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 electromagnetic 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 electromagnetic 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 LPECIT 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, rectifier 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 electromagnetic converter of induction type, shock-power device, electromechanical accelerator, performance indicators, limiting the duration of the armature winding current.

Vystup. 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) відбувається виникнення і наступні ЕДС тягіння. Внаслідок цього робочі показники ЛІЕПІТ знижуються. Методика. Для аналізу електромеханічних характеристик та показників ЛІЕПІТ використана математична модель, в якій розв'язані рівняння, що описують взаємодію електричних, магнітних, механічних і теплових процесів, представлених в розрізненому вигляді. Результати. Для усунення ЕДС тягіння між обмотками ЛІЕПІТ запропоновано 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'язані рівняння, що описують взаємодію електричних, магнітних, механічних і теплових процесів, представлені в розрізненому вигляді. Результати. Для усунення ЕДС тягіння між обмотками ЛІЕПІТ запропоновано 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'язані рівняння, що описують взаємодію електричних, магнітних, механічних і теплових процесів, представлені в розрізненому вигляді. Результати. Для усунення ЕДС тягіння між обмотками ЛІЕПІТ запропоновано 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'язані рівняння, що описують взаємодію електричних, магнітних, механічних і теплових процесів, представлені в розрізненому вигляді. Результати. Для усунення ЕДС тягіння між обмотками ЛІЕПІТ запропоновано 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'язані рівняння, що описують взаємодію електричних, магнітних, механічних і теплових процесів, представлені в розрізненому вигляді. Результати. Для усунення ЕДС тягіння між обмотками ЛІЕПІТ запропоновано 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'язані рівняння, що описують взаємодію електричних, магнітних, механічних і теплових процесів, представлені в розрізненому вигляді. Результати.
Introduction. Linear pulse electromagnetic 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.
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:

\[
R_n(T_n)i_n + L_n \frac{di_n}{dt} + \frac{1}{C_0} \int_0^t i_n dt + M_{12} \frac{di_n}{dt} = 0, \tag{1}
\]

\[
\frac{1}{C_0} \int_0^t i_n * dt = U_0, \tag{2}
\]

\[
R_s(T_s) \cdot i_s + L_s \frac{di_s}{dt} + M_{21} \frac{di_s}{dt} = 0, \tag{3}
\]

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:

\[
R_s(T_s) \cdot i_s + L_s \frac{di_s}{dt} + \frac{1}{C_0} \int_0^t i_s dt + M_{12}(z) \frac{di_s}{dt} + +v_z(t)i_s \frac{dM_{12}}{dz} = 0; \tag{4}
\]

\[
R_s(T_s) \cdot i_s + L_s \frac{di_s}{dt} + M_{21}(z) \frac{di_s}{dt} + i_s \cdot v_s \frac{dM_{12}}{dz} = 0. \tag{5}
\]

Solutions of the equations for currents in the converter windings in recurrent form are presented in [18]. The displacement $h_i$ 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:

\[
f_z(z, t) = i_s(t) i_z(t) \frac{dM_{12}}{dz}(z), \tag{6}
\]

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 $R_s(T_s)$, $M_{12}(z)$. 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 $T_i$ and $T_s$ the displacements $h_i$ 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 $\Delta t$. The value of $\Delta t$ is chosen so that it does not significantly affect the calculation results, while ensuring the required accuracy.

Initial conditions of the mathematical model:

$T_0(0) = T_0$ – the temperature of the $n$-th winding;

$i_0(0) = 0$ – the current of the $n$-th winding;

$h_i(0) = h_{00}$ – the distance between windings;

$w_0(0) = U_0$ – the CES voltage;

$v_z(0) = 0$ – the speed of the armature winding along $z$ 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 $d_{00}=1.3$ mm and impregnated with epoxy compound. The outer diameter of the windings $D_{00}=100$ mm, their inner diameter $D_{00}=10$ 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 $h_{00}=1$ 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 $U_0 = \sqrt{2W_0C_0^{-1}}$. 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 $\theta_1$, 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/mm², and in the armature winding $j_{2m} = 1.41$ kA/mm² (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 $\theta_1 = 2.87$ °C, and the temperature rise of the armature winding is $\theta_2 = 1.86$ °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.

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 30.85 to 7.7 N·s). With such an increase in capacitance $C_0$, the temperature rise of the inductor winding $\theta_1$ 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 \( \theta_2 \). In the converter without current limitation of the short-circuited armature winding, the value \( \theta_2 \) decreases from 2.87 to 1.27 °C. In the presence of the specified limitation due to connection of the diode \( VD \), the value \( \theta_2 \) is lower, than in its absence, and decreases from 2.24 to 0.96 °C.

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 \( \Delta P = 100 \left( P_{im} - P_{if} \right) P_{im}^{-1}, \% \) and the relative criterion of efficiency \( K_{p} = 100 \frac{P_{im}}{j_{im} f_{im} \theta_1}, \% \). 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 \( j_{im} \) and the amplitude of the EDF \( f_{im} \).

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

\[
\eta = 100 C_0^{-1} \left( m_{j} + m_{a} \right) v^2 \left( U_0^2 - U_{1}^2 \right)^{-1}, \%
\]

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.
When using CES with capacity of $C_0=0.5$ mF, the maximum current density in the inductor winding is $j_{lm}=0.87$ kA/mm², and in the armature winding is $j_{2am}=1.19$ kA/mm² (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: $f_{am}=21.16$ kN.

In the converter without current limitation in the short-circuited armature winding, the maximum speed $v_{zm}=11.86$ m/s by the end of the operating cycle is practically not reduced, which provides the efficiency of the electromechanical accelerator $\eta=14.24\%$. The temperature rise of the inductor winding is $\theta_1=1.84$ °C, and the temperature rise of the armature winding $\theta_2=2.02$ °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 $j_{lm}=0.621$ kA/mm², and in the armature winding to $j_{2am}=0.69$ kA/mm², EDF to $f_{am}=7.62$ kN (Fig. 4,b).

By the end of the operating cycle, the temperature rise of the inductor winding increases to $\theta_1=2.6$ °C, and the temperature rise of the armature winding decreases to $\theta_2=1.12$ °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 $v_z=6.69$ m/s. As a result, the efficiency of the converter, reaching the maximum value $\eta_m=5.29\%$, by the end of the operating cycle is reduced to $\eta=3.65\%$.

In order to evaluate the effectiveness of LPECIT when operating as an electromechanical accelerator, we use the values of the relative reduction of speed $\Delta v=100\left(\frac{v_{zm} - v_z}{v_z}\right)\%$ and efficiency $\Delta \eta=100\left(\frac{\eta_m - \eta}{\eta_m}\right)\%$, as well as the relative criterion of efficiency $K^*=100\frac{v_z}{j_{lm}f_{am}\theta_1}\%$. 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 the maximum efficiency $\eta_m$ from 4.24 to 4.02 %, increase the temperature rise of the inductor winding $\theta_1$ from 1.84 to 2.87 °C and reduce the same value for the armature winding $\theta_2$ from 2.02 to 0.78 °C. The value of the relative decrease in the speed of the armature winding $\Delta v$ 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 $K^*$ is almost doubled primarily by reducing the amplitude of the current density in the winding of the inductor $j_{lm}$ from 870.1 to 551.5 A/mm² and the amplitude of the EDF $f_{am}$ 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 $K^*$ 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 $K^*_{b}=2.01$, and in the presence of a diode $K^*_{c}=2.56$. 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 $\eta_m$ increases only in the range of $C_0$ from 0.5 to 2.0 mF and equals to $\eta_m=16.16\%$ at $C_0=0.5$ mF. The temperature rise of the armature winding $\theta_2$ 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](image)

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.

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