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Influence of limiting the duration of the armature winding current
on the operating indicators of a linear pulse electromechanical induction type converter

Introduction. *Linear pulse electromechanical converters of induction type (LPECIT) are used in many branches of science and technology as shock-power devices and electromechanical accelerators. In them, due to the phase shift between the excitation current in the inductor winding and the induced current in the armature winding, in addition to the initial electrodynamic forces (EDF) of repulsion, subsequent EDF of attraction also arise. As a result, the operating indicators of LPECIT are reduced.* ***The purpose*** *of the article is to increase the performance of linear pulse electromechanical induction-type converters when operating as a shock-power device and an electromechanical accelerator by limiting the duration of the induced current in the armature winding until its polarity changes.* ***Methodology.*** *To analyze the electromechanical characteristics and indicators of LPECIT, a mathematical model was used, in which the solutions of equations describing interrelated electrical, magnetic, mechanical and thermal processes are presented in a recurrent form.* ***Results.*** *To eliminate the EDF of attraction between the LPIECIT windings, it is proposed to limit the duration of the induced current in the armature winding before changing its polarity by connecting a rectifier diode to it. It was found that when the converter operates as a shock-power device without limiting the armature winding current, the value of the EDF pulse after reaching the maximum value decreases by the end of the operating cycle. In the presence of a diode in the armature winding, the efficiency criterion, taking into account the EDF pulse, recoil force, current and heating temperature of the inductor winding, increases. When the converter operates as an electromechanical accelerator without limiting the armature winding current, the speed and efficiency decrease, taking into account the kinetic energy and voltage of the capacitive energy storage at the end of the operating cycle. In the presence of a diode in the armature winding, the efficiency criterion increases, the temperature rise of the armature winding decreases, the value of the maximum efficiency increases, reaching 16.16 %.* ***Originality****. It has been established that due to the limitation of the duration of the armature winding current, the power indicators of the LPECIT increase when operating as a shock-power device and the speed indicators when the LPECIT operates as an electromechanical accelerator.* ***Practical value.*** *It was found that with the help of a rectifier diode connected to the multi-turn winding of the armature, unipolarity of the current is ensured, which leads to the elimination of the EDF of attraction and an increase in the performance of the LPECIT.* References 22, figures 5.
Key words: **linear pulse electromechanical converter of induction type, shock-power device, electromechanical accelerator, performance indicators, limiting the duration of the armature winding current.**

Вступ. *Лінійні імпульсні електромеханічні перетворювачі індукційного типу (ЛІЕПІТ) використовуються в багатьох галузях науки і техніки як ударно-силові пристрої та електромеханічні прискорювачі. У них через фазовий зсув між струмом збудження в обмотці індуктора і індукованим струмом в обмотці якоря крім початкових електродинамічних сил (ЕДС) відштовхування виникають і наступні ЕДС тяжіння. Внаслідок цього робочі показники ЛІЕПІТ знижуються.* ***Метою*** *статті є підвищення робочих показників лінійних імпульсних електромеханічних перетворювачів індукційного типу при роботі в якості ударно-силового пристрою та електромеханічного прискорювача за рахунок обмеження тривалості індукованого струму в обмотці якоря до зміни його полярності.* ***Методика.*** *Для аналізу електромеханічних характеристик та показників ЛІЕПІТ використана математична модель, в якій розв'язки рівнянь, що описують взаємопов'язані електричні, магнітні, механічні та теплові процеси, представлені в рекурентному вигляді.* ***Результати.*** *Для усунення ЕДС тяжіння між обмотками ЛІЕПІТ запропоновано обмеження тривалості індукованого струму в обмотці якоря до зміни його полярності шляхом підключення до неї випрямного діода. Встановлено, що при роботі перетворювача в якості ударно-силового пристрою без обмеження струму обмотки якоря величина імпульсу ЕДС після досягнення максимального значення знижується до кінця робочого циклу. За наявності діода в обмотці якоря критерій ефективності, що враховує імпульс ЕДС, силу віддачі, струм і температуру нагрівання обмотки індуктора, підвищується. При роботі перетворювача в якості електромеханічного прискорювача без обмеження струму обмотки якоря відбувається зменшення швидкості і ККД, що враховує кінетичну енергію і напругу ємнісного накопичувача енергії в кінці робочого циклу. За наявності діода в обмотці якоря критерій ефективності підвищується, перевищення температури обмотки якоря зменшується, величина максимального ККД збільшується, досягаючи 16,16 %.* ***Наукова новизна.*** *Встановлено, що за рахунок обмеження тривалості струму обмотки якоря підвищуються силові показники ЛІЕПІТ при роботі в якості ударно-силового пристрою та швидкісні показники при роботі ЛІЕПІТ в якості електромеханічного прискорювача.* ***Практична цінність.*** *Встановлено, що за допомогою випрямного діода, підключеного до багатовиткової обмотки якоря, забезпечується однополярність струму, що зумовлює усунення ЕДС тяжіння і підвищення робочих показників ЛІЕПІТ.* Бібл. 22, рис. 5.
Ключові слова: **лінійний імпульсний електромеханічний перетворювач індукційного типу, ударно-силовий пристрій, електромеханічний прискорювач, робочі показники, обмеження тривалості струму обмотки якоря.**

Введение. *Линейные импульсные электромеханические преобразователи индукционного типа (ЛИЭПИТ) используются во многих отраслях науки и техники в качестве ударно-силовых устройств и электромеханических ускорителей. В них из-за фазового сдвига между током возбуждения в обмотке индуктора и индуцированным током в обмотке якоря помимо первоначальных электродинамических усилий (ЭДУ) отталкивания возникают и последующие ЭДУ притяжения. Вследствие этого рабочие показатели ЛИЭПИТ снижаются.* ***Целью статьи*** *является повышение рабочих показателей линейных импульсных электромеханических преобразователей индукционного типа при работе в качестве ударно-силового устройства и электромеханического ускорителя за счет ограничения длительности индуцированного тока в обмотке якоря до изменения его полярности.* ***Методика.*** *Для анализа электромеханических характеристик и показателей ЛИЭПИТ*

использована математическая модель, в которой решения уравнений, описывающих взаимосвязанные электрические, магнитные, механические и тепловые процессы, представлены в рекуррентном виде. **Результаты.** *Для устранения ЭДУ притяжения между обмотками ЛИЭПИТ предложено ограничение длительности индуцированного тока в обмотке якоря до изменения его полярности путем подключения к ней выпрямительного диода. Установлено, что при работе преобразователя в качестве ударно-силового устройства без ограничения тока обмотки якоря величина импульса ЭДУ после достижения максимального значения снижается к концу рабочего цикла. При наличии диода в обмотке якоря критерий эффективности, учитывающий импульс ЭДУ, силу отдачи, ток и температуру нагрева обмотки индуктора, повышается. При работе преобразователя в качестве электромеханического ускорителя без ограничения тока обмотки якоря происходит уменьшение скорости и КПД, учитывающего кинетическую энергию и напряжение емкостного накопителя энергии в конце рабочего цикла. При наличии диода в обмотке якоря критерий эффективности повышается, превышение температуры обмотки якоря уменьшается, величина максимального КПД увеличивается, достигая 16,16 %.* **Научная новизна.** *Установлено, что за счет ограничения длительности тока обмотки якоря повышаются силовые показатели ЛИЭПИТ при работе в качестве ударно-силового устройства и скоростные показатели при работе ЛИЭПИТ в качестве электромеханического ускорителя.* **Практическая ценность.** *Установлено, что при помощи выпрямительного диода, подключенного к многовитковой обмотке якоря, обеспечивается однополярность тока, что приводит к устранению ЭДУ притяжения и повышению рабочих показателей ЛИЭПИТ.* Библ. 22, рис. 5.

Ключевые слова: **линейный импульсный электромеханический преобразователь индукционного типа, ударно-силовое устройство, электромеханический ускоритель, рабочие показатели, ограничение длительности тока обмотки якоря.**

Introduction. Linear pulse electromechanical converters of induction type (LPECITs) are widely used both for acceleration of an actuator to high speed on a short active site, and for creation of powerful power pulses on object of influence at insignificant movement of an actuator [1-4]. Such converters are widely used in many fields of science and technology as shock-power devices and electromechanical accelerators.

As shock-power devices LPECITs are used for electromagnetic hammers and perforators in construction, for drills and vibrators in the mining industry, for shock seismic sources in exploration, for hammers with a wide range of impact energy and devices for electrodynamic processing of welded joints in mechanical engineering, for vibrating mixers in the chemical and medical-biological industry, for testing devices that provide testing of critical equipment for shock loads, for magnetic-pulse devices that provide pressing of special ceramic powders, for devices that provide cleaning of technological tanks from the adhesion of bulk materials, for devices that ensure the destruction of important information on the drives in case of unauthorized access, etc. [5-9].

As electromechanical accelerators LPECITs are used for high-speed electric devices, for ballistic laser gravimeters, for the systems providing start of unmanned aerial vehicles, for the defensive devices providing protection of responsible objects from the approaching devices, for accelerators in aerospace engineering. etc. [10-15].

In LPECIT, a pulsed current flows in the stationary winding of the inductor when connected to a capacitive energy storage (CES) device which induces a current in the armature winding by means of a magnetic field. Since at the initial moment of time the currents in the windings have the opposite polarity, repulsive electrodynamic forces (EDF) arise between them [16].

When the converter operates as an electromechanical accelerator, the armature winding, which moves under the action of the repulsion EDF, accelerates the actuator. And when operating as a shock-power device, the armature winding with a slight movement provides the transmission of a power pulse to the actuator.

In LPECIT short-circuited armature winding can be made single-turn or multi-turn. In the single-turn design, the armature winding is usually a massive conductive disk. However, the induced current on such a disk is distributed significantly nonuniformly. In the multi-turn design, the armature winding is tightly wound with a wire of relatively small cross section and impregnated with an epoxy-based compound. In such a winding, the induced current is distributed uniformly throughout the cross section, which provides a more uniform force on the actuator.

Studies show that due to the phase shift between the excitation current in the inductor winding and the induced current in the short-circuited armature winding, in addition to the initial repulsion EDF, the following attractive EDF occurs [17]. As a result, the operating performance of the converter is reduced [18]. Attractive EDF occur due to a change in the polarity of the induced current in the armature winding, while the polarity of the excitation current in the inductor winding may remain unchanged.

The attractive EDF can be eliminated by limiting the duration of the induced current in the armature winding before changing its polarity. To do this, it is possible to connect a rectifier diode *VD* to the armature winding (Fig. 1). Current limitation in a magnetic pulse unit to change the effect of EDF on the secondary conductive element using a controlled vacuum discharger is described in [19]. But in that study, the goal was to increase the attractive EDF, whereas for LPECIT such forces are undesirable.
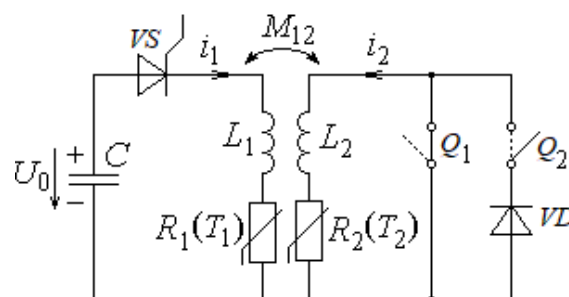

Fig. 1. LPECIT electrical circuit in the absence (Q_1, Q_2 – solid lines) and the presence (Q_1, Q_2 – dashed lines) of the diode *VD* in the armature winding

Ensuring one polarity of the induced current can be realized by connecting the diode *VD* to the multi-turn armature winding, so below we will consider it. However, here the feasibility of limiting the duration of the induced current in the armature winding to change its polarity during the operation of LPECIT as a shock-power device and electromechanical accelerator has not been studied.

The goal of the paper is to increase the performance of linear pulse electromechanical converters of induction type when operating as a shock-power device and electromechanical accelerator by limiting the duration of the induced current in the armature winding to change its polarity.

Consider **the mathematical model** of the LPECIT which uses the lumped parameters of the multi-turn windings of the inductor and armature. To take into account the interconnected electrical, magnetic, mechanical and thermal processes, as well as a number of nonlinear dependencies, the solution of equations describing these processes, are present in recurrent form.

We assume that when operating as a shock-power device, the movement of the armature winding with the actuator is absent, and when operating as an electromechanical accelerator, the armature moves a considerable distance with the actuator, which has a relatively small mass.

To excite LPECIT from CES, we use a unipolar current pulse in the inductor winding formed by the starting thyristor *VS* (Fig. 1). This allows to store some part of the energy in the CES until the end of the operating cycle. To limit the duration of the induced current in the armature winding before changing its polarity, we use a rectifier diode *VD*. We believe that for semiconductor devices *VS* and *VD* the resistance in the forward direction is zero, and in the opposite direction is infinitely large.

Electrical processes in LPECIT when operating as a shock-power device can be described by a system of equations:

$$R_1(T_1)i_1 + L_1\frac{di_1}{dt} + \frac{1}{C_0}\int_0^t i_1 dt + M_{12}\frac{di_2}{dt} = 0, \quad (1)$$

$$\frac{1}{C_0}\int_0^t i_1 \cdot dt = U_0, \quad (2)$$

$$R_2(T_2)\cdot i_2 + L_2\frac{di_2}{dt} + M_{21}\frac{di_1}{dt} = 0, \quad (3)$$

where $n = 1, 2$ are the indices of the windings of the inductor and armature, respectively; R_n, L_n, T_n, i_n are the active resistance, inductance, temperature and current of the n-th winding, respectively; $M_{12}=M_{21}$ is the mutual inductance between the windings; C_0, U_0 are the capacity and initial (charging) voltage of CES.

When LPECIT operates as an electromechanical accelerator, equations (1), (3) take the form:

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

$$+ v_z(t)i_2\frac{dM_{12}}{dz} = 0; \quad (4)$$

$$R_2(T_2)\cdot i_2 + L_2\frac{di_2}{dt} + M_{21}(z)\frac{di_1}{dt} + i_1 v(t)\frac{dM_{12}}{dz} = 0. \quad (5)$$

Solutions of the equations for currents in the converter windings in recurrent form are presented in [18]. The displacement h_z and the speed v_z of the armature winding relative to the inductor winding, presented in a recurrent form [10], take into account the instantaneous value of the axial EDF between the windings:

$$f_z(z,t) = i_1(t)i_2(t)\frac{dM_{12}}{dz}(z), \quad (6)$$

the masses of the armature winding and the actuator, the density of the moving medium and the coefficient of drag.

When LPECIT operates as a shock-power device, between the windings there is a thermal contact through the insulating gasket. The temperature of the windings can be described by recurrent relations [4], which take into account the thermal conductivity and the thickness of the gasket, the coefficients of heat transfer and heat capacities of the windings.

To calculate the characteristics and indicators of LPECIT, we use the algorithm of cyclic action [20], which allows to take into account a set of interconnected electrical, magnetic, mechanical and thermal processes and various nonlinear dependencies, such as $R_n(T_n)$, $M_{12}(z)$. When calculating 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 constant. According to the current values obtained at time t_{k+1}, we calculate the temperature of the windings T_1 and T_2, the displacements h_z and the speed v_z of the armature winding, the mutual inductance M_{12} between the windings. With this approach, linear equations and relations can be used to determine the currents in the calculation time interval Δt. The value of Δt is chosen so that it does not significantly affect the calculation results, while ensuring the required accuracy.

Initial conditions of the mathematical model:
$T_n(0) = T_0$ – the temperature of the n-th winding;
$i_n(0) = 0$ – the current of the n-th winding;
$h_z(0) = h_{z0}$ – the distance between windings;
$u_c(0) = U_0$ – the CES voltage;
$v_z(0) = 0$ – the speed of the armature winding along the z axis.

The main parameters of LPECIT. Consider LPECIT in which the inductor winding (n=1) and the armature winding (n=2) are made in the form of monolithic disk coils, tightly wound with copper wire of circular cross section with diameter d_0=1.3 mm and impregnated with epoxy compound. The outer diameter of the windings D_{ex}=100 mm, their inner diameter D_{in}=10 mm. The axial height of the inductor winding H_1=6 mm and of the armature winding H_2=3 mm. The number of turns of the inductor winding N_1=120 and of the armature winding N_2=60. The initial distance between the windings h_{z0}=1 mm. CES has energy W_0=500 J and its capacitance

C_0 varies in the range from 0.5 to 5 mF with a corresponding change in initial voltage $U_0 = \sqrt{2W_0 C_0^{-1}}$. When LPECIT operates as an electromechanical accelerator, the mass of the actuator m_a=0.5 kg.

We analyze the electromechanical characteristics and performance of LPECIT which has in the armature winding limiting the duration of the induced current before changing its polarity (Q_1 open, Q_2 closed), compared with LPECIT which has no such limitation (Q_1 closed, Q_2 open) (see Fig. 1).

When analyzing the operation of LPECIT, we take into account the following operating indicators: excitation current, heating temperature of the windings and recoil force. The maximum excitation current is proportional to the amplitude of the current density in the inductor winding j_{1m}, the heating temperature of the inductor winding – to the rise of its temperature θ_1, and the recoil force – to the amplitude of the EDF f_{zm}. The maximum excitation current affects the parameters of the electronic source, the heating temperature – the duration of the converter operation in cyclic mode, and the recoil force – the mechanical reliability. For example, for hand-held shock instruments and various stand-alone starters, the recoil force has a negative effect on both the device itself and the service personnel. The force of recoil is especially negative in measuring devices. For example, a ballistic laser gravimeter designed to measure the acceleration of free fall uses an electromechanical catapult, which provides a vertical throw of the angular optical reflector [21]. The recoil force causes autoseismic oscillations that reduce the accuracy of the gravimeter's measurement [22].

When LPECIT operates as a shock-power device, its efficiency will be evaluated by the largest value of the EDF impulse $P_z = \int_0^t f_z(t)dt$ at the minimum values of recoil force, excitation current and heating temperature of the inductor winding.

Figure 2 presents the electromechanical characteristics of LPECIT in the absence (solid lines) and the presence (lines with circles) of limiting the duration of the induced current in the armature winding to change its polarity.

When using CES with capacity of $C_0 = 0.5$ mF the maximum current density in the inductor winding is j_{1m}=1.03 kA/mm^2, and in the armature winding j_{2m}=1.41 kA/mm^2 (Fig. 2,a). The amplitude of the EDF f_{zm}=30.85 kN. In the absence of limitation of the induced current in the short-circuited armature winding (without diode VD in Fig. 1) by the end of the operating cycle the temperature rise of the inductor winding is θ_1=1.58 °C, and the temperature rise of the armature winding is θ_2=2.87 °C. Due to the attractive EDF, the value of the impulse of these forces, reaching the maximum value P_{zm}=12.5 N·s, by the end of the operating cycle decreases to P_{zf}=12.19 N·s.

When using CES of higher capacity (C_0=2.5 mF), and hence lower voltage U_0, the maximum values of current densities in the inductor winding is reduced to j_{1m}=0.67 kA/mm^2, in the armature winding to j_{2m}=0.78 kA/mm^2, EDF to f_{zm}=10.58 kN (Fig. 2,b). But by the end of the operating cycle, the temperature rise of the inductor winding increases to θ_1=2.15 °C, and the temperature rise of the armature winding decreases to θ_2=1.86 °C. The value of the EDF impulse, reaching the maximum value P_{zm}=9.61 N·s, by the end of the operating cycle is reduced to P_{zf}=7.94 N·s.
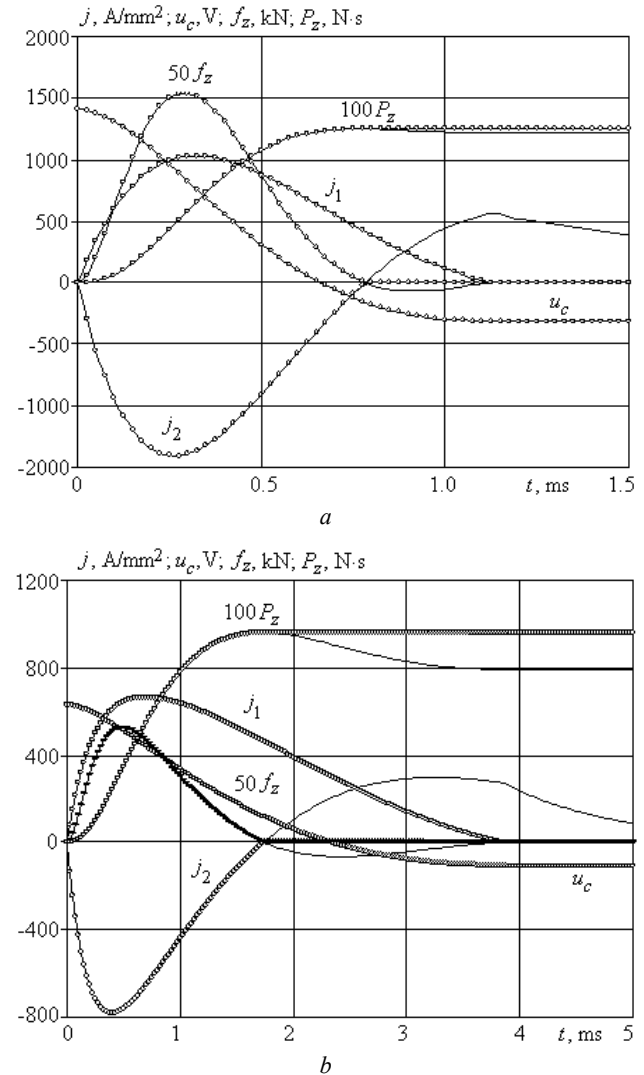

Fig. 2. Electromechanical characteristics of LPECIT when operating as a shock-power device at C_0: 0.5 mF (*a*) and 2.5 mF (*b*)

With increasing capacity C_0 of CES and constant energy W_0=500 J, the voltage U_0 decreases, which causes a change in the main performance of LPECIT (Fig. 3,a).

With increasing C_0 from 0.5 to 5 mF, the amplitude of the EDF f_{zm} decreases by about 5 times (from 30.85 to 6.06 kN), but the value of the maximum impulse of the EDF P_{zm} decreases by about 1.5 times (from 12.5 to 7.7 N·s). With such an increase in capacitance C_0, the temperature rise of the inductor winding θ_1 increases from 1.58 to 2.47 °C. These indicators do not practically depend on the presence or absence of limitation of the

duration of the induced current in the armature winding before changing its polarity. However, the limitation of the current duration affects the temperature rise of the armature winding θ_2. In the converter without current limitation of the short-circuited armature winding, the value θ_2 decreases from 2.87 to 1.27 °C. In the presence of the specified limitation due to connection of the diode VD the value θ_2 is lower, than in its absence, and decreases from 2.24 to 0.96 °C.
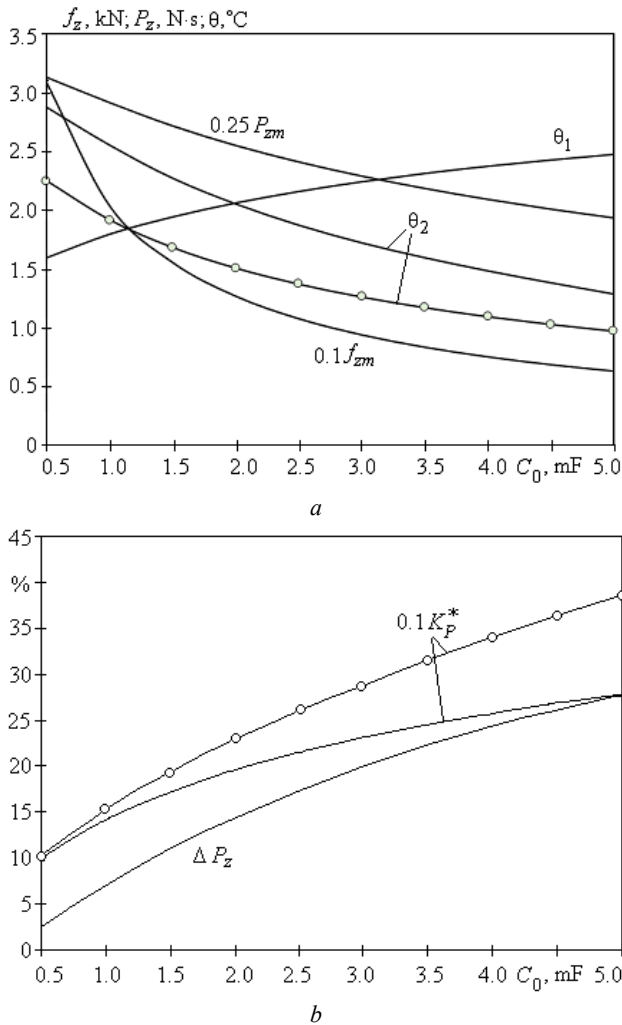

a

b

Fig. 3. Dependence of LPECIT performance at operation as a shock-power device on the capacity of CES when W_0=500 J

In order to evaluate the efficiency of LPECIT operation as a shock-power device depending on the value of the capacity C_0 of CES at W_0=500 J we use the value of the relative reduction of the EDF impulse $\Delta P_z = 100\left(P_{zm} - P_{zf}\right)P_{zm}^{-1}, \%$ and the relative criterion of

efficiency $K_P^* = 100 \dfrac{P_{zf}^*}{j_{1m}^* f_{zm}^* \theta_1^*}, \%$. As a basic variant for

K_P^* we use the converter excited from CES with capacity C_0=0.5 mF without current limitation in the short-circuited armature winding. With an increase in C_0 from 0.5 to 5 mF and the absence of current limitation in the armature winding, the relative decrease in the EDF impulse increases from 2.5 to 27.6 % (Fig. 3,*b*). However,

the efficiency criterion of LPECIT K_p^* increases by 2.78 times primarily due to the reduction of the amplitude of the current density in the inductor winding j_{1m} and the amplitude of the EDF f_{zm}.

If there is imitation of the current duration in the armature winding due to the connection of the diode VD due to the absence of EDF impulse decrease, the value of the efficiency criterion K_p^* increases (by 38.6 % at C_0=0.5 mF) This shows the prospects of this technical solution at LPECIT operation as a shock-power device.

When LPECIT operates as an electromechanical accelerator, its effectiveness will be evaluated by the highest value of efficiency

$$\eta = 100 C_0^{-1}\left(m_2 + m_a\right)v^2\left(U_0^2 - U_1^2\right)^{-1}, \%,$$

which takes into account the kinetic energy of the armature together with the actuator and the residual voltage of the CES at the end of the operating cycle U_1.

Figure 4 presents the electromechanical characteristics of LPECIT in the absence (solid lines) and the presence (lines with circles) of the limitation of the induced current in the armature winding.
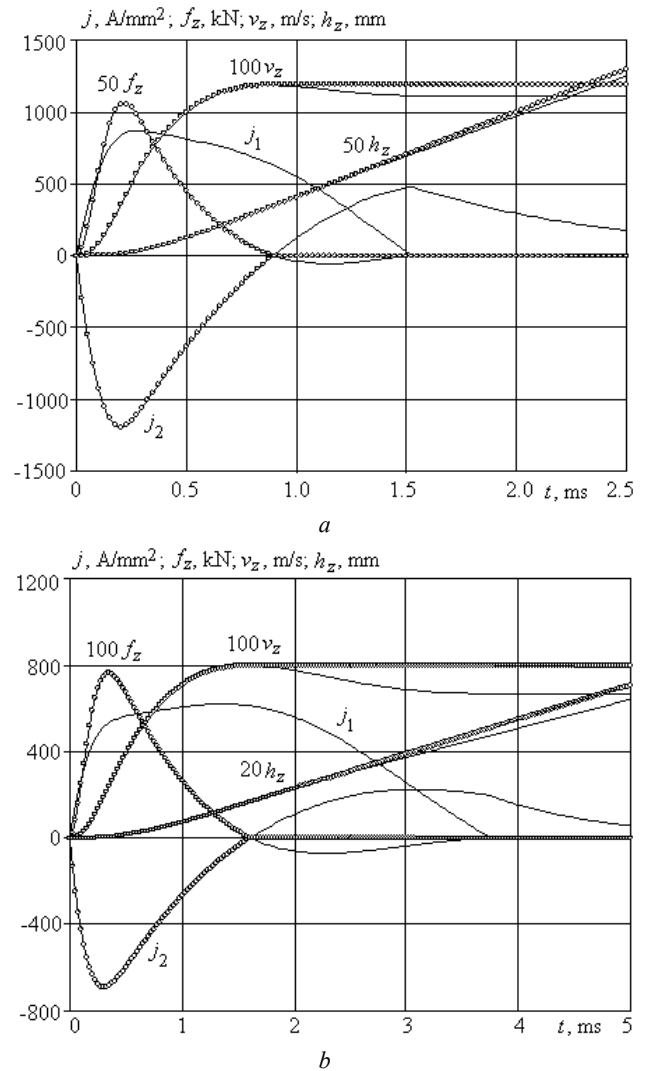

a

b

Fig. 4. Electromechanical characteristics of LPECIT at operation as an electromechanical accelerator at C_0: 0.5 mF (*a*) and 2.5 mF (*b*)

When using CES with capacity of C_0=0.5 mF, the maximum current density in the inductor winding is j_{1m}=0.87 kA/mm^2, and in the armature winding is j_{2m}= 1.19 kA/mm^2 (Fig. 4,*a*), i.e. they are lower than when LPECIT operates as a shock-power device. Accordingly, the amplitude of the EDF is smaller: f_{zm}=21.16 kN.

In the converter without current limitation in the short-circuited armature winding, the maximum speed v_m=11.86 m/s by the end of the operating cycle is practically not reduced, which provides the efficiency of the electromechanical accelerator η=14.24 %. The temperature rise of the inductor winding is θ_1=1.84 °C, and the temperature rise of the armature winding θ_2=2.02 °C. When using CES with capacity of C_0=2.5 mF, the maximum value of the current density in the inductor winding is reduced to j_{1m}=0.621 kA/mm^2, and in the armature winding to j_{2m}=0.69 kA/mm^2, EDF to f_{zm}=7.62 kN (Fig. 4,*b*).

By the end of the operating cycle, the temperature rise of the inductor winding increases to θ_1=2.6 °C, and the temperature rise of the armature winding decreases to θ_2=1.12 °C. The speed of the armature winding, reaching the maximum value v_{zm}=7.97 m/s, by the end of the operating cycle is significantly reduced, amounting to v_{zf}=6.69 m/s. As a result, the efficiency of the converter, reaching the maximum value η_m=5.29 %, by the end of the operating cycle is reduced to η_f=3.65 %.

In order to evaluate the effectiveness of LPECIT when operating as an electromechanical accelerator, we use the values of the relative reduction of speed $\Delta v = 100\left(v_{zm} - v_{zf}\right)v_f^{-1}, \%$ and efficiency $\Delta\eta = 100\left(\eta_m - \eta_f\right)\eta_m^{-1}, \%$, as well as the relative criterion of efficiency $K_v^* = 100\dfrac{v_f^*}{j_{1m}^* f_{zm}^* \theta_1^*}, \%$. As a basic variant we used CES with capacity C_0=0.5 mF in the absence of current limitation in the short-circuited armature winding.

With increasing capacity C_0 from 0.5 to 5 mF (W_0=500 J) and no limitation of the armature winding current (smooth lines in Fig. 5), the maximum speed v_{zm} decreases from 11.86 to 6.19 m/s, which leads to reduce the maximum efficiency η_m from 14.24 to 4.02 %, increase the temperature rise of the inductor winding θ_1 from 1.84 to 2.87 °C and reduce the same value for the armature winding θ_2 from 2.02 to 0.78 °C. The value of the relative decrease in the speed of the armature winding Δv increases from 5.9 to 21.97 %. The value of the relative decrease in efficiency $\Delta\eta$ is manifested only after increasing the capacity C_0 over 1 mF. It increases to $\Delta\eta$=57 % at C_0=5 mF. The relative criterion of the efficiency of the converter K_v^* is almost doubled primarily by reducing the amplitude of the current density in the winding of the inductor j_{1m} from 870.1 to 551.5 A/mm^2 and the amplitude of the EDF f_{zm} from 21.16 to 4.62 kN.

In the presence of current limitation in the armature winding due to the connection of the diode *VD* (line with circles in Fig. 5), the efficiency criterion K_v^* increases,

and to a greater extent with increasing capacity of the energy storage. At C_0=5 mF and in the absence of a diode K_v^*=2.01, and in the presence of a diode K_v^*=2.56. The value of the relative decrease in efficiency $\Delta\eta$ decreases significantly. It occurs only after increasing the capacity above C_0=2.5 mF and increases to $\Delta\eta$=28.86 % at C_0=5 mF. The maximum efficiency η_m increases only in the range of C_0 from 0.5 to 2.0 mF and equals to η_m=16.16 % at C_0=0.5 mF. The temperature rise of the armature winding θ_2 decreases, varying in the specified range from 1.48 to 0.61 °C.
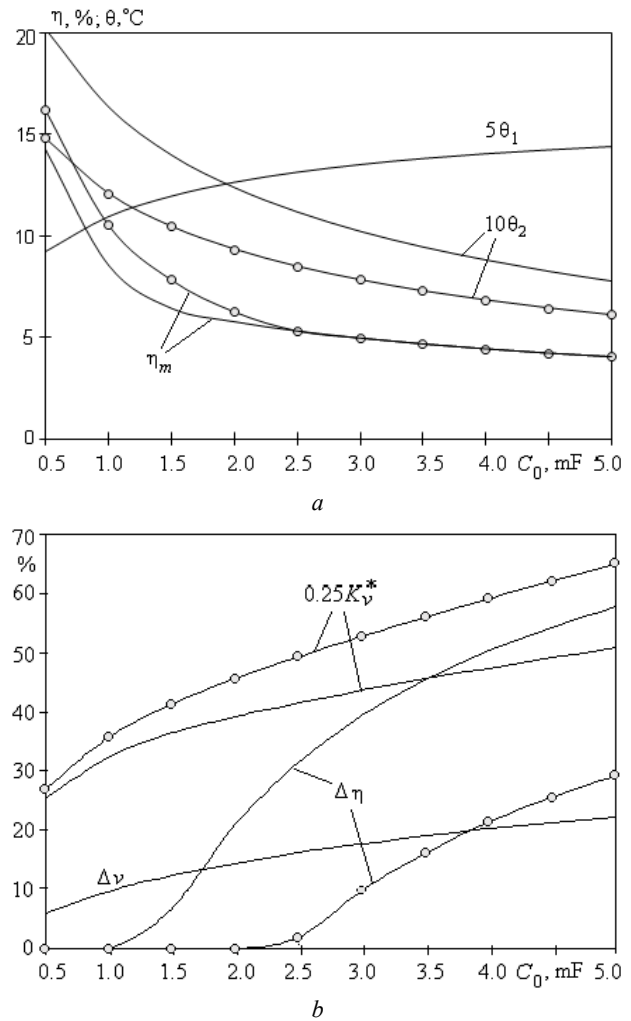

Fig. 5. Dependence of LPECIT performance at operation as an electromechanical accelerator on the capacity of CES at W_0=500 J

Thus, limiting the duration of the induced current in the armature winding before changing its polarity by connecting a rectifier diode to it increases the power performance of LPECIT as a shock-power device and increases the speed indicators of the converter operating as an electromechanical accelerator.

Conclusions.

1. To eliminate the attractive EDF between the windings of LPECIT, it is proposed to limit the duration of the induced current in the armature winding before changing its polarity by connecting a rectifier diode to it.

2. When LPECIT operates as a shock-power device, due to the attractive EDF the value of the moment of these forces, reaching the maximum value, decreases by the end of the operating cycle. When the duration of the current in the armature winding is limited, the value of the efficiency criterion, which takes into account the EDF impulse, recoil force, current and heating temperature of the inductor winding, increases (by 38.6 % at C_0=0.5 mF).

3. When LPECIT operates as an electromechanical accelerator without current limitation in the short-circuited armature winding, there is a decrease in speed and efficiency, which takes into account the kinetic energy and voltage of the CES at the end of the operating cycle. When the induced current in the armature winding is limited due to the connection of the rectifier diode, the efficiency criterion increases, and the temperature rise of the armature winding decreases. The maximum efficiency increases only in the range from 0.5 to 2 mF, amounting to 16.16 % at C_0=0.5 mF. The relative decrease in efficiency from the maximum to the final value decreases and occurs only after increasing the capacity C_0 over 2.5 mF.

Conflict of interest. The authors of the paper declare no conflict of interest.

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: https://doi.org/10.1109/TMAG.2004.839283.
2. Go B., Le D., Song M., Park M., Yu I. Design and Electromagnetic Analysis of an Induction-Type Coilgun System With a Pulse Power Module. *IEEE Transactions on Plasma Science*, 2019, vol. 47, no. 1, pp. 971-976. doi: https://doi.org/10.1109/TPS.2018.2874955.
3. Vilchis-Rodriguez D.S., Shuttleworth R., Barnes M. Modelling Thomson Coils With Axis-Symmetric Problems: Practical Accuracy Considerations. *IEEE Transactions on Energy Conversion*, 2017, vol. 32, no. 2, pp. 629-639. doi: https://doi.org/10.1109/TEC.2017.2651979.
4. Bolyukh V.F., Katkov I.I. Cryogenic Cooling System "KrioBlast" Increased Efficiency and Lowered the Operation Time of Protective Electrical Induction-Induced Devices. *Proceedings of the ASME 2013 International Mechanical Engineering Congress and Exposition. Volume 8B: Heat Transfer and Thermal Engineering*. San Diego, California, USA. November 15-21, 2013. V08BT09A003. ASME. doi: https://doi.org/10.1115/imece2013-62383.
5. Zhou Y., Huang Y., Wen W., Lu J., Cheng T., Gao S. Research on a novel drive unit of fast mechanical switch with modular double capacitors. *The Journal of Engineering*, 2019, vol. 2019, no. 17, pp. 4345-4348. doi: https://doi.org/10.1049/joe.2018.8148.
6. Liu X., Yu X., Ban R., Li Z. Analysis of the Capacitor-Aided Meat Grinder Circuits for an Inductive Pulsed Power Supply. *IEEE Transactions on Plasma Science*, 2017, vol. 45, no. 7, pp. 1339-1346. doi: https://doi.org/10.1109/TPS.2017.2705179.
7. Kondratenko I.P., Zhyltsov A.V., Pashchyn N.A., Vasyuk V.V. Selecting induction type electromechanical converter for electrodynamic processing of welds. *Technical Electrodynamics*, 2017, no. 5, pp. 83-88. (Ukr). doi: https://doi.org/10.15407/techned2017.05.083.
8. Soda R., Tanaka K., Takagi K., Ozaki K. Simulation-aided development of magnetic-aligned compaction process with pulsed magnetic field. *Powder Technology*, 2018, vol. 329, pp. 364-370. doi: https://doi.org/10.1016/j.powtec.2018.01.035.
9. Gorodzha K.A., Podoltsev A.D., Troshchynckyi B.O. Electromagnetic processes in pulsed electrodynamic emitter to excite elastic vibrations in concrete structures. *Technical Electrodynamics*, 2019, no. 3, pp. 23-28. (Ukr). doi: https://doi.org/10.15407/techned2019.03.023.
10. 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: https://doi.org/10.3103/S1068371215070044.
11. Puumala V., Kettunen L. Electromagnetic design of ultrafast electromechanical switches. *IEEE Transactions on Power Delivery*, 2015, vol. 30, no. 3, pp. 1104-1109. doi: https://doi.org/10.1109/tpwrd.2014.2362996.
12. Bolyukh V.F., Schukin I.S., Lasocki J. Influence of the initial winding displacement on the indicators of the electromechanical induction accelerator of cylindrical configuration. *Electrical Engineering & Electromechanics*, 2021, no. 5, pp. 3-10. doi: https://doi.org/10.20998/2074-272X.2021.5.01.
13. Niu X., Li W., Feng J. Nonparametric Modeling and Parameter Optimization of Multistage Synchronous Induction Coilgun. *IEEE Transactions on Plasma Science*, 2019, vol. 47, no. 7, pp. 3246-3255. doi: https://doi.org/10.1109/tps.2019.2918157.
14. Kondratiuk M., Ambroziak L. Concept of the magnetic launcher for medium class unmanned aerial vehicles designed on the basis of numerical calculations, *Journal of Theoretical and Applied Mechanics*, 2016, vol. 54, no. 1, pp. 163-177. doi: https://doi.org/10.15632/jtam-pl.54.1.163.
15. Angquist L., Baudoin A., Norrga S., Nee S., Modeer T. Low-cost ultra-fast DC circuit-breaker: Power electronics integrated with mechanical switchgear. *2018 IEEE International Conference on Industrial Technology (ICIT)*, 2018, pp. 1708-1713. doi: https://doi.org/10.1109/icit.2018.8352439.
16. Bolyukh V.F., Dan'ko V.G., Oleksenko S.V. The Effect of an External Shield on the Efficiency of an Induction-Type Linear-Pulse Electromechanical Converter. *Russian Electrical Engineering*, 2018, vol. 89, no. 4, pp. 275-281. doi: https://doi.org/10.3103/S106837121804003X.
17. Bolyukh V.F., Katkov I.I. Influence of the Form of Pulse of Excitation on the Speed and Power Parameters of the Linear Pulse Electromechanical Converter of the Induction Type. *Volume 2B: Advanced Manufacturing*, Nov. 2019, 8 p. doi: https://doi.org/10.1115/imece2019-10388.
18. Bolyukh V.F., Shchukin I.S. Influence of an excitation source on the power indicators of a linear pulse electromechanical converter of induction type. *Technical Electrodynamics*, 2021, no. 3, pp. 28-36. doi: https://doi.org/10.15407/techned2021.03.028.
19. Ljutenko L.A., Mikhailov V.M. Expansion of cylindrical tubular workpieces on high-voltage magnetic-pulse installation with controlled vacuum discharger. *Electrical Engineering & Electromechanics*, 2021, no. 3, pp. 42-46. doi: https://doi.org/10.20998/2074-272X.2021.3.07
20. Bolyukh V.F., Kashanskyi Y.V., Shchukin I.S. Comparative analysis of power and speed indicators linear pulse electromechanical converters electrodynamic and induction

types. *Technical Electrodynamics*, 2019, no. 6, pp. 35-42. (Rus). doi: https://doi.org/10.15407/techned2019.06.035.
21. Bolyukh V.F., Vinnichenko A.I. Concept of an Induction-Dynamic Catapult for a Ballistic Laser Gravimeter. *Measurement Techniques*, 2014, vol. 56, no. 10, pp. 1098-1104. doi: https://doi.org/10.1007/s11018-014-0337-z.
22. Bolyukh V.F., Omel'chenko A.V., Vinnichenko A.I. Effect of Self-Seismic Oscillations of the Foundation on the Readout of a Ballistic Gravimeter with an Induction-Dynamic Catapult. *Measurement Techniques*, 2015, vol. 58, no. 2, pp. 137-142. doi: https://doi.org/10.1007/s11018-015-0675-5.

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