_2 l_2}{\lambda} \tag{2}$$

where, the designations are generally accepted and do not require explanations. The multiplicity factor of forces is determined:

$$n_p = 1 + \frac{P_x}{P_a}$$

For LW made of copper wires and LE made of aluminum, it is known:

$$\left(S_2 l_2\right) = 2c_2^3 n_{e2} k_u \tag{3}$$

we have, respectively:

$$\left(\frac{l_2}{S_2 S_{T2}}\right) = \frac{k_s}{n_{e2}^2 c_2^3}$$

$$\left(\frac{l_2}{S_2 S_{T2}}\right) = \frac{1}{2n_{e2}^2 c_2^3 \left(1+n_{e2}\right)} \tag{4}$$

From the joint solutions (1) and (2) for the LW from copper wires and for the LE from aluminum, we obtain, respectively:

$$n_{e2} = E_m M_m n_p \tag{5}$$

$$n_{e2} = E_a M_a n_p - 1 \tag{6}$$

where, the coefficients are denoted by:

$$E_m = 2.2585 \times 10^{10} \left(\frac{\rho_2}{\tau_2}\right)_m \tag{7}$$

$$\left(\frac{\rho_2}{\tau_2}\right)_m = \frac{1.72 \times 10^{-8}}{\tau_2}\left(1.063 + 0.0042\tau_2\right) \tag{8}$$

$$M_m = \frac{\left(m_a + m_c + 0.5 m_a m_c\right)^2}{\left(0.909 m_a + m_a + m_c + m_a m_c\right)} \times \\ \times \frac{1}{\left[m_a m_c + 2.92 m_a \lg\left(1 + \frac{\pi}{m_a}\right)\right]} \tag{9}$$

$$E_\alpha = 0.3432 \times 10^{10} \left(\frac{\rho_2}{\tau_2}\right) \tag{10}$$

$$\left(\frac{\rho_2}{\tau_2}\right)_\alpha = \frac{2.8 \times 10^{-8}}{\tau_2}\left(1.063 + 0.0042\tau_2\right) \tag{11}$$

The obtained formulas (5)-(12) made it possible to compile Tables 2-4 with the help of computer programs, where the values of the parameters M_m, M_a, E_m, E_a, n_{e2} for copper and aluminum LE are given. The patterns of change in the values of the coefficients M_m and M_a from the dimensionless values ma and mc show that the smallest values of the coefficient’s m_a and mc occur at m_a=2 and m_c=6, and their largest values correspond to the values m_a=2 and m_c=6.

As it is known at m_a=6 and m_c=6, the value of the specific magnetic conductivity λ and the cross-sectional area of the middle rod S_c is minimal.

When m_a=2 and m_c=6, on the contrary, the values of these parameters reach their maximum values. Therefore, in the first case, the overall dimensions A and B are smaller than in the second case. With an increase in the load capacity and the coefficient M_m and M_a, the value of n_{e2} increases. This leads to an increase in the overall size of the magnetic system H. An increase in the overheating temperature τ_2 leads to a decrease in the coefficients E_m and E_a, due to which the dimensionless value n_{e2} and the overall size H decrease. The given values of the coefficient n_{e2} in Table 4 make it possible to preliminarily choose the minimum values of this coefficient and the corresponding values m_a and m_c. After that, it is not difficult to determine the main dimensions of the magnetic system.

$$M_a = \frac{m_a + m_c + 0.5 m_a m_c}{m_a m_c + 2.92 m_a \log\left(1 + \frac{\pi}{m_a}\right)} \tag{12}$$

according to (1) and (2) for LE from copper and aluminum, we obtain, respectively:

$$\left(c_2\right)_m = 152.922 \times 10^{-3} \sqrt[7]{\frac{k_2^2 I_1^2}{k_{32} n_p M_2 n_{e2} k_3^2}} \tag{13}$$

$$\left(c_2\right)_a = 181.168 \times 10^{-3} \sqrt[7]{\frac{k_2^2 I_1^2}{n_p M_2 n_{e2} k_3^2}} \tag{14}$$

where,

$$k_2 = \frac{k_u U_1 \sqrt{2}}{\omega k_2 B_c} \tag{15}$$

$$M_2 = 875.790 \times 10^3 M_a \tag{16}$$

$$k_3 = 2\frac{m_c^2}{m_a} \tag{17}$$

Further, the remaining dimensions and parameters are determined:

$$c = n_{02} c_2;\quad h_2 = n_{e2} c_2;\ b = m_c.a;\quad S_2 = c_2 h_2;$$

$$S_c = 2c\frac{m_c^2}{m_a};\ a = \sqrt{\frac{S_c}{2m_a}}$$

$$H = 2a + n_{e1} c_1 + n_{e2} c_2 + X_w;$$

$$A = 4a + 2c + 2c_1;\ B = b + 2c_1$$

The resulting expressions take into account the minimum values of the coefficients n_{e1} and n_{e2}, the specified values of the overheating temperature τ_1 and τ_2, the working stroke x_w, the load current I_1, the condition for fulfilling the uniformity of the magnetic field in the working air gap m_a=2÷6 and m_c=2÷6.

Table 2. The values of the coefficients M_m and M_a

m_c	m_a					
	2	3	4	5	6	M_m, M_a
2	0.57346	0.53438	0.51834	0.51058	0.50650	M_m
	0.93837	0.91692	0.91414	0.91672	0.92089	M_a
3	0.59482	0.53044	0.49976	0.48214	0.47085	M_m
	0.95306	0.89554	0.87019	0.85682	0.84895	M_a
4	0.60822	0.52824	0.48910	0.46607	0.45096	M_m
	0.96209	0.88286	0.84481	0.82286	0.80874	M_a
5	0.61741	0.52685	0.48220	0.45574	0.43828	M_m
	0.96821	0.87448	0.82827	0.80099	0.78307	M_a
6	0.62410	0.52590	0.47737	0.44854	0.42948	M_m
	0.97262	0.86852	0.81665	0.78573	0.76525	M_a

Table 3. Dependences of LE parameters on overheating temperature

Parameter	ρ_{20}, Om·m	τ_2, °C			
		80	90	100	110
$\rho_2 \times 10^{-8}$ Om·m	1.72×10^{-8}	2.420	2.494	2.567	2.642
$\rho_2/\tau_2 \times 10^{-12}$		302.50	277.10	256.70	240.18
E_m		6.8323	6.2584	5.7977	5.4246
$\rho_2 \times 10^{-8}$ Om·m	2.87×10^{-3}	4.015	4.135	4.256	4.376
$\rho_2/\tau_2 \times 10^{-12}$		501.890	459.510	425.620	397.880
E_m		1.7226	1.5771	1.4608	1.3652

Table 4. Values n_{e2} for LE from Copper and Aluminum at τ=80 °C and n_p=1

m_c	Material	m_a				
		2	3	4	5	6
2	Al	3.91790	3.65088	3.54131	3.48834	3.46043
	Cu	0.61588	0.57895	0.57416	0.57859	0.58578
3	Al	4.06385	3.62398	3.41436	3.29402	3.21689
	Cu	0.64117	0.54211	0.49848	0.47544	0.46189
4	Al	4.15540	3.60899	3.34158	3.18420	3.08100
	Cu	0.65672	0.52029	0.45476	0.41696	0.39266
5	Al	4.21818	3.59949	3.29443	3.11363	2.99433
	Cu	0.66725	0.50585	0.42629	0.37930	0.34845
6	Al	4.26390	3.59295	3.26141	3.06446	2.93424
	Cu	0.67486	0.49560	0.40628	0.35303	0.31777

4. DETERMINATION OF THE OPTIMAL VALUES FOR THE DIMENSIONS OF THE MAGNETIC CORE

The cross-sectional area of the middle rod S_c=2ab is known from the preliminary calculation and it is a constant value, since it is determined through the given values of the supply voltage and magnetic induction in steel. Taking into account the constancy of S_c, we determine the optimal values of the dimensions of the magnetic core rods a and b. In this case, the cross-sectional perimeter Π_c acquires a minimum value. Insofar as:

$$\Pi_c = 2(2a+b) = 2a(1+m_a)+2a = N_c\sqrt{2S_c} \tag{18}$$

$$S_c = 2ab$$

$$a = \sqrt{\frac{S_c}{2m_a}} = \frac{\sqrt{2S_c}}{2\sqrt{m_a}} \quad , \; b = \sqrt{S_c\frac{m_a}{2}}$$

$$N_c = \frac{2+m_a}{\sqrt{m_a}} \tag{19}$$

then, using the derivative of N_c from m_a we get:

$$\frac{dN_c}{dm_a} = \frac{d}{dm_a}\left(\frac{2+m_a}{\sqrt{m_a}}\right) = 0$$
$$\sqrt{m_a} - \frac{2+m_a}{\sqrt{m_a}} = 0 \tag{20}$$

from the last expression, we determine the optimal value of the coefficient m_a=b/a=2. When m_a=2, the value of Π_c=Π_{smin}, since in this case N_c=N_{smin}.

$$N_{c\min} = \frac{2+2}{\sqrt{2}} = 2.828$$
$$\Pi_{c\min} = 2.828\sqrt{2S_c} = 4.073\sqrt{S_c} \tag{21}$$

then, the optimal values of the dimensions a and b are determined as:

$$a = \sqrt{\frac{S_c}{2m_a}} = \sqrt{\frac{S_c}{2\cdot 2}} = \sqrt{0.25S_c}$$

$$b = \sqrt{S_c\frac{m_a}{2}} = \sqrt{S_c}$$

If we set m_a=1 and m_a=4, then in both cases we get N_c=3. Figure 3 shows graphs of functional dependencies $N_c(m_a)$ and Π_c (m_a). At m_a=2, the active resistances of the EW and LE will also be minimal. As a result, active power losses will be reduced to a minimum.

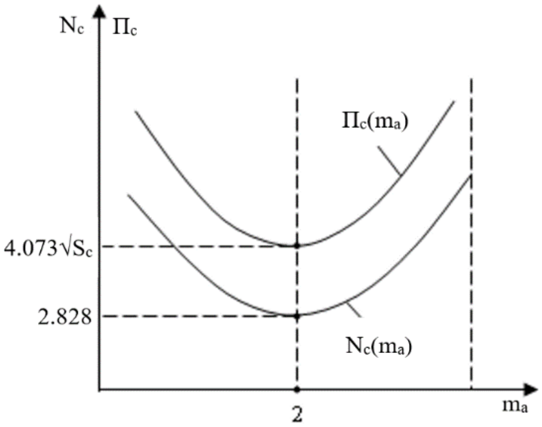


Figure 3. Graphs of functional dependencies N_c (m_a) and $\Pi_c(m_a)$

5. CONCLUSIONS

A generalized method for designing EA with LE with different functional purposes has been developed. Taking into account the design tasks, a mathematical model was compiled based on the parameters of the current modes and forces. Dimensionless quantities and main dimensions of the magnetic system are determined from the mathematical model. By minimizing the dimensionless quantities, the conditions for the thermal stability of the LE and the specified limitation of the overall dimensions of the magnetic system are satis fied. For LE made of copper and aluminum, the numerical values of dimensionless quantities are determined, on the basis of which reference tables are compiled that are necessary for designing EA with LE. The obtained analytical expressions for the main dimensions take into account the specified values of the winding overheating temperature, input and output parameters, and the condition for fulfilling the uniformity of the magnetic field in the working air gap. The optimal values of the dimensions of the magnetic core are determined, at which the perimeter of the cross section of the middle rod acquires a minimum value. In this case, the active resistances of the EW and LE will also be minimal. This leads to minimization of active power losses.

NOMENCLATURES

1. Acronyms

EW: Excitation Winding
LW: Levitation Winding
LE: Levitation Element
ED: Electric Devices
CW: Control Winding

2. Symbols / Parameters

I : Winding Current
Π_c: Cross-Sectional Perimeter
S_c: Cross-Sectional
τ : Winding's Temperature
n_{e2}: Dimensionless Value
P_x: External Forces

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BIOGRAPHY

Najiba M. Piriyeva was born in the Kurdamir, Azerbaijan, in 1973. In 1993, she entered the Energy Department of the Azerbaijan State University of Oil and Industry. She received her bachelor's degree in 1997 and her master's degree in 1999. Since 2003 she has been working as a teacher at the Department of Electromechanics. In 2017, she successfully defended her dissertation on the topic "Optimization of the levitation elements of single-phase levitators" and received a Ph.D. in engineering. Since then, she has been working as an assistant at the Department of Electromechanics. She is the author of 59 scientific papers, 4 of which are textbooks. Married, has two children.