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ELECTROMAGNETIC CALCULATION OF TENSION DEVICES FOR WINDING WIRES OF SMALL CROSS SECTIONS

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Abstract- The main unit of devices for tensioning wires of small cross-section are tracking systems with levitation screens, which allows to accurately stabilize the tension forces of wires during winding operations in the production of coils. To study the characteristics and calculate the main parameters of the tracking system, a mathematical model is compiled that takes into account the movement, overheating temperature and current density of the levitation screen. The thickness and dimensions of the working air gap can be determined considering the depth of penetration of the electromagnetic wave into the levitation screen. The relationship between the parameters are established, which is represented through generalized functional dependencies. They clearly show the regularities of the size change from the dimensionless values of the magnetic core and the ways to determine the optimal parameters of the tracking system.

Keywords: Tracking System, Tensioners, Levitation Screen, Driving Converter Receiving Transducer, Mathematical Model, Generalized Functional Dependencies, Screen and Magnetic Core Sizes.

1. INTRODUCTION

The tension of tape or long materials is one of the most common technological parameters that determine the quality characteristics of products obtained by winding in electrical, paper, textile, as well as in other industries [1-5]. One of the conditions for high-quality winding and increasing the winding speed when performing winding work in the process of preparing coils is to maintain a constant wire tension during the winding process [6]. Some devices, such as superconducting magnets, use winding wire windings with a diameter of less than (0.06-0.08) mm.

For such devices, a certain active resistance of the winding is provided. In the process of winding with small diameters of the winding wire, the tension of the wire significantly affects the value of this resistance. When the wound wire passes from the edge to the edge of the rectangular frame, a sharp change in the wire tension occurs. This can lead to a wire break; for this, a device for stabilizing the wire tension during operation is used. As such a device, a tension stabilizer for long products is used, which works on the principle of a tracking system with levitation screens (TSLS), which gives high accuracy in controlling the tension of the wire [14].

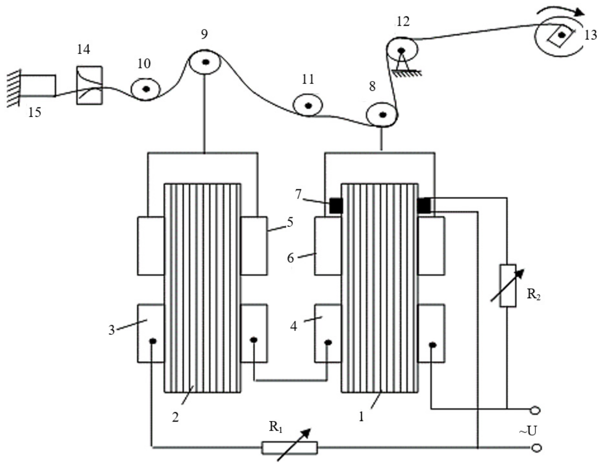

Figure 1. Schematic diagram of the device for precise stabilization and regulation of the tension force of the wires during winding on the frame

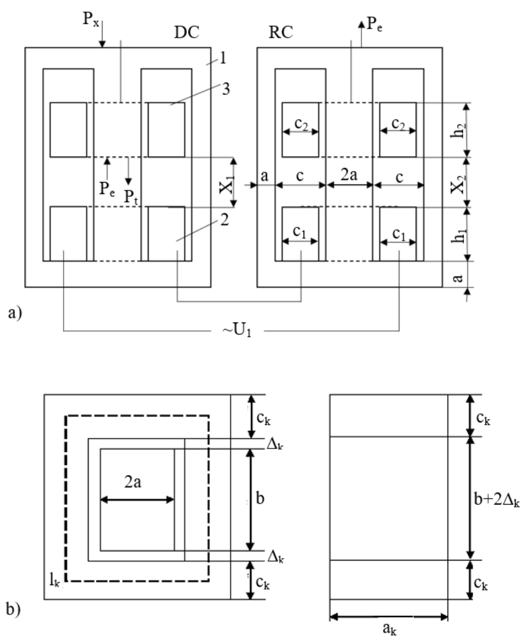

Figure 2. (a) Schematic diagrams of SLE and (b) solid aluminum LE

The advantage of the tension device we are considering over others is the absence of friction between the elements of the TSLS and the unambiguous relationship between the output and input signals. The tracking system under consideration (Figure 1) includes a master and receiving converter (MC and RC).

Each of these converters consists of a magnetic circuit 1 located vertically with a stationary excitation winding (EW) 2 and a levitation screen (LS) 3. The excitation windings 2 of MC and RC are connected in series and are powered by a power frequency voltage source ω=314s^{-1}. The dimensions of the MC and RC are the same, and the magnetic core is made of sheet electrical steel, and the levitation screen is in the form of a rectangular frame made of aluminum (Figure 2) [14].

2. PROBLEM STATEMENT AND MATHEMATICAL MODEL OF A TRACKING SYSTEM WITH LEVITATION ELEMENTS

In works [7-11], devoted to AC stabilizers, force, and displacement converters, as well as insulation thickness meters, the issues of the theory, calculation and application of TSLS are not considered. The need for this arises when there is a need to use TSLS for tensioning devices and remote transmission of movements and forces to working mechanisms. Currently, there is no optimization and calculation of the electromagnetic parameters of the tracking system with a levitation screen. In this paper, considering the depth of penetration of the electromagnetic wave into the levitation screen, the main dimensions are determined, as well as the thickness of the working air gap. As we know (6), the penetration depth of an electromagnetic wave into an aluminum levitation screen at a supply voltage frequency of 50 Hz is about 14 mm. Therefore, the maximum operating air gap must be determined from these conditions [14]. To calculate the parameters of the TSLS of magnetic systems MC and RC, it is necessary to make mathematical models and calculation algorithms. When drawing up a mathematical model, we take into account the following features and assumptions for the calculation of the TSLS:

1) Magnetic systems MC and RC have the same dimensions and in the absence of an external force P_{x1}, the levitation height of the LS X_1 and X_2 are equal. Because of this, the inductors L_1 and L_2, the voltage U' and U'' of the excitation winding at P_{x1} = 0 is also equal.

2) When moving the power line MC up from the external force P_{x1}, the power line RC moves down. In this case, the inductance L_1 and the voltage U' increase, and the inductance L_2 and the voltage U'' decrease. Therefore, the steady - state value of the current I_1 in the FW remains constant. The constancy of the current I_1 leads to a constancy of the lifting force F_e acting on the power line. In this case, the tension force is equal to the force F_e.

3)The steady-state values of the overheating temperature of the excitation windings and the power lines τ_1 and τ_2 of the converters depends on the current value I_1, therefore, at I_1=const, they are also constant.

4) In the working air gap between the parallel rods of the magnetic circuit, the magnetic field is uniform and the conditions $m_a=b/a=1\div6$ and $m_c=b/c=1\div6$ is met.

5) The currents and voltages are sinusoidal and the magnetic resistances of the steel sections are negligible compared to the magnetic resistances of the air sections.

Taking into account the above mentioned, we will present the mathematical model of the TSLS in the following form:

$$F_e = P_T - P_{x1};\; F_e = 0.5\lambda F_1^2 \tag{1}$$

$$L_1 = \lambda(X_1 + h_0)W_1^2 \tag{2}$$

$$U' = \omega F_1 \lambda(X_1 + h_0) \tag{3}$$

$$\Phi'_M = \sqrt{2}k_u \cdot \lambda F_1(X_1 + h_0)/\omega \tag{4}$$

$$F_e = P_T + P_{x1};\; F_e = 0.5\lambda F_1^2 \tag{5}$$

$$L_2 = \lambda(X_2 + h_0)W_1^2 \tag{6}$$

$$U'' = \omega F_1 \lambda(X_2 + h_0) \tag{7}$$

$$\Phi''_M = \sqrt{2}k_u \cdot \lambda F_1(X_2 + h_0)/\omega \tag{8}$$

$$I_1 = \frac{k_u U}{\omega(L_1 + L_2)} \tag{9}$$

$$\tau_1 = \frac{P_1 + P_2}{k_T S_{T1}};\; \tau_2 = \frac{P_2}{k_T S_{T2}} \tag{10}$$

$$F_1 = j_1 k_{31} S_1;\; F_1 = j_2 k_{32} S_2 \tag{11}$$

$$F_2 = b_2 F_1 \tag{12}$$

$$P_1 = I_1^2 R_1;\; P_2 = I_2^2 R_2 \tag{13}$$

$$L_1 + L_2 = \lambda(x_{12} + 2h_0)W_1^2 \tag{14}$$

where,

$$x_{12} = x_1 + x_2;\; h_0 = \frac{h_1}{3};\; h_1 = h_2$$
$$F_1 = I_1 W_1;\; F_2 = I_2 W_2 \tag{15}$$

Equations (1), (2), (3) and (4) refer to MC, and Equations (5), (6), (7) and (8) refer to RC. Expressions (9), (10), (11), (12), (13), (14) and (15) refer to both converters. For aluminum power lines k_{32}=1; W_2=1; F_2=I_2= =$b_2I_1W_1$.

The main dimensions of the power line are its thickness c_2, height h_2 and width a_k. When determining the size of a_k, it is convenient to use the well-known expression [5] for the complex magnetic resistance of the LS:

$$\underline{Z}_{MK} = \frac{j\omega W_2^2\sqrt{2}}{r_k + jx_k}.$$

where, r_k, x_k are the active and inductive electrical resistances of the power line. The resistance r_k depends on the overheating temperature τ_2, but the resistance x_k depends on the levitation coordinate X. As can be seen from the formula (1), the lifting force is determined through the specific magnetic conductivity of the working air gap λ and the size of the magnetic system. Thus, there is a complex relationship between the parameters of electric and magnetic circuits, as well as between given external force P_x, and the overheating temperature τ_1 and τ_2. Therefore, unknown parameters can be determined by a joint solution of Equations (1)-(14).

3. DETERMINATION OF THE MAIN PARAMETERS

If there is no external force (P_x=0), and the FW inductances are equal, then through the working stroke x_p of the LS, according to (2), it is possible to determine:

$$L_1 = L_2 = \lambda W_1^2 (x_p + h_0) \quad (16)$$

where, W_1 is the number of turns of the FW; λ is specific magnetic permeability.

The specific magnetic permeability of the air gap, taking into account the scattering of magnetic fluxes, can be found from the formula:

$$\lambda = 2\mu_0 m_c \sigma_a \quad (17)$$

where, μ_0 =1.256×10^{-6} Hn/m; m_a=b/a; m_c=b/c; σ_a is the scattering ring coefficient of the magnetic circuit:

$$\sigma_a = 1 + 2.92 1\mathrm{g}(1 + \frac{\pi}{m_c}) \quad (18)$$

According to (9), the current in the FW is determined by:

$$I_1 = \frac{k_u U_1}{\omega(L_1 + L_2)} = \frac{k_u U_1}{2\omega L_1}$$

From here, through the parameters of the FW that we know, the inductance is found:

$$L_1 = \frac{k_u U_1}{2\omega I_1} \quad (19)$$

From (16) and (17) we obtain the identity:

$$\frac{x_p + h_0}{U_1} = \frac{k_u}{2\omega\lambda I_1 W_1^2} \quad (20)$$

Since I_1=const, then the right side of Equation (19) is also a constant value. Therefore, the fractional value when the voltage U_1 changes remains constant, but as the voltage U_1 increases, the stroke x_p decreases or increases. This feature of the tracking system is an important property of the driving converter [9-14]. The number of turns of the FW can be determined from the following expression:

$$W_1 = \frac{k_u U_1 \sqrt{2}}{\omega B_M S_c} \quad (21)$$

where, k_u is the coefficient taking into account the decrease in U_1 with the active resistance of the FW; U_1 is the effective value of the voltage at the FW terminals; B_M is maximum value of magnetic induction in steel; S_c=2ab is cross sectional area of the magnetic core (middle rod) ω=2πf=314 s^{-1} [14].

The excitation windings of the MC and RC are connected to each other in accordance with each other in series, in connection with this, the voltage at the terminals of each FW is 0.5U_1. Then, Equation (21) can be rewritten:

$$W_1 = \frac{k_u U_1 \sqrt{2}}{2\omega B_M S_c} \quad (22)$$

The inductance of the excitation winding, taking into account (1) and (2), is written as follows:

$$L_1 = 2\mu_0 m_c \sigma_a (x_p + h_0) W_1^2 \quad (23)$$

In addition to the expression (23), one more expression can be written for the inductance of FW:

$$L_1 = \frac{k_u 0.5 \times U_1 \sqrt{2}}{\omega I_1} = \frac{k_u U_1}{\omega I_1 \sqrt{2}} \quad (24)$$

Then from (23) and (24) for number of turns of FW we get:

$$W_1^2 = \frac{m_1}{m_2 I_1 m_c \sigma_a \sqrt{2}} \quad (25)$$

where are indicated:

$$m_1 = \frac{k_u U_1}{2\omega} \quad (26)$$

$$m_2 = \mu_0 (x_p + h_0) \quad (27)$$

The resulting Equations (25)-(27) clearly show the dependence of the number of turns W_1 on the known values of the parameters U_1, ω, x_p, h_0 and I_1. From (25) it follows that in order to improve the calculation accuracy, it is necessary to calculate the scattering coefficient σ_a and the dimensionless quantities m_a=b/a and mc=b/c [14]. Let us determine the cross-sectional area of the middle rod of the magnetic circuit:

$$S_c = 2ab = 2c^2 \frac{m_c^2}{m_a} \quad (28)$$

Substituting (28) into (22), we obtain the expression for $W_1(m_1, m_a, B_M, c)$:

$$W_1 = \frac{m_{1u} m_a \sqrt{2}}{B_M c^2 m_2^2 2} = \frac{m_1 m_a}{B_M c^2 m_c^2 \sqrt{2}} \quad (29)$$

$$W_1^2 = \left[\frac{m_1 m_a}{B_m c^2 m_2^2 \sqrt{2}} \right]^2 \quad (30)$$

According to (25) and (30), we obtain the identity:

$$\frac{m_1}{m_2 I_1 m_c \sigma_a \sqrt{2}} = \left[\frac{m_1 m_a}{B_M c^2 m_c^2 \sqrt{2}} \right]^2$$

From here we find the functional dependence with (I_1, m_a, m_c):

$$c = k_m \sqrt[4]{I_1 \sqrt[4]{\frac{m_a^2}{m_c^3}} \left[1 + 2.92 \log(1 + \frac{\pi}{m_a}) \right]} \quad (31)$$

where, k_m is defined through the specified parameter values in the design task:

$$k_m = \sqrt[4]{\frac{m_1 m_2}{B_m^2 \sqrt{2}}} \quad (32)$$

After determining the thickness of the working gap, calculate the size of the magnetic circuit (a and b), area (S_c) and the number of turns:

$$b = m_c c; \quad a = \frac{b}{m_a}; \quad S_c = 2ab \quad (33)$$

$$W_1 = \frac{0.5 U_1 k_u \sqrt{2}}{\omega B_M S_c} = \frac{m_1 \sqrt{2}}{B_m S_c} \quad (34)$$

4. INVESTIGATION OF THE RELATIONSHIPS BETWEEN THE PARAMETERS

To illustrate the calculation method, let's consider a tracking system with a LS, which has the following technical design tasks: the voltage at the terminals of the FW U_1=220 V, the current frequency f=50 Hz, the current value in the FW I_1=1.5 A. The height of the FW h_1=30 mm, the height of the LS h_2 = 21 mm, the working stroke x_p=40 mm. We define:

$$m_1 = \frac{k_u U_1}{2\omega} = \frac{0.9\times 220}{2\times 314} = 315.286\times 10^{-3}$$

$$m_2 = \mu_0(x_p + h_0) = 1.256\times 10^{-6}(40+10+7)\times 10^{-3} = 71.592\times 10^{-9}$$

$$m_1\cdot m_2 = 315.286\times 10^{-3}\times 71.592\times 10^{-9}$$

$$\sqrt[4]{\frac{m_1 m_2}{B_m^2\sqrt{2}}} = \sqrt[4]{\frac{22.5719}{1.4^2\sqrt{2}}}10^{-6} = 9.499\times 10^{-3} \qquad (35)$$

According to (31) and (35), we obtain the calculation formula for the functional dependence with (I_1, m_a, m_c):

$$c = 9.499\times 10^{-3}\times\sqrt[4]{I_1}\sqrt[4]{\frac{m_a^2}{m_c^3}\left[1.292\log\left(1+\frac{\pi}{m_a}\right)\right]} \qquad (36)$$

The calculated values of the thickness c at the current value I_1=1.5 A are shown in Table 1. The calculation was made using the EXCEL program.

Table 1. Values of size c in millimeters

m_a \ m_c	1	2	3	4	5	6
1	13.60046	18.099786	21.400335	24.129150	26.511384	28.656013
2	8.086886	10.762197	12.724716	14.347278	15.763763	17.038967
3	5.966407	7.940219	9.388142	10.585249	11.630315	12.571145
4	4.808491	6.399241	7.566161	8.530943	9.373190	10.131431
5	4.067488	5.413099	6.400193	7.216299	7.928753	8.570147
6	3.547647	4.721283	5.582222	6.294027	6.915426	7.474847

Figure 3 shows dependence graphs c (m_a; m_c) according to the calculated values of the c dimension. At the same time, taking into account condition $c_2 \leq 14$ mm (or $c \leq 15$ mm) from Table 1, we select the values c and the corresponding values of the graphic coefficient's m_a and m_c. For example, we choose c=14.347 mm, while finding m_a=4; m_c=2, c_2=13.347 mm. To analyze the relationship between the parameters, consider the following calculation options. Option A. m_a=const; m_c=var. Option B, m_c=const and m_a= var.

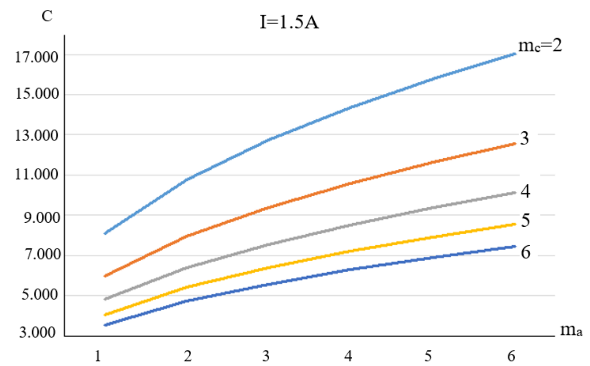

Figure 3. Graphs of dependence with c (m_a; m_c)

Let's consider the calculation of the options separately:
1) m_a = const; m_c = var; c = 14.347 mm; m_a = 4; m_c = 2.
We are counting on: $b = m_c\times c$=2×14.347 mm=28.694 mm;
$a = b/m_a$ = 28.694/4 = 7.173 mm;
$S_c = 2ab$ =411.672×10^{-6} m^2;

$$W_1 = \frac{m_1\sqrt{2}}{B_M S_c} = \frac{315.286\times 10^{-3}}{1.4\times 411.672\times 10^{-6}} = 547$$

2) m_a = const; m_c = var; c=10.585 mm; m_a = 4; m_c = 3.
We are counting on: $b = m_c\times c$ = 31.755 mm =28.694 mm;
$a=b/m_a$ = 7.938 mm;

$$S_c = 2ab = 504.19\times 10^{-6}\,\mathrm{m}^2;$$

$$W_1 = \frac{m_1\sqrt{2}}{B_M S_c} = 631.166\,\mathrm{mm}$$

3) m_c = const; m_a = var; c=15.764 mm; m_a = 5; m_c = 2.
We are counting on: $b = m_c\times c$ = 31.528 mm;
$a=b/m_a$ =6.305 mm;

$$S_c = 2ab = 397.605\times 10^{-6}\,\mathrm{m}^2$$

$$W_1 = \frac{m_1\sqrt{2}}{B_M S_c}$$

4) m_c = const; m_a = var; c=17.039 mm; m_a = 6; m_c = 2.
We are counting on: $b = m_c\times c$ = 34.078 mm;
$a=b/m_a$ = 5.67 mm;

$$S_c = 2ab = 387.103\times 10^{-6}\,\mathrm{m}^2;$$

$$W_1 = \frac{m_1\sqrt{2}}{B_M S_c} = 822.736\text{ mm.}$$

Analyzing the above calculations, we can say that there are a number of relationships between the parameters that can be represented by generalized functional dependencies Π_1 (m_c), Π_2 (m_c), Π_3 (m_a) and Π_4 (m_a) [14].
Figure 4 shows the corresponding dependencies, with m_a=const with m_c=const with m_a=var.

These dependencies can be defined as follows:
Π_1 (m_c) – a; b; S_c; W_1 and Π_2 (m_c)·c
Π_3 (m_c) – b; c; W_1 and Π_4 (m_a) – a; S_c.

An increase in the coefficient m_c under the condition m_a=const leads to an increase in the dimensions a and b, the number of loops W_1 and the area S_c. In this case, the thickness c decreases. Taking into account these regularities, it is not difficult to choose the optimal values of dimensions and parameters. But under the condition m_c=const, an increase in m_a also leads to an increase in the dimensions (c and b) and the number of turns W_1, and to a decrease in the size (a) and the cross-section S_c [14].

The tracking system with levitation screens allows you to accurately stabilize the tension forces of the wires during winding during the production of coils and is the main unit of the devices. A mathematical model has been compiled for calculating the main parameters, as well as studying the characteristics taking into account the displacement, overheating temperature and current density of the levitation screen.

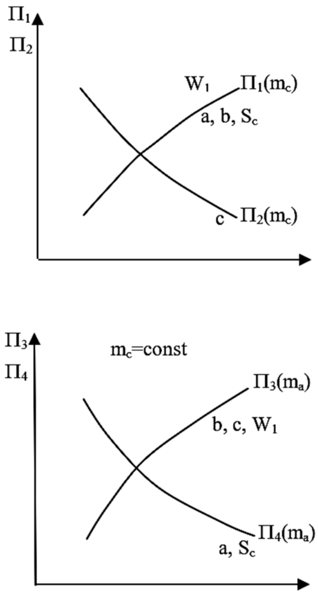

Figure 4. Generalized functional dependencies $\Pi_1(m_c)$, $\Pi_2(m_c)$, $\Pi_3(m_a)$ and $\Pi_4(m_a)$ for the cases m_a = const for m_c = const for m_a = var

The relationship between the parameters through generalized functional dependencies for the regularity of changes in dimensions from the dimensionless values of the magnetic circuit is presented. The ways of determining the optimal parameters of the tracking system are established.

5. CONCLUSIONS

To study the characteristics and calculate the main parameters of the tracking system of the tensioning device, a mathematical model has been compiled that takes into account the displacement, overheating temperature and current density of the levitation screen. The thickness and dimensions of the working air gap take into account the absorption of the electromagnetic wave in the levitation screen and the magnetic scattering of the magnetic circuit. The obtained formulas take into account the parameters that are specified in the terms of reference for the design of a TSLS.

Generalized functional dependences of the parameters on a number of dimensionless quantities are obtained. The optimal values of the levitating screen and the magnetic circuit depend on the values of the current in the excitation coil and the dimensionless values of the magnetic circuit.

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BIOGRAPHIES

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