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INVESTIGATION OF THERMAL PROCESSES IN A LINEAR PULSE-INDUCTION ELECTROMECHANICAL CONVERTER OF CYCLIC ACTION

Purpose. Investigation of the influence of the intensity of cooling of active elements and the period of succession of power pulses on the thermal processes of linear pulse-induction electromechanical converter (LPIEC) operating in a cyclic mode. Methodology. The electromechanical and energy processes of LPIEC, which arise during the direct course of the working cycle, are investigated. It is shown that by the end of the operating cycle, a significant part of the energy is stored in the capacitive energy storage device, and is also converted into thermal energy of the armature and inductor. With a significant number of operating cycles, an unacceptably high temperature rise of LPIEC active elements occurs. To solve this problem, intensive cooling of the winding of the inductor, the movable armature or both of them, as well as an increase in the pulse repetition period are used. It has been experimentally established that when the LPIEC is operating in a cyclic mode, the inductor winding with a steel frame blown with air is heated more slowly than the winding with an insulating frame. The experimental dependences with an accuracy of 6 % coincide with the calculated results. A constructive scheme of the LPIEC of cyclic action with intensive cooling of the stationary winding of the inductor has been developed. Results. A mathematical model of the LPIEC of cyclic action is developed, taking into account a complex of interrelated electromechanical and thermal processes. The solutions of its equations are represented in a recurrent form. The electromechanical and energy processes of LPIEC, which arise during the direct course of the working cycle, are investigated. It is shown that for a considerable number of operating cycles, unacceptably high temperature excesses of active elements of the LPIEC are observed. It is shown that intensive cooling of the winding of the inductor, the movable armature or both of them, and also the increase in the pulse repetition period ensure the temperature stabilization of the LPIEC. Measurements of the temperature on the surface of the winding of the inductor LPIEC during cyclic operation are carried out. A constructive scheme of the LPIEC of cyclic action with intensive cooling of the stationary winding of the inductor has been developed. Originality. A mathematical model of the LPIEC of cyclic action is developed, taking into account a complex of interrelated electromechanical and thermal processes. The solutions of its equations are represented in a recurrent form. It is shown that by the end of the working cycle a significant part of the energy is converted into thermal energy of the armature and inductor. It is determined that for a significant number of operating cycles, unacceptably high temperature excesses of active elements of the LPIEC are observed. It is shown that intense cooling of active elements, as well as an increase in the pulse repetition period, ensure the temperature stabilization of the LPIEC. A design scheme of the LPIEC with intensive cooling of the stationary winding of the inductor has been developed. Practical value. It is shown that by thermal cooling of at least one of the active elements and by increasing the pulse repetition period, the temperature stabilization of the LPIEC is ensured. A constructive scheme of the LPIEC of cyclic action with intensive cooling of the stationary winding of the inductor has been developed. References 13, tables 1, figures 12.
Key words: **linear pulse-induction electromechanical converter, cyclic action, thermal state, mathematical model, electromechanical and energy processes, intensive cooling, experimental studies, constructive scheme.**

Разработана математическая модель линейного импульсно-индукционного электромеханического преобразователя (ЛИИЭП) циклического действия, система уравнений которой учитывает комплекс взаимосвязанных электромагнитных, электромеханических и тепловых процессов. Решения этих уравнений представлены в рекуррентном виде. Исследованы процессы ЛИИЭП, протекающие при прямом ходе рабочего цикла. Показано, что к концу рабочего цикла значительная часть энергии сохраняется в емкостном накопителе энергии, а также преобразуется в тепловую энергию якоря и индуктора. При значительном числе рабочих циклов происходит недопустимый нагрев активных элементов ЛИИЭП. Для решения этой проблемы используется интенсивное охлаждение обмотки индуктора, подвижного якоря или их обоих, а также увеличение периода следования импульсов. Установлено, что при работе ЛИИЭП в циклическом режиме экспериментальные зависимости температуры нагрева обмотки индуктора с точностью до 6 % совпадают с расчетными результатами. Разработана конструктивная схема ЛИИЭП циклического действия с интенсивным водяным охлаждением обмотки индуктора. Библ. 13, табл. 1, рис. 12.
Ключевые слова: **линейный импульсно-индукционный электромеханический преобразователь, циклическое действие, тепловое состояние, математическая модель, электромеханические и энергетические процессы, интенсивное охлаждение, экспериментальные исследования, конструктивная схема.**

Introduction. Linear pulse-induction electromechanical converters (LPIEC) are used in many branches of science, engineering and technology. They are used for cleaning technological equipment and bunkers from the remains of bulk cargo, testing critical products and devices for impact, processing and forming of metal structures. Such converters are used in the mining industry and geological exploration, in mechanical engineering with magnetic pulse welding, stamping, perforation, in various measuring instruments, electromechanical accelerators, etc. [1-4].

In many technical systems, the LPIEC must provide a continuous sequence of power pulses with a specified period of travel. In such a converter, a short period of the load (active mode of operation) is realized in each working cycle, at which intense current pulses are excited in the active elements (inductor and armature), and the armature moves straight with the actuator, and a prolonged pause (passive mode work). During the passive mode, the armature moves backward with actuator under the action, for example, of a return spring, and the

ensuing resting mode of the armature, at which the capacitive energy storage (CES) device is charged. Although this regime resembles repeatedly with a short turn-on time for traditional electric machines, it has significant features [5, 6]. This is due to the fact that the impulse load is so short that the temperature rise in the active elements of the LPIEC occurs practically in adiabatic conditions.

In the cyclical mode of operation, they are subject to investigation:

• permissible excess temperatures of active elements for a given number of operating cycles;

• the power pulse repetition period, in the passive mode of which the active elements of the LPIEC are cooled to a given thermal state;

• allowable number of cycles for a given pulse repetition period and cooling intensity.

In LPIEC, in a forward motion, a stationary inductor driven from a CES, by means of a pulsed magnetic field, induces currents in an electrically conductive armature, which, under the action of electrodynamic forces, provides a rapid movement of actuator in a forward motion, which exerts, for example, impact force on the object. In the reverse course, the armature with the actuator returns to its original position in the zone of maximum magnetic coupling with the inductor, followed by a pause, during which the charge of the CES is performed for the subsequent operating cycle. Thus, in the considered converters with the return-post motion of the armature with actuator, complex spatio-temporal, dependent from each other impulse electrical, magnetic, mechanical and thermal processes [7].

Since pulsed current loads in LPIEC repeatedly exceed similar indicators of electromechanical devices of continuous action, in a cyclic mode of operation a special role is assumed by thermal processes that to a large extent determine the conditions and operating time of the converter. In turn, the thermal state of the LPIEC essentially depends on [6]:

• parameters and constructive performance of the inductor, armature and CES;

• the shape of the winding current of the inductor, determined by the electronic excitation circuit;

• the pulse repetition rate (period);

• the nature of the movement of the armature;

• intensity of cooling of active elements.

However, up to now, these thermal processes have not been practically studied, which can be explained by the complex and interrelated nature of processes of different physical nature, which, moreover, depend on the constructive performance, purpose and conditions of the LPIEC operation. Particularly topical is the question of the effect of the cooling intensity of the active elements of the transducer and the duration of the pulse repetition period on their thermal state.

The goal of the paper is investigations of the influence of the intensity of cooling of active elements and the period of the succession of power pulses on the thermal state of the LPIEC in a cyclic mode of operation.

Design of LPIEC. As the object of research, the LPIEC of cyclic action is chosen, the actuator of which

contains a spring-loaded punch making power pulses along the test plate installed below (Fig. 1) [7].

Fig. 1. General view of the LPIEC of cyclic action

The LPIEC operates in an environment with natural cooling. The electronic circuit of excitation of the inductor provides a series of unipolar current pulses, which allows to save some of the energy in the CES by the end of the working cycle [5].

The LPIEC of the coaxial configuration contains a fixed inductor with a two-layer winding of the disk shape, which is wound with a rectangular copper busbar, is epoxy resin and is laid either in a thick-walled insulating (fiberglass) or in a thin-walled (1 mm) steel frame [8] (Fig. 2). The feature of the steel frame is that through it, it is possible to provide intensive air or water cooling of the winding of the inductor.
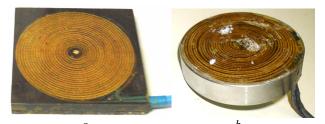

a *b*
Fig. 2. LPIEC inductors with glass-textolite (*a*) and steel (*b*) frames

Coaxially with the inductor there is a copper disk armature, which is connected to the power disk, which ensures the movement of the striker towards the target object. Thus, the actuator consists of a power disk and striker, which are made of stainless non-magnetic steel.

To the power disk, return springs are connected, ensuring a tight clamping of the armature to the inductor before and after the force pulse. The main parameters of the LPIEC are presented in Table 1.

Mathematical model of LPIEC. The mathematical model of the LPIEC of cyclic action should promptly calculate the complex of interrelated electromagnetic, electromechanical and thermal processes in each operational cycle, take into account the variable magnetic coupling between the armature and the inductor winding during a forward stroke, the change in the resistance of the winding of the inductor and the armature due to heating by impulse currents, acting on the armature, the cooling conditions and the thermal interaction of the active elements. It should be taken into account that there are insignificant temperature gradients along the cross-section of active elements [6]. Field methods of

calculation are expedient for applying to the investigation of LPIEC processes under a single operating regime [9, 10].

LPIEC parameters

Designation	Symbol	Value
Outer diameter of inductor winding, mm	D_{ex1}	100
Inner diameter of inductor winding, mm	D_{in1}	10
Height of inductor winding, mm	h_1	10
Outer diameter of armature, mm	D_{ex2}	100
Inner diameter of armature, mm	D_{in2}	10
Height of armature, mm	h_2	2.5
Insulation thickness between inductor winding and armature, mm	ΔZ_0	0.5
Number of turns of inductor winding	w_1	42
Turn section of the inductor winding, mm^2	$a \times b$	1.8×4.8
Coefficient of elasticity of return spring, kN/m	K_p	25.0
Actuator mass, kg	m_a	0.35
CES capacitance, µF	C	3000
CES charging voltage, V	U_0	310

In the cyclic mode of operation, it is advisable to use the LPIEC chain model with lumped parameters [11], and solve the equations in a recurrent form assuming all the parameters on the interval $\Delta t = t_{k+1} - t_k$ are unchanged [12].

Electromagnetic processes arising in the LPIEC at the connection to the CES can be described by the following system of equations:

$$\left[R_1(T_1) + R_0\right] \cdot i_1 + L_1 \frac{di_1}{dt} + \frac{1}{C}\int_0^t i_1 dt + M_{12}(z)\frac{di_2}{dt} + \tag{1}$$

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

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

where $n = 1, 2$ are the indexes of the inductor and the 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 is the capacitance of the CES charged to the voltage U_0; $M_{12}(z) = M_{21}(z)$ is the mutual inductance between the inductor and the armature moved along the axis z with velocity v.

We indicate

$R_1 = R_1(T_1) + R_0; R_2 = R_2(T_2); M = M_{12}(z) = M_{21}(z)$.

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

$$a_3 = \upsilon; \quad a_2 = \chi - 2Mv\frac{dM}{dz}; \quad a_1 = R_1 R_2 + \frac{L_2}{C} - v^2\left(\frac{dM}{dz}\right)^2;$$

$$a_0 = \frac{R_2}{C}; \quad \upsilon = L_1 L_2 - M^2; \quad \chi = R_1 L_2 + L_1 R_2.$$

If the discriminant of its characteristic equation is less than zero, then all the roots are real and the solution for the currents after a series of transformations is represented in a recurrent form [5]

$$i_n(t_{k+1}) = \delta^{-1}\left[1 - \frac{v^2}{R_1 R_2}\left(\frac{dM}{dz}\right)^2\right]^{-1}\left\{\left[i_n(t_k) - \frac{i_m(t_k)v^2}{R_1 R_2}\left(\frac{dM}{dz}\right)^2\right]\times\right.$$

$$\times(\alpha_1 x_2 x_3 + \alpha_2 x_1 x_3 + \alpha_3 x_1 x_2) + \left(\Omega_n - \frac{v\Omega_m}{R_n}\frac{dM}{dz}\right)[\alpha_1(x_2 + x_3) +$$

$$+ \alpha_2(x_1 + x_3) + \alpha_3(x_1 + x_2)] + \left.\left(\Lambda_n - \frac{v\Lambda_m}{R_n}\frac{dM}{dz}\right)(\alpha_1 + \alpha_2 + \alpha_3)\right\}, \tag{4}$$

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

$$\delta = x_1 x_2 (x_2 - x_1) + x_1 x_3 (x_1 - x_3) + x_2 x_3 (x_3 - x_2);$$

$$\alpha_1 = (x_3 - x_2)\exp(x_1 \Delta t); \quad \alpha_2 = (x_1 - x_3)\exp(x_2 \Delta t);$$

$$\alpha_3 = (x_2 - x_1)\exp(x_3 \Delta t);$$

$$x_p = \left\{2\left(a_2^2 - 3a_1 a_3\right)^{0.5}\cos[2\pi(p-1)/3 + \varsigma] - a_2\right\}/3a_3;$$

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

$$\varsigma = \arccos\left[\left(a_2^2 - 3a_1 a_3\right)^{-1.5}\left(4{,}5a_1 a_2 a_3 - a_2^3 - 13.5a_0 a_3^2\right)\right];$$

$$\Omega_n = B_n + \frac{B_m v}{R_n}\frac{dM}{dz}; \quad \Lambda_n = E_n + \frac{E_m v}{R_n}\frac{dM}{dz};$$

$$\gamma_1 = L_2; \quad \gamma_2 = -M;$$

$$B_n = \upsilon^{-1}\left[i_n(t_k)\left(Mv\frac{dM}{dz} - R_n L_m\right) + i_m(t_k)\times\right.$$

$$\times\left.\left(R_m M - L_m v\frac{dM}{dz}\right) - \gamma_k u_c(t_k)\right];$$

$$E_1 = \upsilon^{-2}\left\{i_1(t_k)\left[R_1\left(R_2 M^2 + R_1 L_2^2 - C^{-1}L_2\upsilon\right) - vM\times\right.\right.$$

$$\times\frac{dM}{dz}\left(\chi + 2R_1 L_2\right) + v^2\left(L_1 L_2 + M^2\right)\left.\left(\frac{dM}{dz}\right)^2\right] +$$

$$+ i_2(t_k)\left[v\left(L_2\chi + 2R_2 M^2\right)\frac{dM}{dz} - MR_2\chi - v^2 ML_2\times\right.$$

$$\times\left.\left(\frac{dM}{dz}\right)^2\right] + u_c(t_k)\left.\left(R_2 M^2 + L_2^2 R_1 - 2L_2 vM\frac{dM}{dz}\right)\right\};$$

$$E_2 = \upsilon^{-2}\left\{i_1(t_k)\left[M\left(C^{-1}\upsilon - R_1\chi\right) + v\left(2R_1 M^2 + L_1\chi\right)\times\right.\right.$$

$$\times\frac{dM}{dz} - 2v^2 L_1 M\left.\left(\frac{dM}{dz}\right)^2\right] + i_2(t_k)\left[R_2\left(R_1 M^2 + R_2 L_1^2\right) - \right.$$

$$\left[- Mv\left(2L_1 R_2 + \chi\right)\frac{dM}{dz} + \left(L_1 L_2 + M^2\right)v^2\left(\frac{dM}{dz}\right)^2\right] +$$

$$+ u_c(t_k)\left[v\left(L_1 L_2 + M^2\right)\frac{dM}{dz} - M\chi\right]\right\};$$

u_c is the CES voltage.

If the discriminant of the characteristic equation for equation (3) is greater than zero, then one of its roots is real $x_1 = d$, and the other two are complex conjugate $x_{2,3} = f \pm jg$, and the solution for the currents takes the form:

$$i_n(t_{k+1}) = \left(\xi_n - \frac{\xi_m v}{R_n}\frac{dM}{dz}\right) \Bigg/ \left[1 - \frac{v^2}{R_1 R_2}\left(\frac{dM}{dz}\right)^2\right], \quad (5)$$

where

$$\xi_n = g^{-1}\big[g^2 + (f-d)^2\big]^{-1}\Big\langle g \cdot \exp(d\Delta t)\big[(g^2 + f^2)\Theta_n - 2f\Omega_n + \Lambda_n\big] +$$

$$+ \exp(f\Delta t)\big\{\sin(g\Delta t)\big[d(f^2 - g^2 - fd)\Theta_n + (g^2 + d^2 - f^2)\Omega_n + (f-d)\Lambda_n\big] +$$

$$+ g\cdot\cos(g\Delta t)\big[d(d-2f)\Theta_n + 2f\Omega_n - \Lambda_n\big]\big\}\Big\rangle;$$

$$\Theta_n = i_n(t_k) + \frac{v\cdot i_m(t_k)}{R_n}\frac{dM}{dz}.$$

Mechanical processes in the LPIEC in the general case can be described by the following equation:

$$i_1(t)i_2(t)\frac{dM}{dz}(z) = (m_a + m_2)\frac{dv}{dt} + K_P\Delta z(t) + K_T v(t) + \quad (6)$$

$$+ 0.125\pi\gamma_a\beta_a D_{2m}^2 v^2(t),$$

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

On the basis of equation (6), the value of the displacement of the armature with actuator can be represented in the form of a recurrence relation [5]:

$$\Delta z(t_{k+1}) = \Delta z(t_k) + v(t_k)\Delta t + \vartheta \cdot \Delta t^2 / (m_a + m_2), \quad (7)$$

where $v(t_{k+1}) = v(t_k) + \vartheta \cdot \Delta t/(m_a + m_2)$ is the velocity of the armature with actuator;

$$\vartheta = i_1(t_k)i_2(t_k)\frac{dM}{dz}(z) - K_P\Delta z(t_k) - K_T v(t_k) -$$

$$- 0.125\pi\gamma_a\beta_a D_{2m}^2 v^2(t_k).$$

Thermal processes are largely determined by the period of operation of the LPIEC during the working cycle. So, in the absence of armature movement 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 liner. The temperatures of the n-th active elements of the LPIEC can be described here by the recurrence relation [6]:

$$T_n(t_{k+1}) = T_n(t_k)\xi + (1-\xi)\Big[\pi^{-1}i_n(t_k)R_n(T_n)\big(D_{en}^2 - D_{in}^2\big)^{-1} +$$

$$+ 0.25\pi T_0 D_{en}H_n\alpha_{Tn} + T_m(t_k)\lambda_a(T)d_a^{-1}\Big]\big\{0.25\pi\alpha_{Tn}D_{en}H_n + \quad (8)$$

$$+ \lambda_a(T)d_a^{-1}\big\}^{-1},$$

where

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

$\lambda_a(T)$ is the heat transfer coefficient of the insulating gasket; d_a is the gasket thickness; D_{en}, D_{in} is the outer and inner diameters of the active elements, respectively; α_{Tn} is the heat exchange coefficient of the n-th active element; c_n is the specific heat 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:

$$T_n(t_{k+1}) = T_n(t_k)\chi + (1-\chi)\Big[T_0 + 4\pi^{-2}i_n(t_k)R_n(T_n)\alpha_{Tn}^{-1} \times$$

$$\times D_{en}^{-1}H_n^{-1}\big(D_{en}^2 - D_{in}^2\big)^{-1}\Big], \quad (9)$$

where $\chi = \exp\big\{-0.25\Delta t D_{en}\alpha_{Tn}c_n^{-1}(T_n)\gamma_n^{-1}\big\}$.
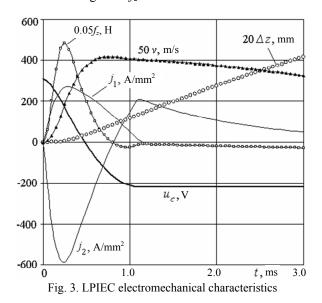
Initial conditions of the system of equations (1) – (9):
$T_n(0) = T_0$ – the temperature of the n-th active element;
$i_n(0) = 0$ – the current of the n-th active element;
$\Delta z(0) = \Delta z_0$ – the initial axial distance between the armature and the inductor winding;
$u_c(0) = U_0$ – the CES voltage;
$v(0) = 0$ – the armature velocity.

Functioning of LPIEC at natural cooling. Electromechanical processes of LPIEC in the direct course of a working cycle with natural cooling (α_{Tn}=20 W·m^{-2}·K^{-1}) are shown in Fig. 3. The current density in the winding of the inductor j_1 is in the form of a polar pulse with a longer fade front compared to the rise front. The maximum value of the induced current density of the armature j_2 of opposite polarity is more than 2 times greater than the current density of the inductor winding. Since the induced current of the armature decays faster, then after 0.8 ms it changes its polarity, increasing until the current in the coil of the inductor stops. After that, the armature current gradually decays. Due to this pattern of current pulses, the electrodynamic force initially has the character of repulsion, and after 0.8 ms, the character of the slight attraction between the armature and the inductor. After the specified time, the resultant force f_z, acting on the armature, becomes inhibitory. The subsequent change in the braking force is due to the elastic deformation of the return spring. Under the action of these forces, the armature with the actuator accomplishes the displacement Δz with a velocity v, which after 0.8 ms decreases under the action of the resultant braking force f_z.

Fig. 3. LPIEC electromechanical characteristics

Let's consider power processes at a direct course of a working cycle of LPIEC. The following energy components take place:

$$W_{p1} = \int i_1^2(t)R_1(T_1)dt \quad \text{– losses in the inductor;}$$

$W_{p2} = \int i_2^2(t) R_2(T_2) dt$ – losses in the armature;

$W_{mag} = 0.5 \sum_{n=1}^{2} L_n i_n^2(t) + M(z) \cdot i_1(t) \cdot i_2(t)$ – magnetic energy;

$W_{kin} = 0.5(m_2 + m_a) v^2(t)$ – kinetic energy;

$W_c = 0.5 \cdot C \cdot u_c^2(t)$ – CES energy;

$W_{pr} = 0.5 \cdot K_P \Delta z^2(t)$ – compressed spring energy.

LPIEC efficiency is estimated by the expression [5]

$$\eta = 100 \frac{(m_a + m_e)v^2 + K_P \Delta z^2}{C(U_0^2 - u_c^2)} \% \qquad (10)$$

at the end of the direct stroke of the working cycle.

Fig. 4 shows the relative values (marked *) of the energy components during the direct stroke of the LPIEC work cycle.
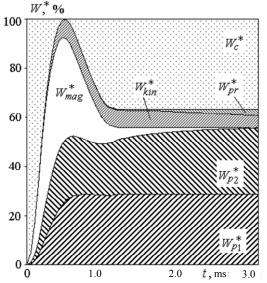

Fig. 4. Relative values of the energetic components at the direct stroke of the LPIEC work cycle
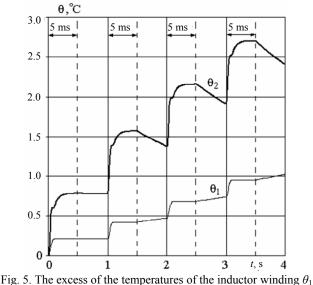
As follows from the presented results, by the end of the working cycle, a significant part of the energy is converted into the thermal energy of the armature (W^*_{p2}=26.8 %) and the inductor (W^*_{p1}=28.7 %). This explains the low efficiency of the LPIEC, which at the end of the direct stroke is η=19.5 %. Note that a significant part of the energy is stored in the CES (W^*_c=36.7 %).

Thermal energy leads to an increase in the temperature rise of the inductor θ_1 and the armature θ_2. In this case, it should be taken into account that in the active mode with the forward motion of the armature with actuator there is no thermal connection between the armature and the inductor. And in the passive mode, after the anchor, under the action of the return spring, takes its initial position, thermal interaction occurs between the active elements of the LPIEC. This thermal interaction is particularly manifested in the cyclic operation of the LPIEC.

Fig. 5 shows the temperature rise of the inductor winding θ_1 and the armature θ_2 during operation of the LPIEC with natural cooling in the cyclic operation mode. The first four operating cycles with the pulse repetition period T_{imp}=1 s are considered. This figure shows the short (5 ms) active mode of the LPIEC operation, in which the armature moves in a straight line, and a long (995 ms) passive mode of operation, in which the armature is mainly in thermal contact with the winding of the inductor.

In the active mode of the LPIEC operation, the temperature rise of the inductor θ_1 and the armature θ_2 is increasing. In this case, the temperature rise of the inductor θ_1 is less than that of the armature θ_2 in the initial operating cycles. In the passive mode, due to thermal contact, there is an increase in the temperature rise of the winding of the inductor and a decrease in the temperature rise of the armature. And with the increase in the number of working cycles, this regularity manifests itself more strongly because of the increasing difference between the temperatures of the armature and the winding of the inductor.

With a significant number of operating cycles, unacceptably high temperature excesses occur at which the epoxy resin of the winding of the inductor is softened: after 400 cycles, the excess of the temperature of the winding of the inductor is θ_1=110 °C, and after 800 cycles – θ_1=170 °C. In this case, the excess temperatures of the winding of the inductor and the armature are practically equalized.

Fig. 5. The excess of the temperatures of the inductor winding θ_1 and the armature θ_2 during cyclic operation (T_{imp}=1 s)

Ways to reduce the heating of LPIEC. One of the ways to solve the problem of unacceptably high heating, which is especially important for the epoxy-coiled inductor winding, is the intensive cooling of it or the anchor.

Consider the effect on the thermal state of the LPIEC of intense water (α_{Tn}=2 kW·m⁻²·K⁻¹) cooling of one or both active elements. Fig. 6 shows the dynamics of temperature rise in the winding of the inductor and the armature during intensive cooling of the inductor (cooling mode I), the armature (cooling mode II) and their co-cooling (cooling mode III) for the first 4 cycles with the pulse repetition period T_{imp}=1 s.
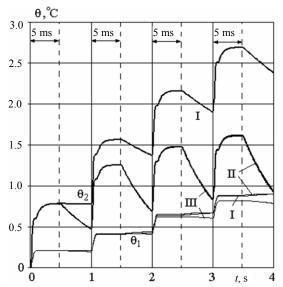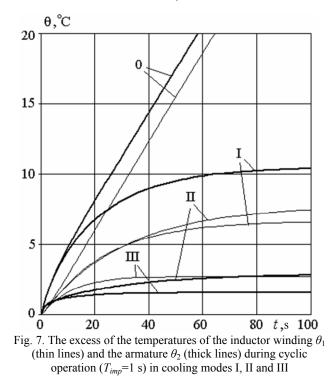
Fig. 6. The excess of the temperatures of the inductor winding θ_1 and the armature θ_2 during cyclic operation (T_{imp}=1 s) in cooling modes I, II and III

When cooling mode I is used, the excess of the temperature of the inductor winding θ_1 decreases by 12 % in the first 4 cycles, while the temperature of the armature θ_2 does not practically change. In the cooling mode II, the armature temperature is reduced by 61 %, while the inductor winding is only 12 % lower. In cooling mode III, the smallest excess occurs both in the winding of the inductor (23 %) and in the armature (62 %). In this case, in the passive mode, the temperature rise of the armature θ_2 decreases substantially, and θ_1 of the winding of the inductor practically does not change. The heating of the active elements changes markedly during the long operation of the LPIEC. Fig. 7 shows the dynamics of temperature excesses of active elements of the LPIEC during operation for 100 s (T_{imp}=1 s).

Fig. 7. The excess of the temperatures of the inductor winding θ_1 (thin lines) and the armature θ_2 (thick lines) during cyclic operation (T_{imp}=1 s) in cooling modes I, II and III

As follows from the presented dependencies, intensive cooling of at least one of the active elements practically prevents inadmissible heating of both elements. Excess of the temperatures of the active elements reach certain values, after which they practically do not change. Thus, intensive cooling of one of the active elements of the LPIEC reduces the heating temperature of the other element. So for 100 working cycles, when cooling mode I is used, the temperature rise of the armature is θ_2 = 10.4 ºC, and in the cooling mode II – the temperature of the inductor winding θ_1 = 7.5 ºC is exceeded.

Another way to reduce the heating of active elements of the LPIEC is to increase the pulse repetition period, at which the passive period increases, and hence the interaction time of the inductor and armature.

Fig. 8 shows the dynamics of temperature excesses of active elements of the LPIEC for four initial operating cycles with a follow-up period of T_{imp}=5 s. With an increase in the pulse repetition period, there is a noticeable decrease in the excess of the temperatures of the active elements.
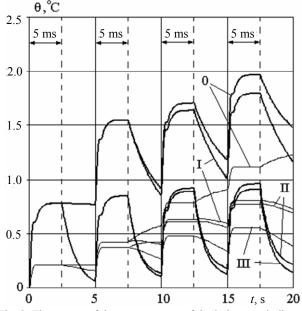

Fig. 8. The excess of the temperatures of the inductor winding θ_1 (thin lines) and the armature θ_2 (thick lines) during cyclic operation (T_{imp}=5 s) with natural cooling (0) and in cooling modes I, II and III

At the pulse repetition period T_{imp}=5 s there is a significant decrease in the temperature rise of the armature θ_2 in the passive mode of the LPIEC operation, including with natural cooling (0). The excess of the temperature of the inductor winding θ_1 in the passive mode of operation of the LPIEC occurs only with natural cooling (0). In cooling modes I, II and III, the temperature rise of the inductor winding θ_2 also decreases.

Fig. 9 shows the dynamics of the relative excess of the temperatures of the inductor θ_1^* and the armature θ_2^* with the natural and intensive cooling of the inductor, the armature and both of them, depending on the value of T_{imp}

per 100 pulses. The values of the excess temperatures are normalized by the corresponding values at T_{imp}=1 s. As follows from the presented values, an increase in the pulse repetition period T_{imp} leads to a decrease in the temperature excesses of both the inductor θ_1 and the armature θ_2 under any cooling method. However, when working with natural cooling of the temperature rise of the winding of the inductor and the armature, the impulses decrease practically linearly and insignificantly with an increase in the pulse repetition period. So, at T_{imp}=5 s in comparison with T_{imp}=1 s the temperature rise of inductor θ_1 decreases by 23 %, and θ_2 of armature – by 28 %.

With intensive cooling of at least one of the active elements of the LPIEC, with a similar increase in the pulse repetition period, the excess of the temperatures of the active elements decreases by 80-90 %. It should be noted that the strongest decrease (by 67-77 %) of temperature elevations occurs with an increase in T_{imp} from 1 s to 2 s. With a further increase in the pulse repetition period, the decrease in temperature excesses occurs much more slowly.
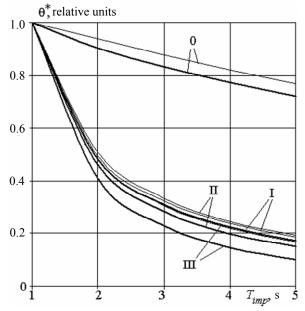

Fig. 9. The dynamics of the relative excesses of the temperatures of the winding of the inductor θ_1^* (thin lines) and the armature θ_2^* (thick lines) with natural cooling (0) and in cooling modes I, II and III per 100 pulses depending on T_{imp}

Thus, intensive cooling of one of the active elements of the LPIEC allows to significantly reduce the temperature excess of both active elements.

Experimental research. To test the main theoretical results, an experimental setup was made, shown in Fig. 10,*a*.

The experimental sample of LPIEC contains a stationary inductor with a two-layer winding of disk shape, which is wound with a rectangular copper busbar, is encased in epoxy resin and is laid either in a thick-walled glass-fiber-reinforced frame or in a thin-walled steel frame with the possibility of intensive cooling (Fig. 2).

Intensive cooling was created by a directional flow of cold air onto the steel frame. Temperature measurements were made on the surface of the winding of the inductor LPIEC during cyclic operation with the pulse repetition period T_{imp}=1 s. The winding temperature was measured with a thermocouple of the M 890G. During measurements, the sensor with the thermocouple was installed in the most heat-stretched area - in the middle of the open side of the winding.

a   *b*

Fig. 10. Experimental installation for LPIEC research with a thin-walled steel framework (*a*) and temperature measurement process (*b*)

It was found that the winding of the inductor with the steel frame blown by air, is heated weaker than the winding with the insulating frame (Fig. 11). We note that during 270 s the temperature of the winding with the insulating frame increased so that its epoxy resin softened. It was found that the experimental dependences with an accuracy of 6 % coincide with the calculated results.
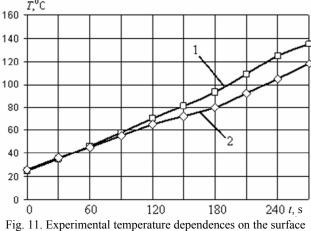

Fig. 11. Experimental temperature dependences on the surface of the inductor winding with the insulating (1) and steel (2) LPIEC frames while working at T_{imp} = 1 s

Constructive scheme of LPIEC with intensive water cooling of the inductor winding. Since the use of intensive water cooling for a movable armature is associated with a number of design difficulties, this cooling is advisable to apply only to the stationary winding of the inductor. Proceeding from this, a constructive scheme of the LPIEC of cyclic action was developed which is shown in Fig. 12 [13].

In the LPIEC of cyclic action upon excitation of the winding 1 of the inductor from the CES, the magnetic

field induces currents in the electrically conducting armature 2, eddy currents. The electrodynamic force that arises between them moves the armature 2 together with the impact disc 3 and the striker 4. The guide part of the striker is connected to a flat piston 5 located inside the cooling chamber 6 with water. Arranged on a flat piston 5 one-way valves 7 with a straight armature stroke freely pass water. In this case, the return spring 8 and the resilient waterproofing bellows 9 surrounding it are stretched. The cooling chamber 6 is located in the insulating housing 10.
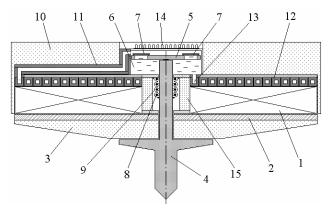

Fig. 12. Constructive scheme of LPIEC of cyclic actions with intensive water cooling of the inductor winding

After the direct stroke under the action of the spring 8, the armature 2 with the striker 4 is reversed, and the one-way valves 7 are closed. The piston 5 pushes water which is squeezed out of the chamber 6. It enters the inlet end 11 of the tube wound in the form of a disc 12, passes through its inner channel and through the outlet end 13 enters the chamber 6. The water circulating in the tube 12 removes heat energy separated in the winding 1, preventing heating of both active elements, since a thermal interaction takes place between them in the passive mode of operation of the LPIEC. The heat of the heated water is drawn from the cooling chamber 6 to the surrounding space through the radiators 14 mounted on its outer side. The guide sleeve 15 serves as a technological framework for the winding 1 of the inductor and protects the waterproofing bellows 9 from mechanical influences. Since the piston 5 is subjected to the action of a resistance force caused mainly by the hydraulic resistance of the water in the internal channel 13 of the multi-turn tube 12, the smooth movement of the striker 4 towards the winding 1 of the inductor occurs. Thus, an unstressed contact of the armature 2 with the winding 1 of the inductor is effected.

Conclusions.

1. A mathematical model of the LPIEC of cyclic action is developed taking into account a complex of interrelated electromagnetic, electromechanical and thermal processes.

2. Electromagnetic, electromechanical and energy processes of LPIEC are investigated which arise during the direct course of the working cycle. It is shown that by the end of the working cycle a significant part of the energy is converted into thermal energy of the armature (26.8 %) and the inductor (28.7 %).

3. At a significant number of working cycles with pulse repetition period of T_{imp}=1 s, unacceptably high temperature excesses of active elements of the LPIEC are observed.

4. One of the ways to solve the problem of heating the winding of the inductor is to intensively cool it, the movable armature or both of them. In this case, the excess of the temperatures of the active elements reach certain values, after which they practically do not change.

5. The increase in the pulse repetition period leads to decrease in the temperature excesses of the active elements of the LPIEC. With an increase in this period, with natural cooling, the excess of the temperatures of the active elements decrease practically linearly and insignificantly. With intensive cooling of at least one of the active elements, the excess of the temperatures of the active elements is reduced by 80-90 %.

6. Temperature measurements were made on the surface of the winding of the inductor LPIEC during cyclic operation with pulse repetition period T_{imp}=1 s. It is established that the winding of the inductor with the steel frame, blown by air, heats up more slowly than the winding with the insulating frame. The experimental dependences with an accuracy of 6 % coincide with the calculated results.

7. The constructive scheme of the LPIEC of cyclic action with intensive water cooling of the inductor winding was developed.

REFERENCES
1. Bissal A. *Licentiate thesis on the design of ultra-fast electromechanical*. Stockholm, Sweden. 2013. 120 p.
2. Chemerys V.T., Bolyukh V.F. Prospectives of new coilgun design development. *Artillery and small arms*, 2008, no.3, pp. 44-52.
3. Bolyukh V.F., Vinnichenko A.I. Concept of an induction-dynamic catapult for a ballistic laser gravimeter. *Measurement Techniques*, 2014, vol.56, iss.10, pp. 1098-1104. **doi: 10.1007/s11018-014-0337-z.**
4. Naumov I.V, Bolyukh V.F., Breslavskiy D.V. Deformation and fracture of the plates during loading cylindrical drummer. *Mechanics and engineer*, 2010, no.1, pp. 207-216. (Rus).
5. Bolyukh V.F., Shchukin I.S. *Lineinye induktsionno-dinamicheskie preobrazovateli* [Linear induction-dynamic converters]. Saarbrucken, Germany, LAP Lambert Academic Publ., 2014. 496 p. (Rus).
6. Bolyukh V.F., Shchukin I.S. The thermal state of an electromechanical induction converter with impact action in the cyclic operation mode. *Russian electrical engineering*, 2012, vol.83, no.10, pp. 571-576. **doi: 10.3103/s1068371212100045**.
7. Bolyukh V.F., Luchuk V.F., Rassokha M.A., Shchukin I.S. High-efficiency impact electromechanical converter. *Russian electrical engineering*, 2011, vol.82, no.2, pp. 104-110. **doi: 10.3103/s1068371211020027**.
8. Bolyukh V.F., Oleksenko S.V. The influence of the parameters of a ferromagnetic shield on the efficiency of a linear induction-dynamic converter. *Russian Electrical Engineering*, 2015, vol.86, no.7, pp. 425-431. **doi: 10.3103/s1068371215070044**.

9. 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**.
10. Podoltsev A.D., Kucheriava I.N. *Mul'tifizicheskoe modelirovanie v elektrotekhnike* [Multiphysical modeling in electrical engineering]. Kyiv: Institute of Electrodynamics of NAS of Ukraine, 2015. 305 p. (Rus).
11. L. Shoubao, R. Jiangjun, P. Ying, Z. Yujiao, Z. Yadong. Improvement of Current Filament Method and Its Application in Performance Analysis of Induction Coil Gun. *IEEE Transactions on Plasma Science*, 2011, vol.39, no.1, pp. 382-389. **doi: 10.1109/tps.2010.2047276.**
12. Bolyukh V.F., Lysenko L.I., Bolyukh E.G. Parameters of high-efficiency pulsed inductive electromechanical converters. *Russian Electrical Engineering*, 2004, vol.75, no.12, pp. 1-11.

13. Bolyukh V.F., Luchuk V.F., Shchukin I.S. *Induktsionno-dinamicheskii elektrodvigatel' tsiklicheskogo deistviia* [Induction-dynamic electric motor of cyclic action]. Patent Russian Federation, no. 2467455, 2012. (Rus).

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