UDC 621.313:536.2.24:539.2 **doi: 10.20998/2074-272X.2018.1.03**

V.F. Bolyukh, A.I. Kocherga, I.S. Schukin

INVESTIGATION OF A LINEAR PULSE-INDUCTION ELECTROMECHANICAL CONVERTER WITH DIFFERENT INDUCTOR POWER SUPPLY CIRCUITS

Purpose. The goal of the paper is to investigate the influence of the power circuits of the linear pulse-induction electromechanical converters (LPIEC), which form the current pulse of excitation of the inductor from the capacitive energy storage (CES), to its electromechanical parameters. Methodology. A circuit mathematical model of LPIEC was developed, on the basis of which recurrence relations were obtained for calculating the interrelated electromagnetic, mechanical, and thermal parameters of the LPIEC. This model makes it possible to calculate the LPIEC parameters for various power circuits, the inductor of which is excited by the CES. Results. It is established that electromechanical LPEC parameters with power circuit forming an aperiodic current excitation pulse of an inductor are better than in LPIEC with excitation of an inductor by an unipolar current pulse, but worse than in LPIEC with excitation of an inductor by a vibrationally damped current pulse. In this converter, during operation, the inductor is heated most, and the armature is heated least. It is established that in LPIEC with power circuit that forms an aperiodic current pulse of excitation of an inductor with the connection of an additional CES, all electromechanical parameters are higher in comparison with the LPIEC with a power circuit that forms a vibrationally damped current excitation pulse of the inductor. However, in this LPIEC the excess of the temperatures of the active elements increases, especially strongly in the inductor, and the efficiency of the converter decreases. Originality. For the first time, the LPIEC has been investigated using the power circuit that forms an aperiodic current pulse of excitation of an inductor with the connection of an additional CES. It is established that in this LPIEC all electromechanical parameters are higher than for LPIEC with power circuits forming an unipolar or oscillating-damped current excitation pulse of the inductor. Practical value. In the LPIEC with power circuit that forms an aperiodic current pulse of excitation of the inductor with the connection of an additional CES, the electromechanical LPIEC parameters increase. This increases the temperature rise of the inductor, and the temperature rise of the armature decreases. The effectiveness of this LPIEC is also reduced. References 12, figures 7.
Key words: **linear pulse-induction electromechanical converters, circuit mathematical model, recurrence relations, inductor feed circuits, capacitive energy storage, chain mathematical model, current excitation pulse of inductor.**

На основе разработанной цепной математической модели получены рекуррентные соотношения для расчета взаимосвязанных электромагнитных, механических и тепловых параметров линейного импульсно-индукционного электромеханического преобразователя (ЛИИЭП). Показано, что электромеханические показатели ЛИИЭП со схемой питания индуктора, формирующей апериодический токовый импульс возбуждения, лучше, чем у ЛИИЭП с возбуждением индуктора однополярным токовым импульсом, но хуже, чем у ЛИИЭП с возбуждением индуктора колебательно-затухающим токовым импульсом. В данном преобразователе в процессе работы наиболее сильно нагревается индуктор и наименее нагревается якорь. Показано, что в ЛИИЭП со схемой питания индуктора, формирующей апериодический токовый импульс возбуждения с подключением добавочного емкостного накопителя энергии, все электромеханические показатели выше по сравнению с ЛИИЭП со схемой питания индуктора, формирующей колебательно-затухающий токовый импульс возбуждения. Однако в этом ЛИИЭП возрастают превышения температур активных элементов, особенно сильно – индуктора и снижается КПД. Библ. 12, рис. 7.
Ключевые слова: **линейный импульсно-индукционный электромеханический преобразователь, цепная математическая модель, рекуррентные соотношения, схемы питания индуктора, емкостной накопитель энергии, токовый импульс возбуждения индуктора.**

Introduction. Linear electric motors of the traditional type (synchronous, induction and direct current) do not allow to provide significant accelerations and impact loads with limited specific indicators. This led to the appearance of special linear pulse electromechanical converters which provide a high speed of the actuator element (AE) on a short active site, and/or create powerful force pulses with a small displacement of it [1-4]. Such converters are used in many branches of science and technology as electromechanical accelerators and shock-power devices [5-7]. They are characterized by [8]:

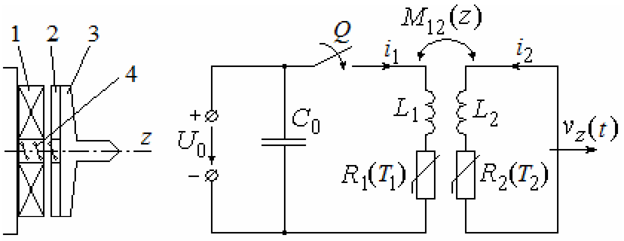
- pulsating, reciprocating, cyclic or one-time operation mode;
- intermittent nature of the energy conversion due to the presence of a back stroke, and often a long pause during the working cycle;
- long duration of energy storage from a capacitive energy storage (CES) in relation to the duration of the working period;
- intensive electromagnetic loads, significantly exceeding those of traditional linear electric motors.

The most widely used linear pulse-induction electromechanical converters (LPIEC) are coaxial configurations, in which the accelerated arm interacts non-contact with a stationary inductor [1, 2, 9]. When the inductor is excited from the CES, eddy currents are induced in the electrically conducting armature. As a result of this, electrodynamic forces (EDF) act on the armature, causing its axial displacement (Fig. 1,*a*).

However, when operating in a dynamic mode with a rapid change in electromagnetic, mechanical and thermal parameters, the efficiency of the LPIEC is not high enough, which requires new approaches to improve its electromechanical performance. One way to increase these indicators is to generate the necessary current pulses of the inductor due to the power circuits that are located between the CES and the inductor. However, to date, no specific studies have been conducted to determine the influence of various inductor power circuits on the electromechanical performance of the LPIEC.

The goal of the paper is investigation of the influence of various inductor power circuits forming its current pulses on the electromechanical parameters of the LPIEC.

Mathematical model. We consider the mathematical circuit model of LPIEC which uses the lumped parameters of the inductor and armature (Fig. 1,*b*).



a *b*

Fig. 1. Design (*a*) and electric (*b*) LPIEC circuits with a free CES discharge on the inductor:
1 – inductor; 2 – armature; 3 – AE; 4 – return spring

In the presented in Fig. 1,*b* electrical circuit after the closure of the key *Q*, a free discharge of the CES occurs to the inductor. Electrical processes in LPIEC can be described by a system of equations [9]:

$$R_1(T_1)i_1 + L_1\frac{di_1}{dt} + \frac{1}{C_0}\int_0^t i_1 dt + M_{12}(z)\frac{di_2}{dt} +$$

$$+ v_z(t) i_2 \frac{dM_{12}}{dz} = 0\,, \quad \frac{1}{C_0}\int_0^t i_1 dt = U_0\,, \tag{1}$$

$$R_2(T_2)\cdot i_2 + L_2\frac{di_2}{dt} + M_{21}(z)\frac{di_1}{dt} + i_1 v(t)\frac{dM_{12}}{dz} = 0\,, \tag{2}$$

where n = 1, 2 are the indexes of inductor and armature, respectively; R_n, L_n, T_n, i_n are the active resistance, inductance, temperature and current of the n-th element, respectively; C_0 is the capacity of CES charged on the voltage U_0; $M_{12}(z)$ is the mutual inductance between inductor and armature moving along the z-axis with speed v_z.

We denote

$R_1 = R_1(T_1); R_2 = R_2(T_2); M_{12} = M_{12}(z);\ v_z = v_z(t)$.

The system of equations (1,) (2) after a series of transformations is reduced to the equation:

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

where

$$a_3 = \upsilon;\ a_2 = \chi - 2Mv_z\frac{dM_{12}}{dz};\ a_1 = R_1R_2 + \frac{L_2}{C_0} - v_z^2\left(\frac{dM_{12}}{dz}\right)^2;$$

$$a_0 = \frac{R_2}{C_0};\ \upsilon = L_1L_2 - M_{12}^2;\ \ \chi = R_1L_2 + L_1R_2\,.$$

The characteristic equation of the differential equation (3) is represented in the canonical form

$$x^3 + r_* x^2 + s_* x + t_* = 0\,, \tag{4}$$

where $r_* = a_2/a_3$; $s_* = a_1/a_3$; $t_* = a_0/a_3$.

Using the substitution $y = x + r_*/3$, equation (4) is reduced to the form

$$y^3 + p_* y + q_* = 0\,, \tag{5}$$

where $p_* = s_* - r_*^2/3$; $q_* = 2(r_*/3)^3 - r_* s_*/3 + t_*$.

The roots of equation (5) are found using the Cardano formula:

$$y_1 = u_* + v_*\,;\quad y_2 = \varepsilon_1 u_* + \varepsilon_2 v_*\,;\quad y_3 = \varepsilon_2 u_* + \varepsilon_1 v_*\,, \tag{6}$$

where $u_* = \sqrt[3]{D^{0.5} - 0.5q_*}$; $v_* = \sqrt[3]{-D^{0.5} - 0.5q_*}$; $\varepsilon_{1,2} = 0.5\left(-1 \pm j\sqrt{3}\right)$; $D = (p_*/3)^3 + (q_*/2)^2$ is the discriminant of equation (5).

If D<0, then the cubic equation (5) has three real roots:

$$y_p = 2\sqrt[6]{-p_*^3/27}\cos\left[\frac{1}{3}\arccos\left(-\frac{q_*}{2\sqrt{-p_*^3/27}}\right) + \frac{2}{3}\pi(p-1)\right], \tag{7}$$

where p = 1, 2, 3.

The solution of the system of equations (1), (2) is found in the form:

$$i_1(t) = A_{11}\exp(x_1 t) + A_{12}\exp(x_2 t) + A_{13}\exp(x_3 t) -$$
$$- v_z\frac{i_2}{R_1}\frac{dM_{12}}{dz}; \tag{8}$$

$$i_2(t) = A_{21}\exp(x_1 t) + A_{22}\exp(x_2 t) + A_{23}\exp(x_3 t) -$$
$$- v_z\frac{i_1}{R_2}\frac{dM_{12}}{dz}, \tag{9}$$

where A_{11},…, A_{23} are the constant determined at the moment of time t_k.

After finding the constants A_{11}, …, A_{23}, the expressions for the currents of the inductor and the armature are represented in a recurrent form:

$$i_n(t_{k+1}) = \delta^{-1}\left\{\left[i_n(t_k) - \frac{i_m(t_k)v_z^2}{R_1R_2}\left(\frac{dM_{12}}{dz}\right)^2\right]\times\right.$$

$$\times(\alpha_1\beta_2\beta_3 + \alpha_2\beta_1\beta_3 + \alpha_3\beta_1\beta_2) + \left(\Omega_n - \frac{v_z\Omega_m}{R_n}\frac{dM_{12}}{dz}\right)[\alpha_1(\beta_2+\beta_3) +$$

$$\left. + \alpha_2(\beta_1+\beta_3) + \alpha_3(\beta_1+\beta_2)] + \left(\Lambda_n - \frac{v_z\Lambda_m}{R_n}\frac{dM_{12}}{dz}\right)(\alpha_1+\alpha_2+\alpha_3)\right\}\times$$

$$\times\left[1 - \frac{v_z^2}{R_1R_2}\left(\frac{dM_{12}}{dz}\right)^2\right]^{-1}, \tag{10}$$

where n = 1, 2 at m = 2, 1;

$$\delta = \beta_1\beta_2(\beta_2 - \beta_1) + \beta_1\beta_3(\beta_1 - \beta_3) + \beta_2\beta_3(\beta_3 - \beta_2);$$

$$\alpha_1 = (\beta_3 - \beta_2)\exp(\beta_1\Delta t)\,;\ \alpha_2 = (\beta_1 - \beta_3)\exp(\beta_2\Delta t)\,;$$

$$\alpha_3 = (\beta_2 - \beta_1)\exp(\beta_3\Delta t)\,;$$

$$\beta_p = \left\{2\left(a_2^2 - 3a_1a_3\right)^{0.5}\cos[2\pi(p-1)/3 + \varsigma] - a_2\right\}/3a_3\,;$$

$$p = 1, 2, 3\,;$$

$$\varsigma = \arccos\left[\left(a_2^2 - 3a_1a_3\right)^{-1.5}\left(4.5a_1a_2a_3 - a_2^3 - 13.5a_0a_3^2\right)\right];$$

$$\Omega_n = B_n + \frac{B_m v_z}{R_n}\frac{dM_{12}}{dz};\ \Lambda_n = E_n + \frac{E_m v_z}{R_n}\frac{dM_{12}}{dz};$$

$$\gamma_1 = L_2;\ \ \gamma_2 = -M_{12}\,;$$

$$B_n = \upsilon^{-1}\left[i_n(t_k)\left(M_{12} v_z \frac{dM_{12}}{dz} - R_n L_m \right) + i_m(t_k) \times \right.$$
$$\left. \times \left(R_m M - L_m v_z \frac{dM_{12}}{dz} \right) - \gamma_k u_c(t_k) \right];$$

$$E_1 = \upsilon^{-2}\left\{ i_1(t_k)\left[R_1\left(R_2 M_{12}^2 + R_1 L_2^2 - C^{-1} L_2 \upsilon\right) - v_z M_{12} \frac{dM_{12}}{dz}(\chi + 2R_1 L_2) + \right.\right.$$
$$\left. + v_z^2\left(L_1 L_2 + M_{12}^2\right)\left(\frac{dM_{12}}{dz}\right)^2 \right] + i_2(t_k)\left[v_z\left(L_2\chi + 2R_2 M_{12}^2\right)\frac{dM_{12}}{dz} - M_{12} R_2 \chi - \right.$$
$$\left.\left. - V^2 M_{12} L_2 \left(\frac{dM_{12}}{dz}\right)^2 \right] + u_c(t_k)\left(R_2 M_{12}^2 + L_2^2 R_1 - 2 L_2 V M_{12} \frac{dM_{12}}{dz} \right) \right\};$$

$$E_2 = \upsilon^{-2}\left\{ i_1(t_k)\left[M_{12}\left(C^{-1}\upsilon - R_1\chi\right) + v_z\left(2R_1 M_{12}^2 + L_1\chi\right)\frac{dM_{12}}{dz} - 2 v_z^2 L_1 M_{12} \times \right.\right.$$
$$\left. \times \left(\frac{dM_{12}}{dz}\right)^2 \right] + i_2(t_k)\left[R_2\left(R_1 M_{12}^2 + R_2 L_1^2\right) - M_{12} v_z (2 L_1 R_2 + \chi)\frac{dM_{12}}{dz} + \left(L_1 L_2 + \right.\right.$$
$$\left.\left.\left. + M_{12}^2\right) v_z^2 \left(\frac{dM_{12}}{dz}\right)^2 \right] + u_c(t_k)\left[v_z\left(L_1 L_2 + M_{12}^2\right)\frac{dM_{12}}{dz} - M_{12}\chi \right] \right\},$$

where $u_c(t_k)$ is the CES voltage at the moment of time t_k.

If the discriminant $D<0$ of the characteristic equation (5), then one of its roots is real $x_1 = d$, and the other two are complex conjugate $x_{2,3} = f \pm jg$. The solution of the system of equations (1), (2) is found in the form:

$$i_1(t) = B_{11}\exp(dt) + \exp(ft)\left[B_{12}\cos(gt) + B_{13}\sin(gt)\right] - - v_z \frac{i_2}{R_1}\frac{dM_{12}}{dz}; \qquad (11)$$

$$i_2(t) = B_{21}\exp(dt) + \exp(ft)\left[B_{22}\cos(gt) + B_{23}\sin(gt)\right] - - v_z \frac{i_1}{R_2}\frac{dM_{12}}{dz}; \qquad (12)$$

where B_{11}, …, B_{23} are the constant determined at the moment of time t_k.

In the final form, the currents of the inductor and the armature can be represented in the form of recurrence relations:

$$i_n(t_{k+1}) = \left(\xi_n - \frac{\xi_m v_z}{R_n}\frac{dM_{12}}{dz} \right) \Bigg/ \left[1 - \frac{v_z^2}{R_1 R_2}\left(\frac{dM_{12}}{dz}\right)^2 \right], \qquad (13)$$

where

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

$$\Theta_n = i_n(t_k) + \frac{v_z i_m(t_k)}{R_n}\frac{dM_{12}}{dz}.$$

Mechanical processes in the LPIEC can be described by equation:

$$i_1(t) i_2(t)\frac{dM}{dz} = \left(m_a + m_2\right)\frac{dv_z}{dt} + K_P \Delta z(t) + K_T v_z(t) + + 0.125\pi\gamma_a\beta_a D_{2m}^2 v_z^2(t), \qquad (14)$$

where m_2, m_a are the mass of the armature and AE, respectively; K_P is the coefficient of elasticity of the return spring; $\Delta z(t)$ is the displacement of the armature with AE; K_T is the coefficient of the dynamic friction; γ_a is the density of the medium; β_a is the coefficient of aerodynamic resistance; D_{2m} is the AE outer diameter.

The efficiency of the axial force action on the armature will be estimated by the value of the EDF impulse:

$$F_z = \int f_z(z,t)\,dt, \qquad (15)$$

where $f_z(z, t)$ is the instantaneous value of axial EDF acting on the armature.

On the basis of equation (14), the value of the displacement of the armature with AE can be represented as a recurrence relation:

$$\Delta z(t_{k+1}) = \Delta z(t_k) + v_z(t_k)\Delta t + \vartheta\cdot\Delta t^2 \big/ \left(m_a + m_2\right), \qquad (16)$$

where $v_z(t_{k+1}) = v_z(t_k) + \vartheta\cdot\Delta t/\left(m_a + m_2\right)$ is the speed of the armature with AE along the z-axis;

$$\vartheta = i_1(t_k) i_2(t_k)\frac{dM}{dz}(z) - K_P\Delta z(t_k) - K_T v_z(t_k) - - 0.125\pi\gamma_a\beta_a D_{2m}^2 v_z^2(t_k).$$

Thermal processes. In the absence of moving the armature which occurs either before the start of the direct stroke or after the return stroke, there is thermal contact between the active elements through the insulating gasket. The temperatures of the n-th active elements of the LPIEC can be described here by the recurrence relation [10]:

$$T_n(t_{k+1}) = T_n(t_k)\xi + (1-\xi)\left[\pi^{-1} i_n(t_k) R_n(T_n)\left(D_{en}^2 - D_{in}^2\right)^{-1} + \right.$$
$$\left. + 0.25\pi T_0 D_{en} H_n \alpha_{Tn} + T_m(t_k)\lambda_a(T) d_a^{-1}\right]\left\{0.25\pi\alpha_{Tn} D_{en} H_n + \right. \qquad (17)$$
$$\left. + \lambda_a(T) d_a^{-1}\right\}^{-1},$$

where $\xi = \exp\left\{ -\frac{\Delta t}{c_n(T_n)\gamma_n}\left(0{,}25 D_{en}\alpha_{Tn} + \frac{\lambda_a(T)}{d_a H_n} \right) \right\}$;

$\lambda_a(T)$ is the thermal conductivity of the insulation gasket; d_a is the gasket thickness; D_{en}, D_{in} are the outer and inner diameters of active elements, respectively; α_{Tn} is the heat transfer coefficient of the n-th active element; c_n is the heat capacity of the n-th active element.

The temperatures of the n-th active elements when moving the armature and the absence of thermal contact between the armature and the inductor can be described by the recurrence relation:

$$T_n(t_{k+1}) = T_n(t_k)\chi + (1-\chi)\left[T_0 + 4\pi^{-2} i_n(t_k) R_n(T_n)\alpha_{Tn}^{-1} \times \right.$$
$$\left. \times D_{en}^{-1} H_n^{-1}\left(D_{en}^2 - D_{in}^2\right)^{-1}\right], \qquad (18)$$

where $\chi = \exp\left\{-0.25\Delta t D_{en}\alpha_{Tn} c_n^{-1}(T_n)\gamma_n^{-1}\right\}$.

Initial conditions for the system of equations (1)–(18): $T_n(0)=T_0$ is the temperature of the n-th active element; $i_n(0)=0$ is the current of the n-th active element; $\Delta z(0)= \Delta z_0$ is the initial axial distance between armature and inductor winding; $u_c(0)=U_0$ is the CES voltage; $v_z(0)=0$ is the armature speed along the z-axis.

The LPIEC efficiency will be estimated by the relation:

$$\eta = 100\frac{\left(m_2 + m_e\right)v_z^2 + K_P\Delta z^2}{C_0 U_0^2}\,\%. \qquad (19)$$

The main parameters of the LPIEC. Let us consider the LPIEC of a coaxial configuration in which the armature is made in the form of a flat disc one side of which faces the inductor, and the other interacts with the AE. Main parameters of LPIEC:

Inductor: outer diameter D_{ex1}=100 mm, inner diameter D_{in1}=10 mm, height H_1=10 mm, section of copper bus $a \times b$ = 1.8×4.8 mm^2, the number of turns of the bus N = 46. The inductor is made in the form of a double-layer winding with external electrical terminals.

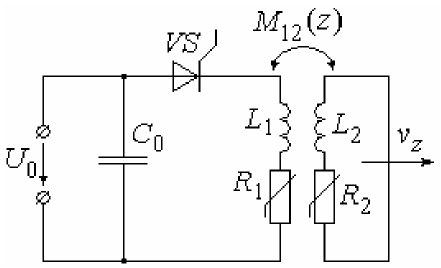
Armature: outer diameter D_{ex2}=100 mm, inner diameter D_{in2}=6 mm, height H_2=2.5 mm. Armature is made of technical copper.

CES: capacitance C_0 = 1 mF, voltage U_0 = 1 kV.

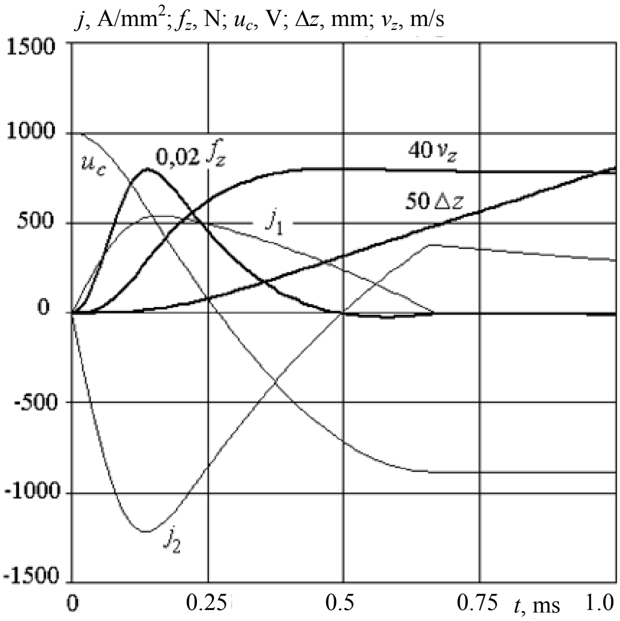
The initial distance between the inductor and the armature is Δz_0 = 1 mm. Coefficient of elasticity of the return spring K_P = 25 kN/m. Weight of the AE m_e = 0.25 kg.

We suppose that in the circuits of the LPIEC inductor power supply, the resistance of the diodes and the thyristor in the forward direction is negligible, and in the opposite direction their conductivity is just as low.

Power supply circuit of the LPIEC inductor forming an unipolar current excitation pulse. The simplest is the power supply circuit of the inductor of the LPIEC which forms an unipolar current excitation pulse in which only the starting thyristor *VS* is used (Fig. 2).



a

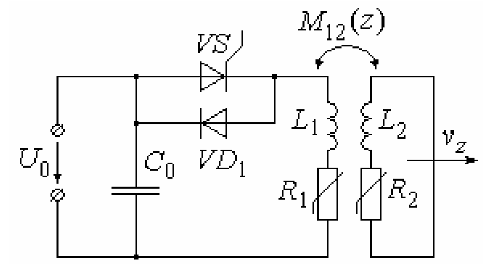


b

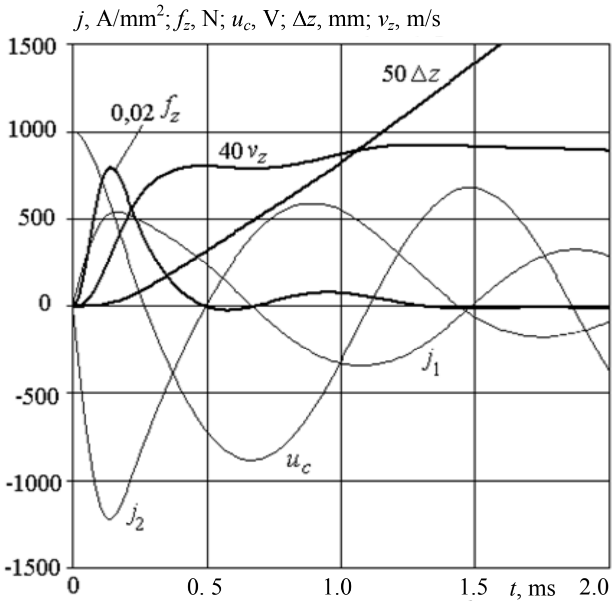
Fig. 2. The electric circuit of the LPIEC forming an unipolar current pulse of the inductor, (*a*) and the electromechanical characteristics of this LPIEC (*b*)

The current pulse in the inductor has a relatively short duration of the leading edge and a longer duration of the trailing edge. This form of the current pulse of the inductor is due to the induction effect of the armature current, which shifts the maximum to the beginning of the excitation process. Note that in the absence of the armature, the inductor current pulse is close in half-sine wave. The maximum values of armature current and inductor due to magnetic coupling occur almost at the same instant of time. The induced current in the armature changes the polarity after 0.5 ms, which causes the appearance of minor brake EDF which act until the current pulse in the inductor passes. The maximum values of current density are: in the inductor j_{1m} = 538.7 A/mm^2, in the armature j_{2m} = 1218.5 A/mm^2. At the instant of the maximum of the current densities, a maximum of the EDF arises, reaching the value f_{zm} = 39.8 kN. The LPIEC considered creates a force impulse F_z = 7.6 Ns, under which the armature, together with the AE, reaches a speed v_z = 17.9 m/s. At the end of the operating cycle, the inductor temperature rise is θ_1 = 0.5 °C, and the temperature rise of the armature is θ_2 = 2 °C. The efficiency of this LPIEC is η = 16.66 %.

The power supply circuit of the LPIEC inductor which forms a vibrationally damped current excitation pulse. The power supply circuit of the LIIEP inductor which forms a vibrationally damped current excitation pulse is realized by shunting the starting thyristor *VS* with a reverse diode VD_1 (Fig. 3).



a



b

Fig. 3. The electric circuit of the LPIEC which forms the oscillating-damped current pulse of the inductor, (*a*) and electromechanical characteristics of this LPIEC (*b*)

The excitation of the LPIEC inductor by a vibrationally-suppressed current pulse leads to a significant change in its electromechanical characteristics. Because of the non-synchronous change in the polarities of the inductor currents and the armature between them, there are both EDF of repulsion, moving the armature with the AE along the *z*-axis, and the EDF of the attraction, which retard the armature. We can note the presence of the main (up to 0.5 ms) and additional (in the interval 0.7-1.3 ms) EDF of repulsion. The additional EDF of repulsion is much less than the main forces, primarily because of the weakened magnetic coupling between the inductor and the armature removed from it.

In the power supply circuit of the LPIEC inductor which forms a vibrational-damped current excitation pulse, an increased EDF impulse F_z = 9.46 Ns acts on the armature, so that together with AE it reaches the speed v_z = 22.3 m/s. At the end of the operating cycle, the inductor temperature rise is θ_1 = 1 ºC, and the temperature rise of the armature θ_2 = 2.4 °C. The efficiency of this LPIEC is increased to the value η = 24.88 %.

However, in the inductor supply circuits that form an unipolar and oscillating-damped excitation current pulses, the voltage of the CES u_c changes its polarity which requires the use of special nonpolar capacitors.

Power supply circuit of the LPIEC inductor forming an aperiodic current excitation pulse. The power supply circuit of the LPIEC inductor which forms an aperiodic current excitation pulse is realized by shunting the inductor with an inverse diode VD_0. This circuit allows the use of electrolytic capacitors with increased specific energy parameters (Fig. 4).

Until the voltage on the CES becomes zero, the currents in the inductor and armature are described by the relations (10) and (13). In the following, currents are described by a system of equations [11]:

$$R_n(T_n)i_n(t)+L_n\frac{di_n}{dt}+M_{nm}(z)\frac{di_m}{dt}+i_m(t)v_z(t)\frac{dM_{nm}}{dz}=0\ ,\qquad(20)$$

where m = 1, 2 at n = 2, 1.

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

$$\left(1-K_{12}^2\right)\frac{d^2i_1}{dt^2}+\left(\gamma_1+\gamma_2-2\xi_1\chi_2\right)\frac{di_1}{dt}+\left(\gamma_1\gamma_2-\chi_1\chi_2\right)i_1=0\ ,\qquad(21)$$

where

$$\gamma_n=\frac{R_n}{L_n};\ \xi_n=\frac{M_{nm}(z)}{L_n};\ \chi_n=\frac{v_z(t)}{L_n}\frac{dM_{nm}}{dz};\ K_{12}=\frac{M_{nm}(z)}{(L_nL_m)^{0,5}}.$$

The characteristic equation of the differential equation (21) has two real roots

$$x_{1,2}=\frac{1}{1-K_{12}^2}\Big\langle\xi_1\chi_2-0.5\cdot(\gamma_1+\gamma_2)\pm\Big\{\left[0.5(\gamma_1+\gamma_2)-\xi_1\chi_2\right]^2+\left(K_{12}^2-1\right)\left(\gamma_1\gamma_2-\chi_1\chi_2\right)\Big\}^{0.5}\Big\rangle.\qquad(22)$$

Expressions for currents in the final form are described by recurrence relations:

$$i_n(t_{k+1})=\frac{1}{x_1-x_2}\Bigg\{i_n(t_k)\left[x_1\exp(x_2\Delta t)-x_2\exp(x_1\Delta t)\right]+\frac{\exp(x_1\Delta t)-\exp(x_2\Delta t)}{1-K_{12}^2}\left[i_n(t_k)(\xi_n\chi_m-\gamma_n)+i_m(t_k)\left(\gamma_m\xi_n-\chi_n\right)\right]\Bigg\}.\qquad(23)$$

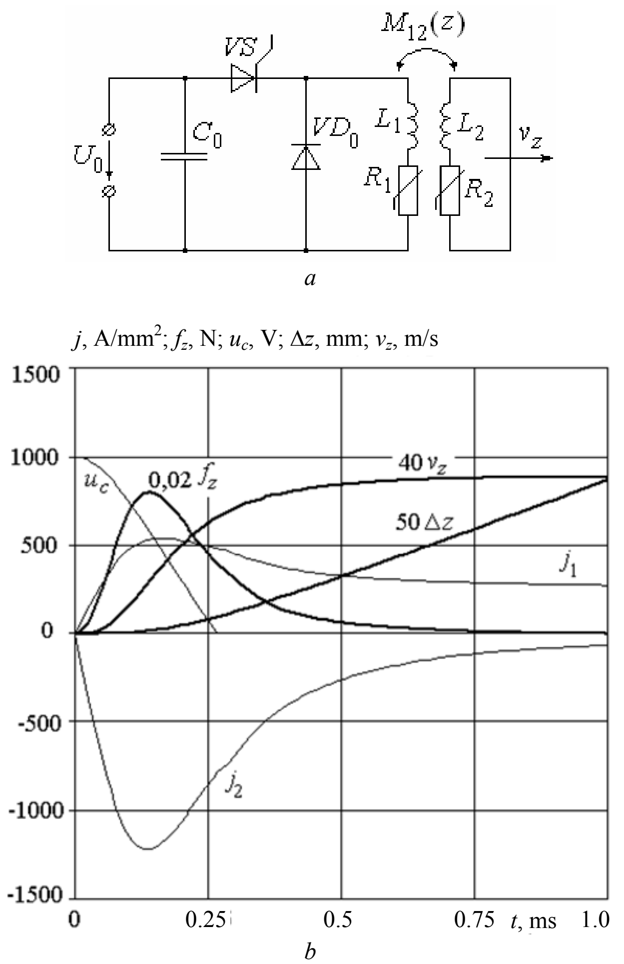


Fig. 4. The electrical circuit of the LPIEC which forms the aperiodic current pulse of the inductor, (*a*) and the electromechanical characteristics of this LPIEC (*b*)

At an aperiodic current pulse of an inductor, the LPIEC retains both the polarity of the CES voltage u_c and the polarity of the inductor and armature currents (Fig. 4). After reaching the CES voltage u_c = 0, the current in the inductor starts to flow through the inverse diode VD_0. Due to the preservation of the polarity of the currents, only the repulsion EDF act on the armature, the value of the impulse being F_z = 8.85 Ns. The armature, together with AE, reaches the speed v_z = 20.8 m/s. At the end of the operating cycle, the inductor temperature rise θ_1 is 1.1 °C, and the temperature rise of the armature θ_2 is 1.7 °C. The efficiency of the LPIEC η is 22.23 %.

Electromechanical indices of LPIEC with aperiodic current pulse of inductor are better than in LPIEC with excitation of inductor by unipolar current pulse, but worse than in LPIEC with excitation of inductor by oscillating-damped current pulse. In the converter with an aperiodic current pulse of the inductor, the inductor is heated more warmly and the armature heating is lowered.

Power supply circuit of the LIIEP inductor forming an aperiodic current excitation pulse with the connection of an additional CES. The preservation of the polarity of the voltage u_c in the power circuit of the LIIEP inductor forming an aperiodic current excitation pulse opens up prospects for improving this circuit, for example, by connecting an additional CES-1 during the discharge of the initial CES-0 with the parameters C_0 and U_0 [12]. The additional CES-1 with capacity C_1 is pre-charged to voltage U_1 which is less than the voltage U_0 of the original CES-0 (Fig. 5). During the discharge of the CES-0, when the voltage $u_c<U_1$, the CES-1 is connected via the diode VD_1, increasing the discharge capacitance to the value C_0+C_1.

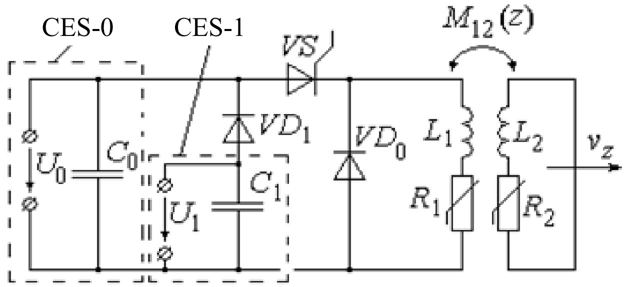


Fig. 5. The electrical circuit of the LPIEC which forms an aperiodic current pulse of the inductor with the connection of an additional CES-1

Since this circuit has not been practically studied, let us consider the effect of the parameters of the additional CES-1 on the electromechanical parameters of the LPIEC. First, consider the effect of the value of the voltage U_1 of the additional CES-1 on the LPIEC indicators, since its value determines the moment of connection to the initial CES-0. Let us consider three options for connecting an additional CES-1: before (U_1=0.7U_0), at the time (U_1=0.6U_0) and after (U_1=0.5U_0) reaching the maximum EDF acting on the armature. We will use an additional CES-1 for which $C_1 = C_0$.

The efficiency of the LPIEC with this circuit of the inductor supply will be estimated by the relation

$$\eta = 100\frac{(m_2 + m_e)v^2 + K_P \Delta z^2}{C_0 U_0^2 + C_1 U_1^2}\ \%. \tag{24}$$

At the moment of connection of the additional CES-1, up to the maximum of the EDF (U_1=0.7U_0) at the leading edge of the current pulses of the inductor and the armature, perturbations are observed (Fig. 6,*a*). This gives rise to a corresponding perturbation at the leading edge of the EDF curve. After connecting the additional CES-1, the voltage u_c begins to decrease more slowly. Compared with the use of only the original CES-0, the maximum values of the current densities have increased: in the inductor, up to 603.6 A/mm^2, in the armature up to 1324.6 A/mm^2. This led to an increase in the EDF maximum to 47.2 kN, the EDF impulse to 11.5 Ns, and the armature speed with AE to 27.1 m/s. However, due to the energy of the additional CES-1, the efficiency of the LPIEC is reduced to 18.8 %. In addition, when the LPIEC operates with this inductor feed circuit, higher temperature rises ($\theta_n = T_n - T_0$) of the inductor θ_1 = 2.1 °C and an armature θ_2 = 2.2 °C are observed, in comparison with the previously considered circuits.

When connecting the additional CES-1 at the time of the appearance of the maximum of the EDF ($U_1 = 0.6U_0$), local growth of the values of the current pulses of the inductor and the armature is observed (Fig. 6,*b*).

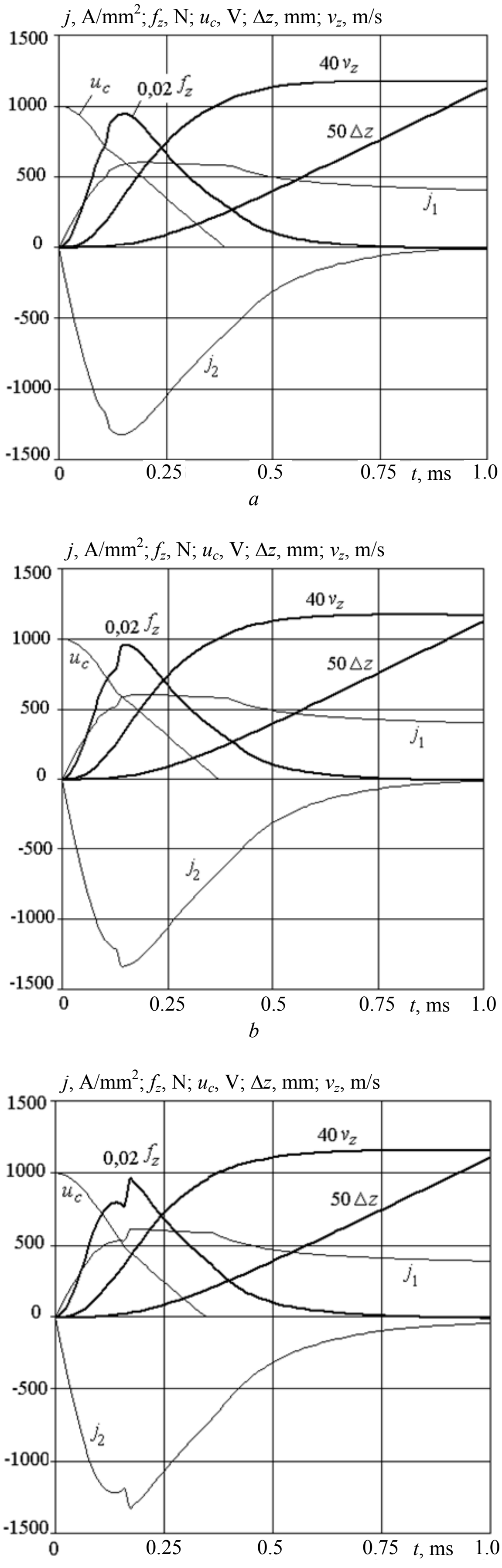


Fig. 6. Electromechanical characteristics of LPIEC when connecting an additional CES-1 charged to voltage U_1: 0.7U_0 (*a*); 0.6U_0 (*b*); 0.5U_0 (*c*)

At that moment, a corresponding increase in EDF occurs. Despite a certain change in electromechanical characteristics, on the whole, the indicators of the LPIEC remained virtually unchanged compared to the previous version ($U_1 = 0.7U_0$). When CES-1 is connected, after the appearance of the maximum of the EDF ($U_1 = 0.5U_0$), a local increase in the values of the current pulses of the inductor and the armature on their trailing edge is observed (Fig. 6,*c*).

After connecting the ENE-1, the current in the inductor begins to decrease more slowly until the instant $u_c = 0$.

Thus, the additional CES-1 and with small and high values of voltages U_1, which are connected, respectively, on the back and front edges of the EDF, allow increasing the electromechanical performance of the LPIEC. For example, when connecting CES-1 with low voltage ($U_1 = 0.15U_0$), the armature speed increases by 27 %, the value of the EDF impulse increases by 27 %, and the efficiency decreases by 25 %. When connecting CES-1 with high voltage ($U_1 = 0.75U_0$), the armature speed increases by 29.7 %, the value of the EDF impulse increases by 29.6 %, and the efficiency decreases by 18.7 %.

With this power circuit, all electromechanical parameters of the LPIEC are higher in comparison with the LPIEC with the circuit of the inductor supply forming a vibrationally damped current excitation pulse. So, when using CES-1 with voltage $U_1 = 0.6U_0$, the maximum value of the EDF f_{zm} is increased by 20 %, and the value of the EDF impulse F_z and the speed of the armature v_z by 21.6 %. In this case, the temperature rise of the inductor θ_1 increases by 2.12 times, and the temperature rise of the armature θ_2 decreases by 11.3 %. The efficiency of the LPIEC η is reduced by 32.2 %.

We note that the electromechanical indicators of the LPIEC using an additional CES-1 with voltage $U_1 = 0.6U_0$ are higher than in the LPIEC with a power circuit that forms an aperiodic current excitation pulse of the inductor with initial capacitance $C_0 = 2$ mF.

LPIEC indicators also depend on the capacitance C_1 of the additional CES-1 (Fig. 7).

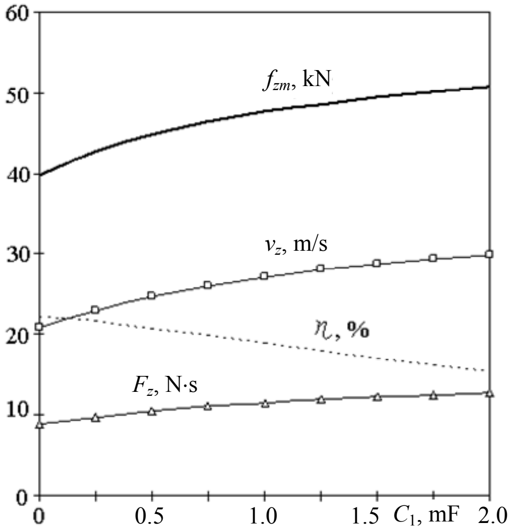


Fig. 7. Dependence of electromechanical indicators of LPIEC on capacitance C_1 at $U_1 = 0.6U_0$

With increasing this capacity, all main electromechanical indicators of the LPIEC grow. Thus, as the capacitance C_1 increases from zero to 2 mF, the maximum current density of the inductor j_{1m} increases by 24.3 %, the armature current density j_{2m} by 12.8 %, the maximum EDF value F_z by 27.6 %, the EDF impulse value F_z and the armature speed v_z by 43.6 % . However, in this case, the temperature rise of the inductor θ_1 increases by 2.7 times, the armature temperature rise θ_2 by 40.7 %. The efficiency of the LPIEC η is reduced by 45.2 %.

Thus, LPIEC with the power circuit of the inductor which forms an aperiodic current excitation pulse with connection of an additional CES-1 provides increased electromechanical parameters. However, it should be borne in mind that the additional CES-1 leads to increased heating of the inductor and armature, as well as to a decrease in the efficiency of the LPIEC.

Conclusions.

1. With the use of the developed circuit mathematical model, recurrence relations were obtained for calculating the interrelated electromagnetic, mechanical, and thermal parameters of the LPIEC with different inductor power circuits.
2. It is established that the electromechanical indicators of the LPIEC with the power supply circuit of the inductor forming the aperiodic current excitation pulse are better than in the LPIEC with the excitation of the inductor by a unipolar current pulse, but worse than in the LPIEC with excitation of the inductor by a vibrationally damped current pulse. In the converter with an aperiodic current excitation pulse, the inductor is heated most strongly, and the armature is least strongly heated.
3. It is established that in the LPIEC with the power supply circuit of the inductor forming an aperiodic current excitation pulse with the connection of an additional CES, all electromechanical parameters are higher in comparison with the LPIEC with the power circuit forming the oscillating-damped current excitation pulse of the inductor. However, in this LPIEC there is an increased heating of active elements, especially an inductor, and a decrease in efficiency occurs.

REFERENCES

1. Balikci A., Zabar Z., Birenbaum L., Czarkowski D. Improved performance of linear induction launchers. *IEEE Transactions on Magnetics*, 2005, vol.41, no.1, pp. 171-175. **doi: 10.1109/tmag.2004.839283.**

2. D.-K. Lim, D.-K. Woo, I.-W. Kim, D.-K. Shin, J.-S. Ro, T.-K. Chung, H.-K. Jung. Characteristic Analysis and Design of a Thomson Coil Actuator Using an Analytic Method and a Numerical Method. *IEEE Transactions on Magnetics*, 2013, vol.49, no.12, pp. 5749-5755. **doi: 10.1109/tmag.2013.2272561**.

3. Tomashevsky D.N., Koshkin A.N. Modeling of linear impulse electric motors. *Russian Electrical Engineering*, 2006, no.1, pp. 24-27. (Rus).

4. Bolyukh V.F., Oleksenko S.V., Shchukin I.S. Comparative analysis of linear pulse electromechanical converters electromagnetic and induction types. *Technical Electrodynamics*, 2016, no.5, pp. 46-48. (Rus).

5. Bissal A., Magnusson J., Engdahl G. Comparison of two ultra-fast actuator concept. *IEEE Transactions on Magnetics*, 2012, vol.48, no.11, pp. 3315-3318. **doi: 10.1109/tmag.2012.2198447.**

6. Young-woo Jeong, Seok-won Lee, Young-geun Kim, Hyun-wook Lee. High-speed AC circuit breaker and high-speed OCD. *22nd International Conference and Exhibition on Electricity Distribution (CIRED 2013)*, 2013, 10-13 June, Stockholm, Paper 608. **doi: 10.1049/cp.2013.0834.**
7. Li W., Koh C.S. Parametric analysis of Thomson-coil actuator using adaptive equivalent circuit method. *Digests of the 2010 14th Biennial IEEE Conference on Electromagnetic Field Computation*, May 2010, pp. 1-9. **doi: 10.1109/cefc.2010.5481673.**
8. Bolyukh V.F., Oleksenko S.V., Katkov I.I. The use of fast cryogenic cooling and ferromagnetic core greatly increases efficiency of a linear induction-dynamic converter. *Proceedings of the 13th cryogenics 2014 IIR int. conf.* Praha, Czech Republic, 7-11 April, 2014, Paper ID: 012, pp. 268-275.
9. Bolyukh V.F., Shchukin I.S. *Lineinye induktsionno-dinamicheskie preobrazovateli* [Linear induction-dynamic converters]. Saarbrucken, Germany, LAP Lambert Academic Publ., 2014. 496 p. (Rus).
10. Bolyukh V.F., Markov A.M., Luchuk V.F., Shchukin I.S.. Energy processes and efficiency of a dynamic induction percussion converter. *Electrical engineering and electromechanics*, 2009, no.2, pp. 9-14. (Rus). **doi: 10.20998/2074-272X.2009.2.02.**
11. Bolyukh V.F., Markov A.M., Luchuk V.F., Shchukin I.S. Theoretical and experimental studies of an induction-dynamic motor excited from a polar capacitive reservoir. *Technical electrodynamics. Thematic issue «Problems of modern electrical engineering»*. 2006, part 2, pp. 65-70. (Rus).
12. Ivashin V.V., Ivannikov N.A. *Induktsionno-dinamicheskiy privod* [Induction-dynamic drive]. Patent Russian Federation, no. 2485614, 2013. (Rus).

Received 10.11.2017

V.F. Bolyukh[1], *Doctor of Technical Science, Professor,*
A.I. Kocherga[1], *Postgraduate Student,*
I.S. Schukin[2], *Candidate of Technical Science, Associate Professor,*
[1] National Technical University «Kharkiv Polytechnic Institute»,
2, Kyrpychova Str., Kharkiv, 61002, Ukraine,
phone +380 57 7076427,
e-mail: vfbolyukh@gmail.com
[2] Firm Tetra, LTD,
2, Kyrpychova Str., Kharkiv, 61002, Ukraine,
phone +380 57 7076427,
e-mail: tech@tetra.kharkiv.com.ua

How to cite this article:
Bolyukh V.F., Kocherga A.I., Schukin I.S. Investigation of a linear pulse-induction electromechanical converter with different inductor power supply circuits. *Electrical engineering & electromechanics*, 2018, no.1, pp. 21-28. **doi: 10.20998/2074-272X.2018.1.03.**