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Electromagnetic efficiency in induction levitators and ways to improve it

***Abstract**. 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.*

***Streszczenie.** Urządzenia elektrotechniczne z elementem lewitacyjnym mają szerokie zastosowanie w automatyzacji procesów produkcyjnych ze względu na swoją prostą konstrukcję, dużą dokładność i niezawodność. W procesach automatyzacji procesów technologicznych często wymagane jest automatyczne sterowanie położeniami ruchomych części mechanizmów roboczych za pomocą siły zewnętrznej i napięcia prądu przemiennego. W takich przypadkach konieczny staje się również pomiar siły zewnętrznej, ustabilizowanie prądu na zmiennym obciążeniu i uzyskanie kilku nominalnych wartości prądu na obciążeniu. Pomimo prostoty konstrukcji lewitatorów indukcyjnych (IL) są one skuteczniej zaangażowane w rozwiązywanie tych problemów, pod działaniem wydajności lewitatora indukcyjnego nie występują siły tarcia, skok roboczy części ruchomej jest kontrolowany automatycznie i dodatkowe elementy nie są wymagane (**Sprawność elektromagnetyczna w lewitatorach indukcyjnych i sposoby poprawy**)*
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Keywords: method, levitation element, electromagnetic efficiency, induction levitator, power, current, source, levitation winding, excitation winding, control system.
Słowa kluczowe: metoda, element lewitacji, sprawność elektromagnetyczna, lewitator indukcyjny, moc, prąd, źródło, uzwojenie lewitacji, uzwojenie wzbudzenia, układ sterowania.

Introduction

From the scientific and technical literature, the areas of application of induction levitators (IL) are known:
- supply of galvanic baths with stabilized currents;
-control of the insulation thickness during the winding process;
- stabilization of the tension force of wires of small sections during winding;
-support for controlling the vertical position on the frame of working mechanisms;
- tracking system for remote transmission of movements and efforts of the working mechanism;
- controlled system for light-beam soldering, etc.

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 (e.g.mechanical springs, guides, gearboxes, bearings, etc.).

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 [1-20].

Statement and solution of the problem..

The design of a simple induction levitator consists of a stepped magneto wire, a fixed excitation winding and levitation elements. On the basis of this, the induction levitator (IL), composed in different directions of electrical devices, additional windings (output and compensation windings) are located in the magnetic circuit. Levitation element consist of a short-circuited copper winding or a short-circuited aluminum frame. To improve the characteris tics of the induction levitator (figure 1a) used as an electrical control device for automation, it is necessary to increase its electromagnetic efficiency. For this purpose, the work determines and analyzes the quality factor of the induction levitator, considers ways to increase the electromagnetic efficiency.

Based on the law of conservation of energy for an induction levitator (IL) in a steady state, we can write [1,2]:

$$\oint_S \left[\bar{E} \times \bar{H}\right] dS = \int_V \bar{H} \frac{\partial B}{\partial t} dV + \int_V \sigma \bar{E}^2 dV \quad , \qquad (1)$$

where the closed surface *S* limits the volume *V* of the electromagnetic circuit of the system.

The left side of equation (1) represents the electromagnetic power entering the system from the network through the surface *S*. Inside the volume *V*, this power is divided into two components [11-13]. Magnetic power:

$$P_M = \int_V \bar{H} \frac{\partial B}{\partial t} dV \ , \qquad (2)$$

expressing the change in magnetic energy over time:

$$P_M = \frac{\partial W_m}{\partial t} \qquad (3)$$

and electrical power:

$$P_e = \int_V \sigma \bar{E}^2 dV \qquad (4)$$

going to cover P_e losses in circuits with currents. On the basis of this, the induction levitator (IL), like any other electromagnetic device, can be represented in the form of two interconnected circuits - electric and magnetic. A universal quantity characterizing the useful output of an electromagnetic device is the electromagnetic efficiency, which is determined by the ratio of the magnetic power entering the system to the power of electrical losses :

$$\eta_{EM} = \frac{P_M}{P_e} = \frac{\int_V \bar{H} \frac{\partial B}{\partial t} dV}{\int_V \sigma \bar{E}^2 dV} \qquad (5)$$

After a series of transformations, we get:

(6) $$\eta_{EM} = \frac{1}{iR} \times \frac{di}{dt},$$

where R and L are the active resistance and inductance of the electrical circuit of the system, and i - is the current flowing through it.

It should be noted that the increment in magnetic energy is equivalent to perfect mechanical work [5-7], ie.

(7) $$dW_m = dW_{mex} = f_e dx$$

Therefore, electromagnetic efficiency also characterizes the ratio of mechanical power to electrical losses:

(8) $$\eta_{EM} = \frac{f_e}{P_e} \times \frac{dx}{dt}$$

If the current in the electric circuit is a sinusoidal function of time $i=I_m \sin(\omega t+\varphi)$, then it follows from (6) that :

(9) $$\eta_{EM} = \frac{\omega L}{R} ctg(\omega t+\varphi) = \frac{x}{R} ctg(\omega t+\varphi)$$

those. electromagnetic efficiency proportional to the quality factor of the electrical circuit:

(10) $$Q = \frac{\omega L}{R}$$

If we imagine the induction levitator as a magnetic system consisting of two interlocked electric and magnetic circuits, then the quality factor can be determined through a simple formula :

(11) $$Q = \omega G_M G_e$$

The conductivity of the electrical G_e and magnetic G_M loops are defined as:

(12) $$G_M = \mu \frac{S_M}{l_M}; G_e = \sigma \frac{S_e}{l_e},$$

where σ and μ are specific electrical and magnetic conductivity; l_e, l_m, S_e and S_m are the lengths and cross-sectional areas of the electric and magnetic circuits.

For the simplest electromagnetic system, which is a coil of W turns on a closed ferromagnetic core, the length l_m and the cross-sectional area S_m of the magnetic circuit coincide with the length l_c and the area S_c of the core section [10-17]. As for the electric circuit, its length l_e and cross-sectional area S_e are determined in the form:

(13) $$l_e = \frac{l_{wire}}{W}; S_e = S_{wire} W$$

Where l_c and S_c are the length and cross-section of the coil wire.Considering the induction levitator as a single-loop system with equivalent active $R_1=r_1+r_{1n}$ and inductive resistances $x_1=x_{11}-x_{1n}$, its quality factor can be represented as [4]:

(14) $$Q = \frac{x_1}{R_1} = \frac{x_{11} - x_{1n}}{r_1 + r_{1n}}$$

If we neglect the scattering of the excitation winding (EW) and levitation winding (LW), instead of (14) we get:

(15) $$Q = \frac{Q_1 - k^2 \frac{x_{22}}{r_1} Q_2^*}{1 + k^2 \frac{r_2}{r_1} Q_2^*}$$

where $k=W_1/W_2$; $Q_1=x_{11}/r_1$ -quality factor excitation winding; $Q_2=x_{22}/r_2$ -quality factor levitation windings; $Q_2^* = \frac{Q_2^2}{1+Q_2^2}$.

Quality factor excitation winding Q_2 is a function of the coordinates of the levitation of the levitation windings x, therefore the quality factor of the induction levitator Q also depends on x. If we take into account $r_{1n}=k^2 r_2$, which according to (14) and (15) corresponds to the expression for the quality factor Q at $x=0$, then from (15) we obtain :

(16) $$Q = \frac{Q_1 + Q_1 Q_2^2 - Q_2^2}{1 + 2Q_2^2}$$

Using expression (16) for the excitation current and electrodynamic force, one can write:

(17) $$I_1 = \frac{U_1}{r_1} \times \frac{1 + Q_2^2}{\sqrt{\left(1 + 2Q_2^2\right)^2 + \left(Q_1 + Q_1 Q_2^2 - Q_2^2\right)^2}}$$

(18) $$F_e = \frac{1}{2}\left(I_1 W_1\right)^2 \lambda \times Q_2^*$$

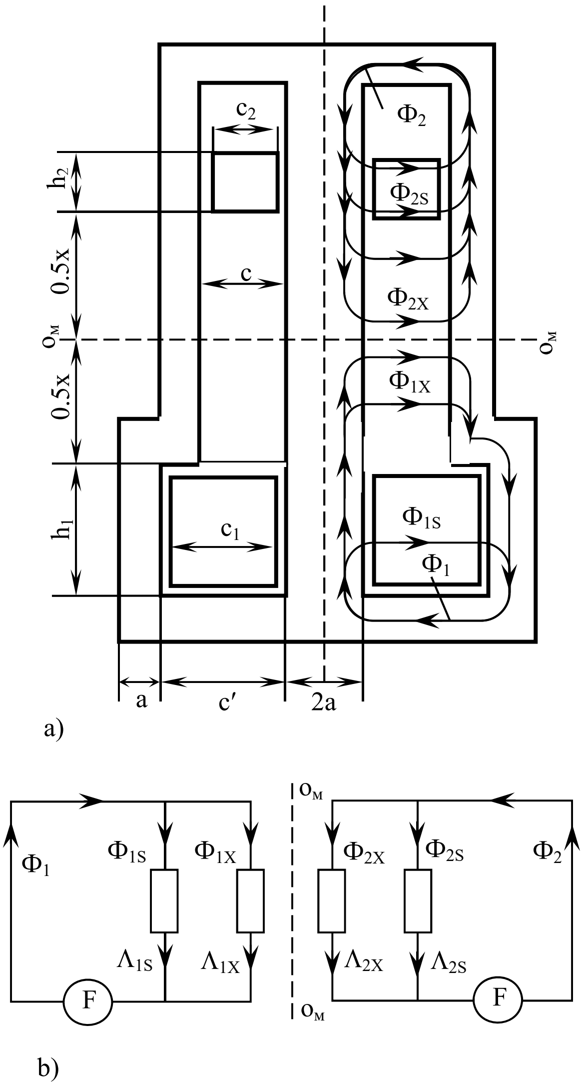

Figure 1. Generally accepted schemes for the distribution of magnetic fluxes (a) and the equivalent circuit of the magnetic circuit for an induction levitator (b).

It is quite obvious that of all possible device designs, the best one is the one with a higher quality factor *Q*. conductive and magnetic materials with high specific conductivity σ and μ. With a constant volume of the electromagnetic system, the most rational use of active materials takes place when the quality factor *Q* is maximum.

To determine the quality factors Q_1, Q_2 and Q ,we will compose the equivalent circuit of the induction levitator magnetic circuit (fiqure 1). The equivalent circuit is made according to the well-known scheme of distribution of magnetic fluxes in a two-winding transformer, where the line of separation of magnetic fluxes O_M (magnetic neutral) divides the interwinding distance *x* along the barks. The magnetic fluxes of the windings consist of leakage fluxes (Φ_{1s} and Φ_{2s}) which are closed with in the height of the windings (h_1 and h_2) and fluxes (Φ_{1x} and Φ_{2x}) passing through the (0.5*x)* sections. The corresponding magnetic conductivities along the path of the flows are denoted by Δ_{1s}, Δ_{1x} and Δ_{2s}, Δ_{2x}. Magnetic fluxes Φ_1 and Φ_2 are determined: $\Phi_1=F_1\Lambda_1$; $\Phi_2=F_2\Lambda_2$.

The resulting magnetic conductivity on the path of the fluxes Φ_1 and Φ_2 are defined as:

(19) $$\Lambda_1 = \Lambda_{1s} + \Lambda_{1x}\,; \Lambda_2 = \Lambda_{2s} + \Lambda_{2x}$$

Taking into account the distributed nature of the leakage fluxes of the windings Φ_{1s} and Φ_2 for their flux flows, one can write :

$$\psi_{1s} = \int_0^{h_1} \frac{W_1}{h_1} dy_1 d\Phi_{1s} = \frac{\lambda_s}{h_1^2} I_1 W_1 \int_0^{h_1} y_1 dy_1 = \frac{h_1}{3}\lambda_s I_1 W_1^2$$

$$\psi_{2s} = \int_0^{h_2} \frac{W_2}{h_2} dy_2 d\Phi_{2s} = \frac{\lambda_s}{h_2^2} I_2 W_2 \int_0^{h_2} y_2 dy_2 = \frac{h_2}{3}\lambda I_2 W_2^2$$

Where:

$$d\Phi_{1s} = \left(\frac{W_1}{h_1} I_1\right) \times \left(y_1 \lambda_s\right) dy_1\,; d\Phi_{2s} = \left(\frac{W_2}{h_2} I_2\right) \times \left(y_2 \lambda\right) dy_2$$

Then, to determine the leakage inductances of the windings, we can write:

(20) $$L_{1s} = \frac{\psi_{1s}}{I_1} = \mathrm{W}_1^2 \lambda_s \frac{h_1}{3}\,; L_{2s} = \frac{\psi_{2s}}{I_2} = \mathrm{W}_2^2 \lambda \frac{h_1}{3}$$

Specific magnetic conductivity of air gaps c' and c are determined from well-known formulas [7-9,18-20] :

(21) $$\lambda_s = 2\mu_0 \frac{b}{c'} \sigma'_b\,; \lambda = 2\mu_0 \frac{b}{c} \sigma_{\mathrm{b}}$$

Buckling coefficients σ_b' and σ_b depend on the dimensions of the magnetic circuit *a, b, c. c*′. Magnetic fluxes Φ_{1s},, Φ_{1x} ,Φ_{2s} and Φ_{2x} respectively, are determined from the expressions:

(22) $$\Phi_{1s} = F_1 \Lambda_{1s}\,; \Phi_{1x} = F_1\left(\frac{1}{2}\lambda x\right); \quad \Phi_{2s} = F_2 \Lambda_{2s}\,; \Phi_{2x} = F_2\left(\frac{1}{2}\lambda x\right)$$

The inductances of the windings are determined:

(23) $$L_1 = L_{1s} + L_{1x} = W_1^2 \lambda \left(\frac{h_1}{3n_\lambda} + \frac{1}{2}x\right)$$

(24) $$L_2 = L_{2s} + L_{2x} = W_2^2 \lambda \left(\frac{h_2}{3} + \frac{1}{2}x\right)$$

Accordingly, for the quality factors of the windings, we obtain:

(25) $$Q_1 = \frac{\omega}{r_1} W_1^2 \lambda \left(\frac{h_1}{3n_\lambda} + \frac{1}{2}x\right)$$

(26) $$Q_2 = \frac{\omega}{r_2} W_2^2 \lambda \left(\frac{h_1}{3n_\lambda} + \frac{1}{2}x\right),$$

where: $n_\lambda = \frac{\lambda}{\lambda_s} = \frac{c'}{c} \times \frac{\sigma_b}{\sigma'_b}\,; \mathrm{n}_\lambda > 1$

Resulting inductance and quality factor field winding:

(27) $$L = L_1 + k^2 L_2 = W_1^2 \lambda \left(\frac{h_1}{3n_\lambda} + \frac{h_2}{3} + x\right)$$

(28) $$Q = \frac{\omega L}{R} = \frac{\omega(L_1 + k^2 L_2)}{r_1 + k^2 r_2} = \frac{\omega W_1^2 \lambda}{r_1 + k^2 r_2}\left(\frac{h_1}{3n_\lambda} + \frac{h_2}{3} + x\right)$$

Current field winding is determined:

(29) $$I_1 = \frac{U_1}{\sqrt{R^2 + (\omega L)^2}} = \frac{U_1}{R\sqrt{1 + Q^2}} = \frac{U_1}{RQ},$$

where: *Q*>>1.

To increase the electromagnetic efficiency or quality factor, it is necessary to increase the specific magnetic permeability of the working air gap [15-18]. To do this, increase the values of the coefficients $m_a=b/a$ and $m_c=b/c$.

Conclusions

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.

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.

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