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INFLUENCE OF AN EXCITATION SOURCE ON THE POWER INDICATORS OF A LINEAR PULSE ELECTROMECHANICAL CONVERTER OF INDUCTION TYPE

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The purpose of the article is to evaluate the efficiency of an induction-type linear pulse electromechanical converter (LPEC) when operating in shock-power mode and excitation from an alternating voltage source (AVS) in comparison with excitation from a capacitive energy storage (CES). A mathematical model of an induction-type LPEC has been developed both when excited by a unipolar pulse from a CES and from an AVS using lumped parameters of the windings, which takes into account the interrelated electromagnetic, mechanical and thermal processes. It has been found that when the LPEC is excited from the AVS with a voltage frequency of 50 Hz, the electrodynamic force takes on a periodic decaying character with a significant prevalence of positive components of forces over negative ones. The maximum value of the force is much less, and the value of its impulse is much greater than in the LPEC, excited from the CES. With an increase in the frequency of the AVS voltage from 50 to 150 Hz, the highest value of the current density of the inductor winding decreases, and in the armature winding it increases. The greatest values of force and impulse of force are realized at a voltage frequency of 150 Hz. With an increase in the AVS frequency, the relative indicator of the efficiency of the LPEC increases. References 15, figures 4.
Key words: linear pulse electromechanical converter of induction type, mathematical model, alternating voltage source, capacitive energy storage, electromechanical processes and power indicators.

Introduction. Linear pulse electromechanical converters (LPEC), designed to create powerful force pulses on the target, are used in many branches of science, engineering and technology as shock-power devices. In construction, electromagnetic hammers and perforators are used, in the mining industry – cutters for crushing oversized objects and shock vibrators [1], in geological exploration – vibration-seismic sources, in mechanical engineering – hammers with a large range of impact energy [2] and devices for electrodynamic processing of welded compounds [3], in the chemical industry – magnetic-pulse presses for ceramic powders [4, 5], in the biomedical industry – vibrating mixers, in technological equipment – impact devices for cleaning process containers from the adhesion of bulk materials, in the electronics industry – devices for testing critical equipment for shock loads, etc. [6].

The most widely used LPEC of induction type of coaxial configuration [7, 8]. Capacitive energy storage (CES) with electronic devices that provide polar current in the inductor winding are mainly used as an excitation source for such converters [9]. However, such sources, as a rule, are charged to high voltage, which requires special equipment and increased safety measures for the service personnel. The duration of the force impact on the object is insignificant and is limited by the discharge time of the CES, which is undesirable for a number of technological operations [10]. Due to the significant value of the shock power impulse in the device, there is a significant return to the inductor winding, which reduces the efficiency and reliability of the shock device [11].

To increase the LPEC performance, various technical solutions were used, for example, an external ferromagnetic or electromagnetic screen [12, 13]. One of the ways to reduce these disadvantages is to change the shape of the current pulse using the electronic system of the excitation source [9]. At one time, for the excitation of an induction-type LPEC, an alternating voltage source (AVS) of increased frequency was considered [14]. However, such studies concerned the LPEC, operating as an electromechanical accelerator, when the time of effective interaction of the accelerated armature winding with the inductor winding is insignificant. When the LPEC operates in a shock-power mode with a small displacement of the actuator between the windings of the inductor and the armature, a strong magnetic connection is maintained during the working process. This allows you to increase the time of force impact on the object. But the question arises about the effectiveness of the force effect developed by the LPEC when it is excited from the AVS and the justification of the frequency of its voltage.

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The purpose of the article is to evaluate the efficiency of the induction-type LPEC when operating in the shock-force mode and excitation from the AVS in comparison with the excitation from the CES.

Mathematical model of LPEC. Consider an induction-type LPEC with a small displacement of the armature winding, interconnected with the actuator, in which the magnetic coupling between the windings changes slightly during the excitation of the inductor winding both from the CES and from the AVS of increased frequency. In the mathematical model of the LPEC, we use the lumped parameters of the fixed inductor winding and the movable armature winding, as used in [15]. To take into account the interrelated electrical, magnetic, mechanical and thermal processes in the LPEC, as well as a number of nonlinear dependences, for example, the resistance of the windings on temperature, the solutions of the equations describing these processes will be presented in a recurrent form. To calculate the indicators and time characteristics of the LPEC, we use a numerical-analytical algorithm of cyclic action. For this, the workflow is divided into a number of numerically small time intervals $\Delta t = t_{k+1} - t_k$, within which all values are considered unchanged. At each *k*-th cycle, using the parameters calculated at the time instant t_k as the initial values, the parameters are calculated at the time instant t_{k+1}. To determine the currents over the time interval Δt, we use linear equations with unchanged parameter values. We choose a small value of the calculated step Δt so that it does not have a significant effect on the calculation results on a computer, while ensuring the required accuracy.

We neglect the resistance of connecting wires and auxiliary equipment. We assume a strictly axial arrangement of multi-turn disk windings and axial movement of the armature winding with a significant mechanical load. We assume that there is no movement (recoil) of the inductor winding.

The change in the spatial position of the actuator is taken into account by the change in flux linkage Ψ between the windings of the inductor and the armature:

$$\frac{d\Psi}{dt} = M_{12}(z)\frac{di_n}{dt} + v_z(t)\cdot i_n \frac{dM_{12}}{dz}, \tag{1}$$

where n=1, 2 are the indices of the inductor and armature windings, respectively; $M_{12}(z)$ is the mutual inductance between the windings; v_z is the speed of movement of the armature winding along the z axis; i_n is the current of the n-th winding.

Mathematical model of electromagnetic processes when LPEC excited from the CES. We will consider the excitation of the LPEC from the CES with a polar pulse, which is provided by a shunt reverse diode. We assume its resistance in the forward direction is negligible, and in the opposite direction, its conductivity is just as low.

Based on equation (1), the electromagnetic processes in the LPEC windings on the time interval $\{0,t_1\}$ can be described by a system of equations [11]:

$$R_1(T_1)i_1 + L_1\frac{di_1}{dt} + \frac{1}{C_0}\int_0^t i_1 dt + M_{12}(z)\frac{di_2}{dt} + v_z(t)i_2\frac{dM_{12}}{dz} = 0, \quad \frac{1}{C_0}\int_0^t i_1 dt = U_0, \tag{2}$$

$$R_2(T_2)\cdot i_2 + L_2\frac{di_2}{dt} + M_{21}(z)\frac{di_1}{dt} + i_1 v(t)\frac{dM_{21}}{dz} = 0, \tag{3}$$

where t_1 is the time at which the voltage of the CES u_C=0; R_n, L_n, T_n are the active resistance, inductance, temperature and current of the n-th winding, respectively; C_0 is the capacity of the CES charged to a voltage U_0.

Let's introduce the notation: $R_1 = R_1(T_1); R_2 = R_2(T_2); M = M_{12} = M_{21}(z);\ v_z = v_z(t)$.

The system of equations (2), (3) after a series of transformations is reduced to the equation:

$$a_3\frac{d^3 i_1}{dt^3} + a_2\frac{d^2 i_1}{dt^2} + a_1\frac{di_1}{dt} + a_0 i_1 = 0, \tag{4}$$

where $a_3 = L_1L_2\left(1-K_M^2\right)$; $a_2 = L_1R_2 + L_2R_1 - 2\varsigma M$; $\varsigma = v_z\frac{dM}{dz}$; $a_1 = R_1R_2 + L_2C_0^{-1} - \varsigma^2$; $a_0 = R_2C_0^{-1}$;

$K_M = M\left(L_1L_2\right)^{-0.5}$ is the coefficient of magnetic coupling between windings.

The characteristic equation of the differential equation (4) is represented as:

$$x^3 + \chi x^2 + \xi x + \kappa = 0, \tag{5}$$

where $\chi = a_2/a_3$; $\xi = a_1/a_3$; $\kappa = a_0/a_3$.

Using the replacement $y = x + \chi/3$, equation (5) is reduced to the form:

$$y^3 + \varpi y + \upsilon = 0, \tag{6}$$

where $\varpi = \xi - \chi^2/3$; $\upsilon = 2(\chi/3)^3 - \chi\xi/3 + \kappa$.

The roots of equation (6) are found using the Cardano formula:

$$y_1 = \vartheta + \nu;\; y_2 = \varepsilon_1\vartheta + \varepsilon_2\nu;\; y_3 = \varepsilon_2\vartheta + \varepsilon_1\nu, \tag{7}$$

where $\vartheta = \sqrt[3]{D^{0,5} - 0{,}5\upsilon}$; $\nu = \sqrt[3]{-D^{0,5} - 0{,}5\upsilon}$; $\varepsilon_{1,2} = 0{,}5\left(-1 \pm j\sqrt{3}\right)$; $D = (\varpi/3)^3 + (\upsilon/2)^2$ is the discriminant of an equation (6).

If $D < 0$, then cubic equation (6) has three real roots:

$$y_p = 2\sqrt[6]{-\varpi^3/27}\,\cos\left[\frac{1}{3}\arccos\left(-\frac{\upsilon}{2\sqrt{-\varpi^3/27}}\right) + \frac{2}{3}\pi(p-1)\right],\quad p=1,\,2,\,3. \tag{8}$$

After a series of transformations, we obtain an expression for the currents in the LPEC windings when excited from the CES:

$$i_n(t_{k+1}) = \delta^{-1}\left\{\left[i_n(t_k) - \frac{i_m(t_k)\varsigma^2}{R_1R_2}\right](\alpha_1\beta_2\beta_3 + \alpha_2\beta_1\beta_3 + \alpha_3\beta_1\beta_2) + \left(\Omega_n - \frac{\Omega_m\varsigma}{R_n}\right)[\alpha_1(\beta_2+\beta_3) + \right.$$

$$\left. + \alpha_2(\beta_1+\beta_3) + \alpha_3(\beta_1+\beta_2)] + \left(\Lambda_n - \frac{\Lambda_m\varsigma}{R_n}\right)(\alpha_1+\alpha_2+\alpha_3)\right\}\left[1 - \frac{\varsigma^2}{R_1R_2}\right]^{-1}, \tag{9}$$

where m=1, 2 at n=2, 1; $\delta = \beta_1\beta_2(\beta_2-\beta_1) + \beta_1\beta_3(\beta_1-\beta_3) + \beta_2\beta_3(\beta_3-\beta_2)$; $\Omega_n = B_n + B_m\varsigma R_n^{-1}$; $\Delta t = t_{k+1} - t_k$;
$\Lambda_n = E_n + E_m\varsigma R_n^{-1}$; $\alpha_1 = (\beta_3-\beta_2)\exp(\beta_1\Delta t)$; $\alpha_2 = (\beta_1-\beta_3)\exp(\beta_2\Delta t)$; $\alpha_3 = (\beta_2-\beta_1)\exp(\beta_3\Delta t)$;
$\beta_p = \left\{2\left(a_2^2 - 3a_1a_3\right)^{0,5}\cos[2\pi(p-1)/3 + \phi] - a_2\right\}/3a_3$; $\phi = \arccos\left[\left(a_2^2 - 3a_1a_3\right)^{-1,5}\left(4{,}5a_1a_2a_3 - a_2^3 - 13{,}5a_0a_3^2\right)\right]$;
$\gamma_1 = L_2$; $\gamma_2 = -M_{12}$; $B_n = \upsilon^{-1}[i_n(t_k)(M_{12}\varsigma - R_nL_m) + i_m(t_k)(R_mM_{12} - L_m\varsigma) - \gamma_k u_c(t_k)]$;

$$E_1 = a_3^{-2}\left\{i_1(t_k)\left[R_1\left(R_2M_{12}^2 + R_1L_2^2 - C_0^{-1}L_2\upsilon\right) - M_{12}\varsigma(\tau + 2R_1L_2) + \varsigma^2\left(L_1L_2 + M_{12}^2\right)\right] + i_2(t_k)\times\right.$$
$$\left.\times\left[\left(L_2\tau + 2R_2M_{12}^2\right)\varsigma - M_{12}R_2\tau - M_{12}L_2\varsigma^2\right] + u_c(t_k)\left(R_2M_{12}^2 + L_2^2R_1 - 2L_2M_{12}\varsigma\right)\right\};$$
$$E_2 = a_3^{-2}\left\{i_1(t_k)\left[M_{12}\left(C_0^{-1}a_3 - R_1\tau\right) + \varsigma\left(2R_1M_{12}^2 + L_1\tau\right) - 2\varsigma^2L_1M_{12}\right] + i_2(t_k)\left[R_2\left(R_1M_{12}^2 + R_2L_1^2\right) - \right.\right.$$
$$\left.\left. - M_{12}\varsigma(2L_1R_2 + \tau) + \left(L_1L_2 + M_{12}^2\right)\varsigma^2\right] + u_c(t_k)\left[\varsigma\left(L_1L_2 + M_{12}^2\right) - M_{12}\tau\right]\right\},$$

where $u_c(t_k)$ ia the CES voltage at time t_k; $\tau = a_2 + 2M\varsigma$.

If the discriminant of the characteristic equation (6) $D > 0$, then one of its roots is real $x_1 = d$, and the other two are complex conjugate $x_{2,3} = f \pm jg$. After a series of transformations, we obtain an expression for the currents in the windings:

$$i_n(t_{k+1}) = \left(\zeta_n - R_n^{-1}\zeta_m\varsigma\right)\left(1 - \varsigma^2R_1^{-1}R_2^{-1}\right)^{-1}, \tag{10}$$

where $\zeta_n = g^{-1}\left[g^2 + (f-d)^2\right]^{-1}\left\langle g\cdot\exp(d\Delta t)\left[\left(g^2+f^2\right)\Theta_n - 2f\Omega_n + \Lambda_n\right] + \exp(f\Delta t)\left\{\sin(g\Delta t)d\left(f^2 - g^2 - fd\right)\Theta_n + \right.\right.$
$\left.\left. + \left(g^2 + d^2 - f^2\right)\Omega_n + (f-d)\Lambda_n\right] + g\cdot\cos(g\Delta t)\left[d(d-2f)\Theta_n + 2f\Omega_n - \Lambda_n\right]\right\}\right\rangle$; $\Theta_n = i_n(t_k) + i_m(t_k)R_n^{-1}\varsigma$.

Electromagnetic processes in the LPEC in the time interval $\{t_1,\ \infty\}$ are described by a system of equations:

$$R_n(T_n)i_n(t) + L_n\frac{di_n}{dt} + M_{nm}(z)\frac{di_m}{dt} + i_m(t)\varsigma = 0. \tag{11}$$

After a series of transformations, this system is reduced to the equation:

$$\left(1 - K_M^2\right)\frac{d^2i_1}{dt^2} + (\gamma_1 + \gamma_2 - 2\xi_1\chi_2)\frac{di_1}{dt} + (\gamma_1\gamma_2 - \chi_1\chi_2)i_1 = 0, \tag{12}$$

where $\gamma_n = R_nL_n^{-1}$; $\xi_n = ML_n^{-1}$; $\chi_n = \varsigma L_n^{-1}$.

Expressions for the currents in the LPEC windings when excited from the CES in the time interval $\{t_1,\ \infty\}$ are finally described by the recurrence relations:

$$i_n(t_{k+1})=\left\{i_n(t_k)\left[x_1\exp(x_2\Delta t)-x_2\exp(x_1\Delta t)\right]\left(\exp(x_1\Delta t)-\exp(x_2\Delta t)\right)\left(1-K_M^2\right)^{-1}\times\right.$$

$$\left.\times\left[i_n(t_k)(\xi_n\chi_m-\gamma_n)+i_m(t_k)(\gamma_m\xi_n-\chi_n)\right]\right\}(x_1-x_2)^{-1}, \qquad (13)$$

where $x_{1,2}=\left(1-K_M^2\right)^{-1}\left\langle\xi_1\chi_2-0,5\cdot(\gamma_1+\gamma_2)\pm\left\{\left[0,5(\gamma_1+\gamma_2)-\xi_1\chi_2\right]^2+\left(K_M^2-1\right)(\gamma_1\gamma_2-\chi_1\chi_2)\right\}^{0,5}\right\rangle$.

Mathematical model of the electromagnetic processes of the LPEC when excited from the AVS. Electromagnetic processes in the LPEC windings when excited from the AVS can be described by a system of equations:

$$R_1(T_1)i_1+L_1\frac{di_1}{dt}+M_{12}(z)\frac{di_2}{dt}+i_2\varsigma=u(t), \qquad (14)$$

$$R_2(T_2)i_2+L_2\frac{di_2}{dt}+M_{21}(z)\frac{di_1}{dt}+i_1\varsigma=0, \qquad (15)$$

where $u(t)=U_m\sin(\omega t+\psi_u)$ is the AVS voltage; R_n, L_n, T_n sre the active resistance, inductance, temperature and current of the n-th winding, respectively; $\omega=2\pi\nu$; ν is the frequency of the AVS voltage; ψ_u is the initial voltage phase.

Let's introduce the notation: $u=u(t)$.

We will find solutions for currents in the form:

$$i_1=uR_1^{-1}-i_2R_1^{-1}\varsigma+A_{11}\exp(\alpha_1 t)+A_{12}\exp(\alpha_2 t), \qquad (16)$$

$$i_2=-i_1R_1^{-1}\varsigma+A_{21}\exp(\alpha_1 t)+A_{22}\exp(\alpha_2 t), \qquad (17)$$

where $\alpha_{1,2}=-0.5a_2a_3^{-1}\pm\left\{0.25a_2^2a_3^{-2}-\left[R_1R_2-\varsigma^2\right]a_3^{-1}\right\}$ are the roots of the characteristic equation for the free component described by the differential equation:

$$a_3\frac{d^2i_1}{dt^2}+a_2\frac{di_1}{dt}+\left(R_1R_2-\varsigma^2\right)i_1=0, \qquad (18)$$

$A_{11}, A_{12}, A_{21}, A_{22}$ are the arbitrary constants determined at time t_k for free components of currents, equal to

$$A_{1l}=\frac{\alpha_m\left[i_2(t_k)\varsigma R_1^{-1}-u(t_k)R_1^{-1}+i_1(t_k)\right]-\Xi}{(\alpha_m-\alpha_l)\exp(\alpha_l t_k)}; \qquad (19)$$

$$A_{2l}=\frac{\alpha_m\left[i_2(t_k)+i_1(t_k)\xi R_2^{-1}\right]-\iota}{(\alpha_m-\alpha_l)\exp(\alpha_l t_k)}, \qquad (20)$$

where l=1, 2; m=3-l; $\Xi=L_1^{-1}\left(1-K_M^2\right)^{-1}\left\{u(t_k)+i_1(t_k)\left(ML_2^{-1}\varsigma-R_1\right)+i_2(t_k)\left(MR_2L_2^{-1}-\varsigma\right)\right\}$;
$\iota=L_2^{-1}\left(1-K_M^2\right)^{-1}\left\{i_2(t_k)\left(ML_1^{-1}\varsigma-R_2\right)-u(t_k)ML_1^{-1}+i_1(t_k)\left(MR_1L_1^{-1}-\varsigma\right)\right\}$.

In the final form, the currents in the LPEC windings when excited from the AVS are described by the expressions:

$$i_1(t_{k+1})=-\frac{i_2(t_k)\varsigma}{R_1}+\left[u(t_k)-R_1i_1(t_k)-i_2(t_k)\varsigma\right]\frac{\alpha_1\exp(\alpha_2\Delta t)-\alpha_2\exp(\alpha_1\Delta t)}{R_1(\alpha_2-\alpha_1)}+\frac{u(t_k)}{R_1}+$$
$$+\frac{\exp(\alpha_2\Delta t)-\exp(\alpha_1\Delta t)}{L_1L_2(\alpha_2-\alpha_1)\left(1-K_M^2\right)}\left\{u(t_k)L_2+\left[M\varsigma-R_1L_2\right]i_1(t_k)+\left[R_2M-L_2\varsigma\right]i_2(t_k)\right\}; \qquad (21)$$

$$i_2(t_{k+1})=-\frac{i_1(t_k)\varsigma}{R_2}+\left[i_2(t_k)+\frac{i_1(t_k)\varsigma}{R_2}\right]\frac{\alpha_2\exp(\alpha_1\Delta t)-\alpha_1\exp(\alpha_2\Delta t)}{\alpha_2-\alpha_1}+\frac{\exp(\alpha_2\Delta t)-\exp(\alpha_1\Delta t)}{L_1L_2(\alpha_2-\alpha_1)\left(1-K_M^2\right)}\times$$
$$\times\left\{i_1(t_k)\left[R_1M-L_1\varsigma\right]-u(t_k)M+i_2(t_k)\left[M\varsigma-R_2L_1\right]\right\}, \qquad (22)$$

where $u(t_k)=U_m\sin(\omega t_k+\psi_u)$.

The magnitude of displacement of the armature winding with an actuator of mass m_a relative to the stationary inductor winding is described by the recurrence relations presented in [13]. The temperatures of the LPEC windings are described by the recurrence relations presented in [12].

When implementing the equations describing electrical, magnetic, mechanical and thermal processes on computer technology, a cyclic algorithm is used. At each numerically small calculated step Δt, the values of the currents i_n, temperatures T_n, resistances $R_n(T_n)$ of the windings, the thermal conductivity coefficient of the insulating pad between the windings $\lambda_a(T)$ are sequentially calculated; values of axial electrodynamic force $f_z(z,t)$, speed v_z and displacement h_z of the armature winding, mutual inductance $M(z)$ between the windings.

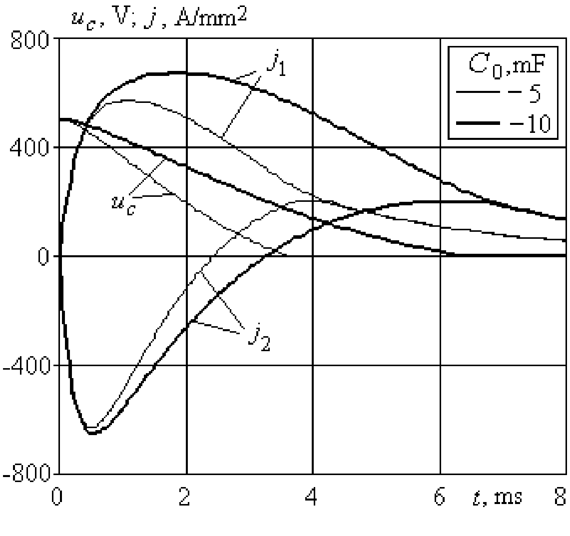
Initial conditions of the mathematical model: $T_n(0)=T_0$ is the temperature of the n-th winding; $i_n(0)=0$ is the current of the n-th winding; $h_z(0)=h_{z0}$ is the distance between the windings; $u_c(0)=U_0$ is the CES charge voltage; $u(0)=U_m \sin\psi_u$ is the AVS voltage; $v_z(0)=0$ is the armature winding speed.

The efficiency of the LPEC will be estimated by the highest values of the pulse of the electrodynamic force $P_z=\int f_z(z,t)dt$, where $f_z(z,t)=i_1(t)i_2(t)\frac{dM_{12}}{dz}(z)$ is the instantaneous value of the electrodynamic force acting on the armature winding and the efficiency indicator $K_P=P_z/W_g$, where W_g is the excitation source energy; $W_g=0.5C_oU_0^2$ is the CES energy; $W_g=\int_0^{t_s} u(t)i_1(t)dt$ is the AVS energy during excitation t_s. In this case, the temperature rise of the windings $\theta_n=T_n-T_0$ should be minimal.

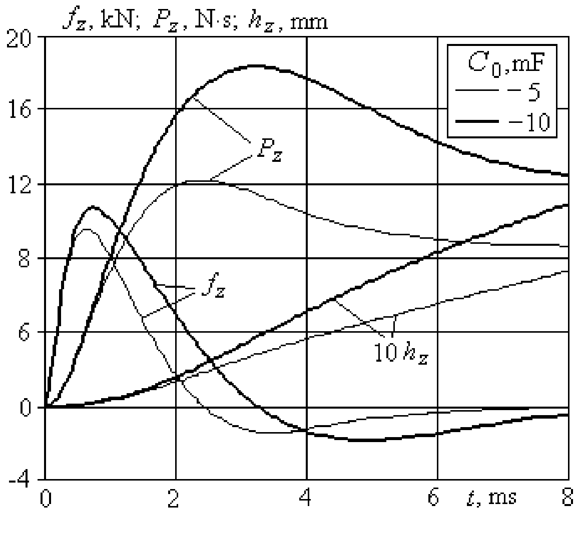
Consider a LPEC, in which the inductor winding (n=1) and the armature winding (n=2) are tightly wound with a copper wire with a diameter of d_0=1.4 mm. The windings are made with the same radial dimensions: outer diameter $D_{1ex}=D_{2ex}$=100 mm, inner diameter $D_{1in}=D_{2in}$=10 mm. Axial heights of the inductor windings H_1=6 mm and armature H_2=3 mm. The number of turns of the windings of the inductor w_1=120 and the armature w_2=60. The windings are made in the form of monolithic discs by impregnation and subsequent hardening of epoxy resin. The windings are installed coaxially and the initial distance between them is h_{z0}=0.5 mm. The mass of the actuator, which is affected by the armature winding, is m_a=100 kg. The coefficient of elasticity of the return spring is K_P =25 25 kN/m. The amplitude of the AVS voltage is U_m=300 V, and its frequency ν can vary from 50 to 250 Hz.

The CES contains a reverse diode that provides a polar excitation current in the inductor winding, and has the following parameters: capacitance C_0=5 mF, voltage U_0=500 V. Similar parameters of the CES are used in the technology of electrodynamic treatment of welded joints [3] and in magnetic-pulse presses for powders ceramics [5].

Electromechanical indicators of MIEP with excitation from the CES. When the LPEC is excited from the CES with a capacity of C_0=5 mF, its voltage u_c decreases to zero at the time t=3.38 ms, remaining this way in the future (Fig. 1). The discharge current in the inductor winding with density j_1 has the form of a polar pulse with a maximum value of j_{1m}=571 A/mm^2. At the initial moment of time, the current induced in the armature winding with a density j_2 with respect to the inductor current has the opposite polarity, but after a certain time (t=2.43 ms) it changes polarity. The maximum value of the current density in the armature winding is j_{2m}=626.7 A/mm^2. The electrodynamic force f_z, acting on the armature winding has the form of a damped pulse, with an initial prevailing positive (repulsive) component until the time t = 2.43 ms and a subsequent insignificant negative (attractive) component. The maximum value of the repulsive force acting on



a



b

Fig. 1

the armature winding is f_{zm}=9.55 kN. Due to the indicated nature of the change in the force f_z, the magnitude of the pulse of the electrodynamic force, reaching the maximum value P_z=12.17 N·s, by the end of the considered time interval t=8 ms decreases to the value P_z=8.63 N·s. In this case, the temperature rises of the inductor and armature windings are θ_1=3.1 ºC and θ_2=1.7 ºC, respectively.

Since the duration of the power effect of the LPEC is insignificant (t=2.43 ms), to increase it, the capacity of the CES can be increased. However, with an increase in the energy of the CES by two times due to the use of a capacitance C_0=10 mF, an increase in the main indicators of the LPEC does not occur to the same extent. The time interval at which the voltage u_c=0 increases by 75%. The maximum value of the current in the inductor winding increases by 17.1%, and the corresponding value in the armature winding practically does not change (increases by 1.3%). The maximum repulsive force f_{zm} also increases slightly (by 11.4%). But the maximum value of the force impulse P_z increases significantly (by 50.3%). The disadvantages of a twofold increase in the capacity of the CES include a significant (2.15 times) increase in the temperature rise of the inductor winding θ_1. In this case, the temperature rise of the armature winding θ_2 increases by only 31.5%. The relative indicator of the efficiency of this converter $K_p^* = K_p / K_{pC}$, where K_{pC} is the indicator of the efficiency of the basic LPEC, excited from the CES with C_0=5 mF, decreases and is K_p^*=0.719.

Thus, an increase in the capacity of the CES makes it possible to increase the duration and magnitude of the pulse of the electrodynamic force. However, the power indicators and the duration of such an impact increase to a lesser extent than the capacity of the CES increases. In addition, with such an excitation of the LPEC, it is necessary to take into account that the maximum value of the electrodynamic force is significant, which is undesirable for a number of technical devices, for example, due to strong recoil or the formation of an inhomogeneous density of ceramic powder in an induction-dynamic press.

Electromechanical indicators of LPEC under excitation from AVS. A significant increase in the duration and magnitude of the electrodynamic force with a decrease in its maximum value allows the use of AVS to excite the LPEC. In Fig. 2 shows the electromechanical characteristics of the LPEC when excited from the AVS with a voltage frequency ν=50 Hz. With this excitation, the current in the inductor winding takes on a periodic character with a phase shift with respect to the voltage u. The greatest value of the current occurs in the first half-period, subsequently reaching a constant value. The maximum current density in the inductor winding is j_{1m}=683.6 A/mm^2, which is more than in the basic LPEC with CES C_0=5 mF. The induced current in the armature winding also takes on a periodic nature, changing with a phase shift close to 180º. The largest value of the current density in the armature winding occurs in the second half-period, amounting to j_{2m}=264.1 A/mm^2, which is much lower than in the base LPEC.

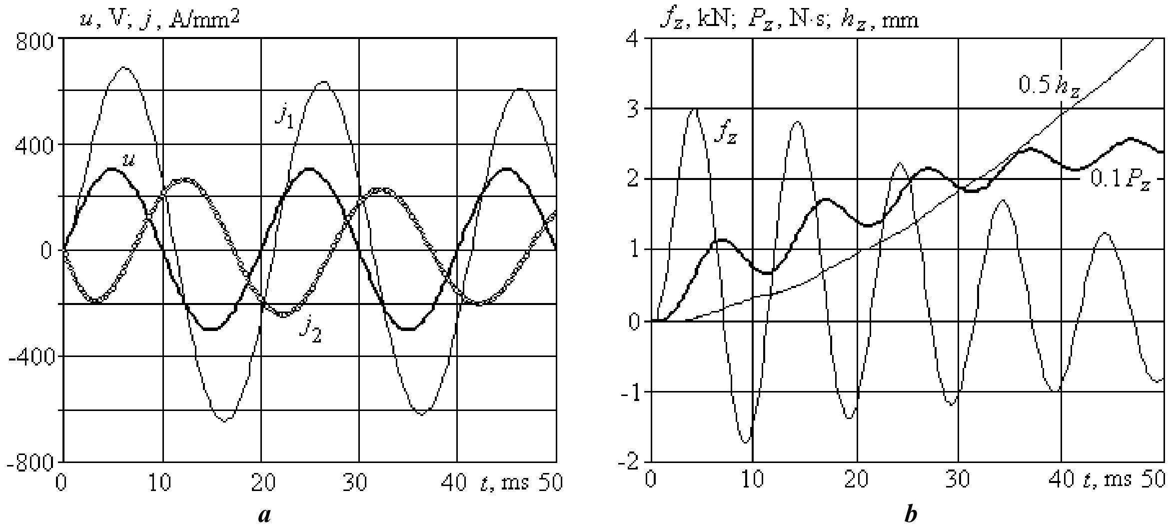
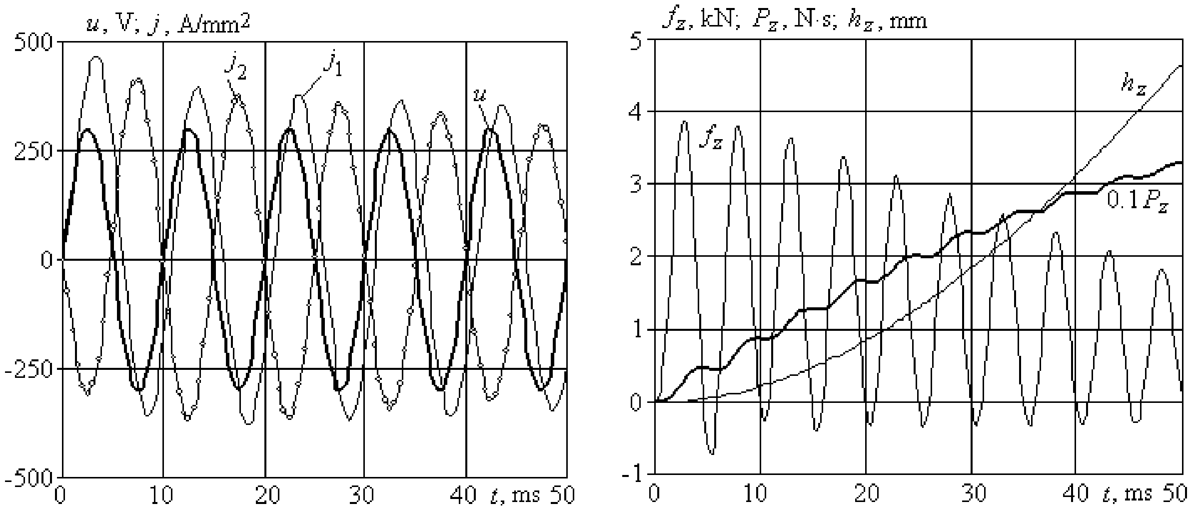


Fig. 2

Due to this nature of the change in currents in the LPEC windings, the electrodynamic force takes on a periodic decaying character with a significant prevalence of positive (repulsive) components over negative (attractive) components of the force. The maximum value of the first half-period of the repulsive force is f_{zm}=2.98 kN, which is much less than in the LPEC with CES. Due to the indicated nature of the change in the force f_z, the magnitude of the impulse of the electrodynamic force P_z has the character of a decelerating increase with periodic decreases caused by the attracting components of the force. At the moment of time t=50 ms, the value of the force impulse is P_z=2323.6 N·s, which is much higher than in the LPEC with CES.

However, the disadvantage of excitation of LPEC from AVS is increased thermal loads. So at t=50 ms, the temperature rise of the windings are θ_1=39.2 ºC and θ_2=4.4 ºC. These indicators, especially in the inductor winding, are much higher than in the LPEC with CES, and they can limit the duration of the excitation process of the LPEC from the AVS.

When the LPEC is excited from the AVS of increased frequency, the electromechanical processes change significantly (Fig. 3).



a ***b***

Fig. 3

When using the AVS with a voltage frequency ν=200 Hz compared with a frequency ν=50 Hz, the maximum value of the current density in the inductor winding decreases (j_{1m}=460.7 A/mm^2), and the corresponding value in the armature winding increases (j_{2m}=410.2 A/mm^2). In this case, the currents in the windings change practically in antiphase with a small phase shift, as a result of which the positive components of the electrodynamic force significantly exceed the negative ones. The largest value of the first positive component of the force increases to f_{zm}=3.82 kN, and the value of the force impulse at time t=50 ms increases to P_z=39.5 N·s. An advantage of the higher frequency AVS is the equalization of their temperature rises. So at t=50 ms, the temperature rise of the inductor winding decreases to θ_1=11.3 ºC, and the temperature rise of the armature winding increases to θ_2=8.1 ºC. Thus, with an increase in the frequency of the AVS voltage, a significant increase in the value of the force pulse occurs with a decrease in the temperature rise of the inductor winding. To estimate the effect of the frequency ν AVS on the electromechanical and thermal indicators of the LPEC allows Fig. 4.

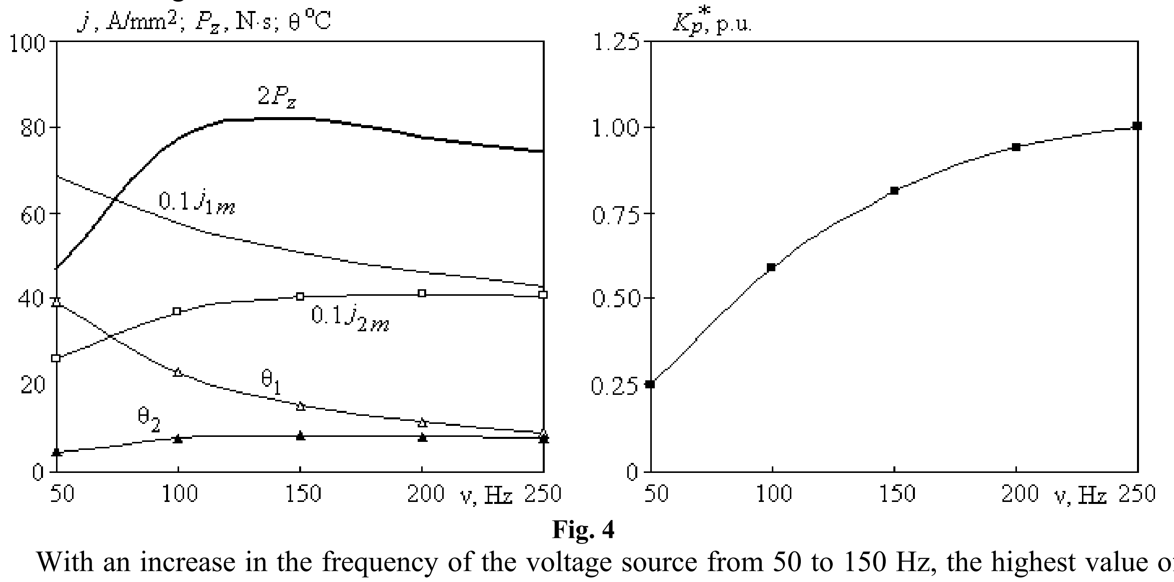


Fig. 4

With an increase in the frequency of the voltage source from 50 to 150 Hz, the highest value of the current density of the inductor winding j_{1m} decreases, the armature winding j_{2m} increases. The temperature rises of the windings θ_1 and θ_2 take on a similar character. The magnitude of the impulse of the electrodynamic force P_z in the range of $\nu \in (50...150)$ Hz increases, taking the greatest value P_z=40.9 N·s, and decreases subsequently. Note that the largest value of the electrodynamic force also takes on an almost similar character, reaching f_{zm}=3.94 kN at a frequency of ν=150 Hz. With an increase in the frequency ν of the AVS, the relative efficiency indicator $K_p^* = K_p / K_{pC}$ increases, reaching $K_p^* = 1$ at ν=250 Hz.

The initial phase of the voltage at the time of connecting the LPEC to the AVS can take on a value in the range $\psi_u \in (0;180^0)$. To assess the influence of the initial phase of the AVS voltage on the magnitude of the pulse of the electrodynamic force P_z, we use the relative indicator:

$$\Delta P_z = 200 \frac{P_{z\max} - P_{z\min}}{P_{z\max} + P_{z\min}}, \%,$$

where $P_{z\max}$, $P_{z\min}$ are the maximum and minimum value of the force impulse P_z, respectively.

Calculations show that at ν=50 Hz the relative force exponent is ΔP_z=13%, at ν=150 Hz – ΔP_z = 2%, and at ν=250 Hz – ΔP_z=0.6%. Thus, with an increase in the frequency of the AVS voltage, the influence of the initial phase of the voltage on the magnitude of the force pulse decreases.

Conclusions.

1. A mathematical model of an induction-type LPEC has been developed when excited by both a unipolar pulse from the CES and from the AVS using the lumped parameters of the windings, which takes into account the interrelated electromagnetic, mechanical and thermal processes.
2. It has been established that an increase in the capacity of the CES makes it possible to increase the duration of the force action and the magnitude of the impulse of the electrodynamic force. However, the power indicators and the duration of such an impact increase to a lesser extent than the increase in the capacity of the CES. When the LPEC is excited from the CES, the maximum value of the electrodynamic force is significant.
3. When the LPEC is excited from the AVS with a voltage frequency of 50 Hz, the currents in the windings change periodically with a phase shift close to 180º, the largest value of which occurs in the initial period. The electrodynamic force takes on a periodic decaying character with a significant prevalence of positive components of forces over negative ones. The maximum magnitude of the force is much less, and the magnitude of the impulse of the force is much greater than in the LPEC, excited from the CES. However, when excited from the AVS, the excess of the winding temperatures, especially in the inductor winding, is much higher than in the LPEC, excited from the CES.
4. With an increase in the frequency of the AVS voltage from 50 to 150 Hz, the highest value of the current density in the inductor winding decreases, and in the armature winding it increases. The highest values of the electrodynamic force f_{zm}=3.94 kN and its impulse P_z=40.9 N · s are realized at a frequency of ν=150 Hz. With an increase in the frequency of the AVS voltage, the relative indicator of the efficiency of the LPEC increases. The influence of the initial voltage phase, at which the LPEC is connected to the AVS, decreases with an increase in the source frequency.

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УДК 621.313.282

ВПЛИВ ДЖЕРЕЛА ЗБУДЖЕННЯ НА СИЛОВІ ПОКАЗНИКИ ЛІНІЙНОГО ІМПУЛЬСНОГО ЕЛЕКТРОМЕХАНІЧНОГО ПЕРЕТВОРЮВАЧА ІНДУКЦІЙНОГО ТИПУ

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Метою статті є оцінка ефективності лінійного імпульсного електромеханічного перетворювача (ЛІЕП) індукційного типу під час роботи в ударно-силовому режимі і збудженні від джерела змінної напруги (ДЗН) в порівнянні зі збудженням від ємнісного накопичувача енергії (ЄНЕ). Розроблено математичну модель ЛІЕП індукційного типу як під час збудження однополярним імпульсом від ЄНЕ, так і від ДЗН з використанням зосереджених параметрів обмоток, яка враховує взаємозалежні електромагнітні, механічні та теплові процеси. Встановлено, що у разі збудження ЛІЕП від ДЗН з частотою напруги 50 Гц електродинамічна сила приймає періодичний загасаючий характер зі значним превалюванням позитивних складових сил над негативними. Максимальна величина сили значно менше, а величина її імпульсу значно більше, ніж в ЛІЕП, який збуджується від ЄНЕ. Зі збільшенням частоти напруги ДЗН від 50 до 150 Гц найбільше значення щільності струму обмотки індуктора зменшується, а в обмотці якоря підвищується. Найбільші величини сили і імпульсу сили реалізуються за частоти напруги 150 Гц. У разі збільшення частоти напруги ДЗН відносний показник ефективності ЛІЕП підвищується. Бібл. 15, рис. 4.

Ключові слова: лінійний імпульсний електромеханічний перетворювач індукційного типу, математична модель, джерело змінної напруги, ємнісний накопичувач енергії, електромеханічні процеси і силові показники.

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