UDC 621.313:536.2.24:539.2

https://doi.org/10.33271/nvngu/2020-3/073

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INFLUENCE OF PULSE EXCITATION ON ELECTROMECHANICAL INDICATORS OF A LINEAR PULSE CONVERTER OF ELECTRODYNAMIC TYPE

Purpose. Investigation of the effect of pulsed excitation of the electronic circuit-controlled inductor and armature windings, powered with the capacitive energy storage (CES) source, on the speed and power indicators of a linear pulse electrodynamic converter (LPEC).

Methodology. On the basis of the developed numerical model, the influence of pulsed excitation — vibrationally damped, half-wave, aperiodic, and aperiodic with recharge, on the characteristics and performance of LPEC is studied. The mathematical model of the LPEC, using the lumped parameters of the stationary winding of the inductor and the movable winding of the armature, takes into account the interconnected electromagnetic, mechanical and thermal processes, presenting their solutions in a recursive form.

Findings. It was found that the pulse excitation of the LPEC insignificantly affects the maximum speed, the pulse of electrodynamic forces (EDF) and the temperature rise of the inductor winding. The highest values of the maximum speed and impulse of an EDF arise upon excitation by a vibrationally damped current pulse, while the smallest ones – upon excitation by an aperiodic pulse. The LPEC excitation by an aperiodic current pulse with recharge allows the use of a reduced charge voltage for rechargeable CES. With a decrease in this voltage and with conservation of the energy of the CES, the amplitude of the EDF decreases by 31.5 %, but due to the delay of electromagnetic processes, the pulse of the EDF increases by 3 %, and the efficiency – by 8.2 %.

Originality. A comprehensive criterion for the LPEC efficiency was introduced, which takes into account the amplitude of the excitation current, the mass of the windings, the temperature of the inductor winding, the magnitude of the EDF pulse, the efficiency, and the maximum speed for a given reliability coefficient. Using this criterion, we found that in terms of power and speed indicators, the most efficient is a converter excited by an aperiodic current pulse with recharge, and the quality of work is a converter excited by an aperiodic pulse.

Practical value. The influence of the width of the copper bus and the corresponding axial heights of the windings of the inductor and the armature on the speed and power performance of the LPEC using vibration-damping, half-wave, aperiodic and aperiodic with recharge current pulses is established.

Keywords: *linear pulse converter of electrodynamic type, a comprehensive efficiency criterion, an excitation current pulse*

Introduction. Linear pulse converters provide a high speed of the actuator movement in a short active section [1], and/or powerful power (shock-mechanical) pulses on the target [2].

Such converters are used in electromagnetic hammers and rotary hammers, in devices for driving piles and anchors [3], in rock dividers and vibrators, in seismic sources for geological exploration, in presses with a large range of impact energy, in vibratory mixers and batchers for the chemical and biomedical industries, in magnetic-pulse devices for impact pressing of ceramic powders, in shock-mechanical devices for cleaning containers from adhering bulk materials, in devices for destroying digital information carriers, in high-speed electric devices and valve-switching equipment [4], in smooth damping and high-speed elements stopping devices [5], in test complexes for testing critical products for shock loads [6], in catapults of unmanned aerial vehicles [7], in propelling devices for fighting fires, and others.

One of the promising devices is a linear pulse electrodynamic type converter (LPEC), the windings of which are excited from a capacitive energy storage device (CES) [8]. Converters of electrodynamic type, in spite of a more complex design, have higher electromechanical indices in comparison with converters of induction and electromagnetic types [9].

In the LPEC, which has a coaxial configuration, the fixed inductor and the accelerated armature are made in the form of monolithic disk windings that are tightly wound with a copper bus, the turns of which are fastened with epoxy resin. In the windings of the inductor *1* and the armature *2*, current is generated from a switching power supply containing either only the main CES *3* with a capacitance C_0 and voltage U_0 or, in addition, a recharge CES *4* with parameters C_1, U_1 (Fig. 1). The armature winding (AW) *2* is connected to the inductor winding (IW) *1* and to an impulse power supply using, for example, flexible current leads *m, n*. IW and AW are connected in series electrically and counter-magnetic field. As a result of this, the same current flows in the windings and between them there are electrodynamic repulsive forces (EDF), which cause axial movement of the AW *2* with the actuating element *5* relative to the IW *1*.

During the operation of the LPEC, a change in the magnetic coupling between the AW and the IW occurs, and their active resistance increases due to the amplifying current of high density. In addition, the efficiency of the pulse converter

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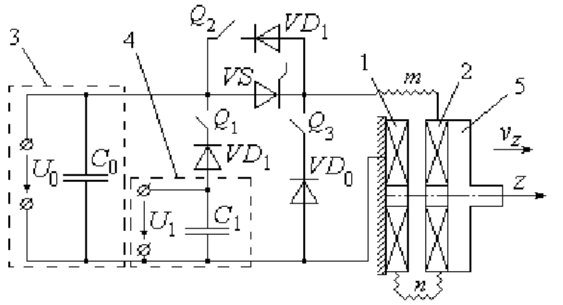

Fig. 1. LPEC circuit, forming various pulses of the excitation current

is not high enough [9]. This requires new approaches to improving its electromechanical performance.

Several approaches are known to increase the efficiency of linear pulse converters, namely, through the use of design improvements [10], cryogenic cooling of windings [11], optimization of geometric parameters [12], intensive cooling without the use of special refrigerant [13], and so on. One of the ways to increase the speed and power indicators of linear pulse converters is the formation of a current pulse of excitation of its windings using an electronic circuit-controlled power source containing the CES. Such studies were carried out for linear pulse converters of induction type with the use of a single-section [14] or two-section CES [15]. However, such studies have not been conducted for electrodynamic-type transducers, which makes the task relevant.

Purpose. Investigation of the effect of pulsed excitation of the electronic circuit-controlled inductor and armature windings, powered with the CES source on the speed and power indicators of an LPEC.

The LPEC numerical model. Consider the mathematical model of the LPEC, in which the lumped parameters of the IW and AW are used for the free discharge of the main CES with parameters C_0, U_0. The electrical processes in this converter can be described by the equations [9]

$$\left[R_1(T_1)+R_2(T_2)\right]\cdot i+\frac{\mathrm{d}\psi}{\mathrm{d}t}+\frac{1}{C_0}\int_0^t idt=0;$$

$$u_C=\frac{1}{C_0}\int_0^t idt=U_0, \tag{1}$$

where $n = 1, 2$ are the indices of IW and AW, respectively; R_n, T_n are resistance and temperature of the n^{th} winding; i is the excitation current of the windings; u_C is the CES voltage;

$$\frac{d\psi}{dt}=\left[L_1-2M_{12}(z)+L_2\right]\frac{di}{dt}-2iv_z(t)\frac{dM_{12}}{dz}, \tag{2}$$

where L_n is the inductance of the n^{th} winding; M_{12} is the mutual inductance between the stationary IW and the mobile AW, which moves along the z axis with a speed v_z.

Substituting equation (2) in (1) we obtain

$$\left(R^*-\xi\right)\cdot i+\left[L^*-2M_{12}(z)\right]\frac{di}{dt}+\frac{1}{C_0}\int_0^t idt=0, \tag{3}$$

where $R^* = R_1(T_1) + R_2(T_2)$; $L^* = L_1 + L_2$; $\xi=2v_z(t)\dfrac{dM_{12}}{dz}$.

The solution of equation (3) can be represented as

$$i=A_1\exp(\alpha_1 t)+A_2\exp(\alpha_2 t), \tag{4}$$

where A_1, A_2 are arbitrary constants;

$$\alpha_{1,2}=\frac{\pm\left\{0.25\left[R^*-\xi\right]^2-\left[L^*-2M_{12}(z)\right]C_0^{-1}\right\}^{0.5}+0.5\left(R^*-\xi\right)}{2M_{12}(z)-L^*}$$ –

roots of the characteristic equation.

To represent the solution in a recurrent form, we define the values of arbitrary constants A_1 and A_2 at the time t_k.

If $\left(R^*-\xi\right)>2\sqrt{\left(L^*-2M_{12}(z)\right)C_0^{-1}}$, then after a series of transformations we get

$$A_{1,2}=\frac{u_C(t_k)+\left(R^*-\xi\right)i(t_k)+\alpha_{2,1}\cdot i(t_k)\left[L^*-2M_{12}(z)\right]}{\left[L^*-2M_{12}(z)\right]\exp\left(\alpha_{1,2}t_k\right)\left(\alpha_{2,1}-\alpha_{1,2}\right)}. \tag{5}$$

Substituting expressions (5) into equation (4) we obtain the expression for the current

$$\begin{aligned}i(t_{k+1})={}&\frac{u_C(t_k)+\left(R^*-\xi\right)i(t_k)}{\left(L^*-2M_{12}(z)\right)\left(\alpha_2-\alpha_1\right)}\times\\&\times\left[\exp\left(\alpha_1\Delta t\right)-\exp\left(\alpha_2\Delta t\right)\right]+\\&+\frac{i(t_k)}{\alpha_2-\alpha_1}\left[\alpha_2\exp\left(\alpha_1\Delta t\right)-\alpha_1\exp\left(\alpha_2\Delta t\right)\right],\end{aligned} \tag{6}$$

where $\Delta t = t_{k+1} - t_k$.

The voltage on the CES is described by the equation

$$\begin{aligned}u_C(t_{k+1})={}&\frac{u_C(t_k)+\left(R^*-\xi\right)i(t_k)}{\alpha_2-\alpha_1}\left[\alpha_2\exp\left(\alpha_1\Delta t\right)-\right.\\&\left.-\alpha_1\exp\left(\alpha_2\Delta t\right)\right]+\frac{\left[L^*-2M_{12}(z)\right]i(t_k)}{\alpha_2-\alpha_1}\times\\&\times\left[\alpha_2^2\exp\left(\alpha_1\Delta t\right)-\alpha_1^2\exp\left(\alpha_2\Delta t\right)\right].\end{aligned} \tag{7}$$

If $\left(R^*-\xi\right)<2\sqrt{\left(L^*-2M_{12}(z)\right)C_0^{-1}}$, then we present the roots of the characteristic equation in a complex form

$$\alpha_{1,2}=-\delta\pm j\omega_1=\omega_0\exp\left(j(\pi\pm\theta)\right), \tag{8}$$

where

$$\delta=0.5\frac{R^*-\xi}{L^*-2M_{12}(z)};\qquad \omega_0=\left[C_0\left(L^*-2M_{12}(z)\right)\right]^{-0.5};$$

$$\theta=\mathrm{arctg}\left(4\frac{L^*-2M_{12}(z)}{\tilde{N}_0\left(R^*-\xi\right)^2}-1\right)^{0.5};$$

$$\omega_1=\left(\frac{1}{C_0\left(L^*-2M_{12}(z)\right)}-\left(\frac{R^*-\xi}{2\left[L^*-2M_{12}(z)\right]}\right)^2\right)^{0.5}.$$

Substituting the values of the roots (8) in equations (6) and (7) and taking into account that

$$2j\sin(\omega_1\Delta t)=\exp(j\omega_1\Delta t)-\exp(-j\omega_1\Delta t),$$

we get

$$\begin{aligned}i(t_{k+1})={}&-\omega_1^{-1}\exp\left(-\delta\Delta t\right)\left\{\frac{u_C(t_k)+\left(R^*-\xi\right)\cdot i(t_k)}{L^*-2M_{12}(z)}\times\right.\\&\left.\times\sin\left(\omega_1\Delta t\right)+\omega_0 i(t_k)\sin\left(\omega_1\Delta t-\theta\right)\right\}.\end{aligned} \tag{9}$$

The voltage on the CES is described by the equation

$$\begin{aligned}&u_C(t_{k+1})=-\omega_0\omega_1^{-1}\exp\left(-\delta\Delta t\right)\left\{\left[u_C(t_k)+\left(R^*-\xi\right)\cdot i(t_k)\right]\times\right.\\&\left.\times\sin\left(\omega_1\Delta t-\theta\right)+i(t_k)\omega_0\left(L^*-2M_{12}(z)\right)\sin\left(\omega_1\Delta t-2\theta\right)\right\}.\end{aligned} \tag{10}$$

If $\left(R^*-\xi\right)=2\sqrt{\left(L^*-2M_{12}(z)\right)C_0^{-1}}$, then $\delta = \omega_0$ and the LPEC current is described by the expression

$$i(t_{k+1})=\left\{i(t_k)\delta-\left(L^*-2M_{12}(z)\right)^{-1}\left[u_C(t_k)+\left(R^*-\xi\right)\cdot i(t_k)\right]\right\}\times \\ \times\exp\left(-\delta\Delta t\right)\Delta t. \tag{11}$$

And the voltage on the CES is described by the expression

$$u_C(t_{k+1}) = [u_C(t_k) - i(t_k)(L^* - 2M_{12}(z))\delta + (R^* - \xi)\cdot i(t_k)] \times \\ \times (\delta\Delta t + 1)\exp(-\delta\Delta t) + i(t_k)[(L^* - 2M_{12}(z))\delta - R^* + \xi]. \tag{12}$$

If the LPEC is excited by an aperiodic pulse, then the current in the time interval $\{0, t_1\}$, where t_1 is the time at which the voltage of the CES $u_C = 0$, is described by expressions (6, 9, 11), and in the interval $\{t_1, \infty\}$ – by the expression

$$i(t_{k+1})=i(t_k)\exp\left(\frac{\left(\xi-R^*\right)\Delta t}{L^*-2M_{12}(z)}\right). \tag{13}$$

Mechanical processes of the LPEC can be described by the equation [11]

$$i^2(t)\frac{dM_{12}}{dz}=\left(m_a+m_2\right)\frac{dv_z}{dt}+K_P\Delta z(t)+ \\ +K_T v_z(t)+0.125\pi\gamma_a\beta_a D_{2m}^2 v_z^2(t), \tag{14}$$

where m_2, m_a is the mass of the AW and the actuating element, respectively; K_P is the coefficient of elasticity of the return spring; $\Delta z(t)$ is the amount of displacement of the AW with the actuator; K_T is the coefficient of dynamic friction; γ_a is the density of the moving medium; β_a is the drag coefficient; D_{2m} is the outer diameter of the actuator.

Based on equation (14), the magnitude of the displacement of the AW with the actuating element can be represented as a recurrence relation

$$s(t_{k+1}) = s(t_k) + v_z(t_k)\Delta t + \vartheta\Delta t^2/(m_a + m^2), \tag{15}$$

where $v_z(t_{k+1}) = v_z(t_k) + \vartheta\Delta t/(m_a + m_2)$ is AW speed with an executive element along the z axis; $\vartheta=i^2(t_k)\dfrac{dM}{dz}(z)-$ $-K_P\Delta z(t_k)-K_T v_z(t_k)-0.125\pi\gamma_a\beta_a D_{2m}^2 v_z^2(t_k)$.

Thermal processes. In the absence of AW movement, which occurs either before the start of the forward stroke or after the reverse stroke, there is a thermal contact between the windings of the inductor and the armature through the insulating gasket. The temperature of the LPEC windings can be described by the recurrence relation [13]

$$T_n(t_{k+1})=T_n(t_k)\zeta+\left(1-\zeta\right)\left[\pi^{-1}i_n(t_k)R_n(T_n)\left(D_{en}^2-D_{in}^2\right)^{-1}+ \\ +0.25\pi T_0 D_{en}H_n\alpha_{Tn}+T_m(t_k)\lambda_a(T)d_a^{-1}\right]\times \\ \times\left\{0.25\pi\alpha_{Tn}D_{en}H_n+\lambda_a(T)d_a^{-1}\right\}^{-1}, \tag{16}$$

where $\zeta=\exp\left\{-\dfrac{\Delta t}{C_n(T_n)\gamma_n}\left(0.25D_{en}\alpha_{Tn}+\dfrac{\lambda_a(T)}{d_a H_n}\right)\right\}$; $\lambda_a(T)$ – thermal conductivity coefficient of the insulating gasket; d_a – gasket thickness; D_{en}, D_{in} – the outer and inner diameters of the windings, respectively; α_{Tn} – heat transfer coefficient of the n^{th} winding; C_n – heat capacity of the n^{th} winding.

The temperature of the windings when moving the AW can be described by the recurrence relation

$$T_n(t_{k+1})=T_n(t_k)\chi+ \\ +\left(1-\chi\right)\left[\left[T_0+4\pi^{-2}i_n(t_k)R_n(T_n)\alpha_{Tn}^{-1}D_{en}^{-1}H_n^{-1}\left(D_{en}^2-D_{in}^2\right)^{-1}\right]\right], \tag{17}$$

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

The initial conditions of the mathematical model of the LPEC are as follows:

$T_n(0) = T_0$ – temperature of the n^{th} winding;
$i(0) = 0$ – winding current;
$s(0) = s_0$ – axial distance between windings;
$u_c(0) = U_0$ – CES voltage;
$v_z(0) = 0$ – AW velocity along the z axis.

In order to take into account the complex of interconnected electrical, magnetic, thermal and mechanical processes and various nonlinear dependencies, we use the following approach. The whole workflow in numerical calculation is divided into a large number of small time intervals $\Delta t = t_{k+1} - t_k$, within which all quantities are considered unchanged. Based on the current values obtained at the time instant t_{k+1} we estimate the temperature of the windings T, the displacement and speed of the AW, the mutual inductance M_{12} between the fixed IW and mobile AW, and so on. The obtained values are used to calculate the current for the next time interval $\Delta t = t_{k+2} - t_{k+1}$. The value of the skin layer in the windings is estimated according to the calculation results and, if necessary, an iterative process of adjusting the resistance is carried out. With this approach, linear equations and relations can be used to determine the excitation current in a small calculated time interval Δt. The value of the calculation step Δt is chosen so that it does not significantly affect the calculation results.

The force effect of LPEC will be estimated by the amplitude F_{zm} and the magnitude of the pulse EDF [9]

$$P_1=\int F_z(z,t)dt, \tag{18}$$

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

We will evaluate the speed indicators by the magnitude of the maximum speed of the AW with the actuator V_m.

The efficiency of LPEC will be evaluated by the ratio, %

$$\eta=100\frac{\left(m_2+m_a\right)v_z^2+K_P s^2}{C_0\left(U_0^2-U_a^2\right)}, \tag{19}$$

where U_a is residual voltage CES after the working cycle, with a minimum temperature rise of the n^{th} winding $\theta_n = T_n - T_0$.

Main parameters of LPEC. Let us consider an LPEC, in which the moving AW and the stationary IW are made in the form of flat coaxially mounted disks. In AW, one end side faces the IW, and the second is connected to the actuator (Fig. 1). IW and AW are made the same and are wound with a copper bus section $a \times b$. The outer diameter of the n^{th} winding $D_{en} =$ $= 100$ mm, its inner diameter $D_{in} = 10$ mm. Each winding is wound in two rows and contains 60 turns of a copper busbar with a thickness of $a = 1.2$ mm. The initial distance between the windings is $\Delta z_0 = 1$ mm. The coefficient of elasticity of the return spring $K_P = 25$ kN/m. The mass of the actuating element is $m_a = 0.25$ kg.

The LPEC can be excited by various current pulses (Fig. 1):

- vibration-damping ones (keys Q_1 and Q_3 are open, and key Q_2 is closed);
- half-wave ones (keys Q_1, Q_2 and Q_3 are open);
- aperiodic ones (keys Q_1 and Q_2 are open, key Q_3 is closed);
- aperiodic with recharge ones (key Q_2 is open, and keys Q_1 and Q_2 are closed).

When excited by vibrationally-damped, half-wave and aperiodic pulses, the main CES has the following parameters: capacitance $C_0 = 2.0$ mF, voltage $U_0 = 0.5$ kV.

Consider the influence of the excitation current pulse on the LPEC parameters, both windings of which are wound with a copper bus of the same width b, selected from a series – 2.4, 3.6 and 4.8 mm in two layers. The axial height of each two-layer winding H_n is, respectively, 5.2 mm, 7.6 mm and 10.0 mm.

When the LPEC is excited by a vibrationally damped pulse, voltage CES u_c and current density in windings j change polarity (Fig. 2). Since the currents in the IW and AW flow in opposite directions, the EDFs acting between them are a sequence of decaying repulsion pulses.

The largest impulse of EDF $P_I = 8.59$ Ns occurs in LPEC, the windings of which are wound with a copper bus of the greatest width $b = 4.8$ mm from the considered series. However, the highest speed $V_{zm} = 11.68$ m/s is developed by LPEC, in which the windings are wound with the narrowest busbar $b = 2.4$ mm. Note that with a double increase in the width of the copper busbar, the maximum current in the windings increases slightly – by 12 %, but the maximum density decreases significantly – by 78 %. As a result, with an increase in the width of the copper busbar b, and hence a corresponding increase in the axial height of the windings H_n their temperature excesses θ_n decrease by more than 2 times. Depending on the width of the copper busbar b the excess of the temperature of the IW θ_1 is 8–16 % more than the excess of the temperature of the AW θ_2. Therefore, in the future, when evaluating the thermal state of the LPEC, we will focus on the excess of the temperature of the IW.

The highest efficiency value $\eta = 18.9$ % is demonstrated by the LPEC, the windings of which are wound with a medium-width bus $b = 3.6$ mm from the considered series

When the LPEC is excited by a half-wave pulse, the voltage of the CES u_c changes polarity, and the polarity of the current density in the windings j remains unchanged (Fig. 3).

The largest magnitude of the EDF P_I pulse also occurs in the LPEC, the windings of which are wound with a copper bus of the greatest width $b = 4.8$ mm, however, compared with a vibrationally damped pulse, it is somewhat (3 %) lower. The excess of the temperature of the IW for this converter in comparison with the excitation considered above is reduced by 25 %. The highest speed V_{zm} is developed by the LPEC, in which the windings are wound with the narrowest busbar $b = 2.4$ mm. Moreover, it is almost equal to the maximum speed of the LPEC with vibrationally damped excitation pulse. Due to the fact of a half-wave pulse excitation, part of the energy is stored in the CES, the converter efficiency increases to 19.5 %.

However, when the LPEC is excited by vibrational-damping and half-wave current pulses, the voltage of the CES u_c changes polarity, which requires the use of special non-polar capacitors.

When the LPEC is excited with an aperiodic pulse, both the current and the voltage of the CES retain their polarity, which allows the use of electrolytic capacitors of increased energy intensity (Fig. 4).

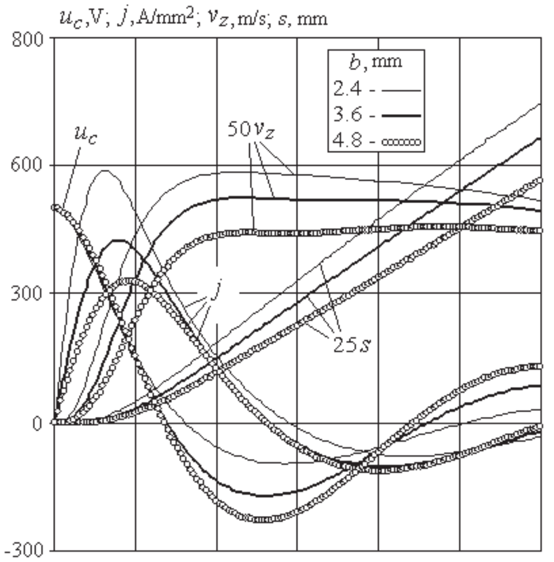

Fig. 2. Electromechanical characteristics of the LPEC excited by a vibrationally damped current pulse

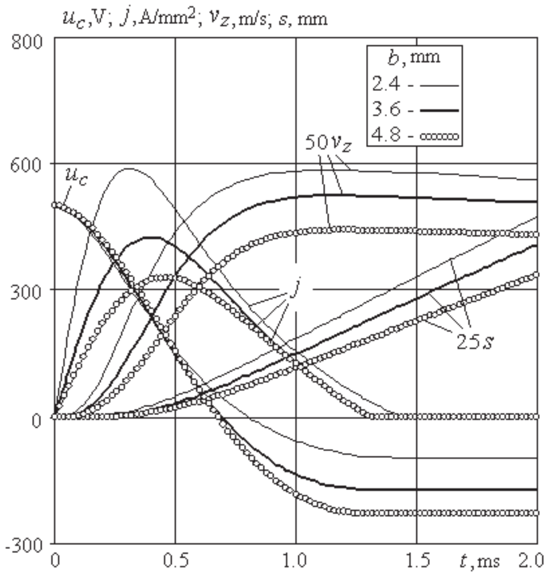

Fig. 3. Electromechanical characteristics of the LPEC excited by a half-wave current pulse

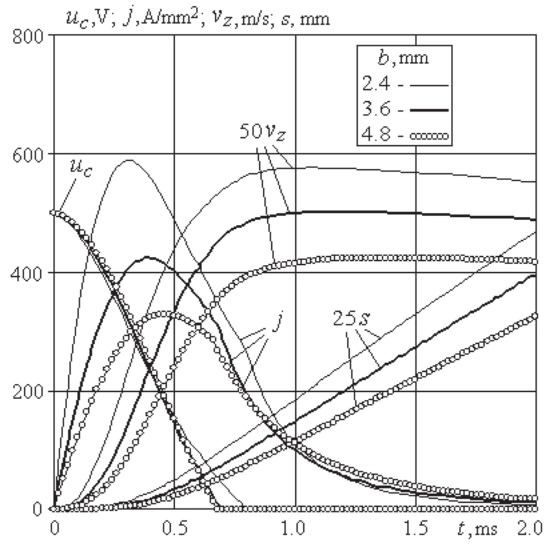

Fig. 4. Electromechanical characteristics of the LPEC excited by an aperiodic current pulse

Compared with the LPEC, excited by a vibrationally damped pulse, in the converter under consideration, the maximum speed V_{zm} and EDF pulse P_I decrease slightly (depending on the width of the copper bus b is 1–7 %). The temperature rise of the IW θ_1 for a given pulsed excitation is lower than when excited by a vibrationally damped pulse, but higher than when excited by a half-wave pulse. The highest speed $V_{zm} = 11.68$ m/s and the highest efficiency value $\eta = 16.6$ % occur in the LPEC, the windings of which are wound with a wire of the smallest width $b = 2.4$ mm.

For all the pulsed excitations considered above, the maximum currents in the LPEC windings wound with a copper bus of the same width are the same, and the temperature rise of the IW θ_1 is higher than the temperature rise of the AW θ_2.

Fig. 5 allows a more complete assessment of the effect of the width of the copper busbar b from which the LPEC windings are wound when excited by vibrationally damped (F), half-wave (I) and aperiodic (A) pulses. As follows from the presented dependences, pulsed current excitation of the winding insignificantly affects the maximum speed V_{zm}, the EDF pulse P_I and the temperature excess of the inductor winding

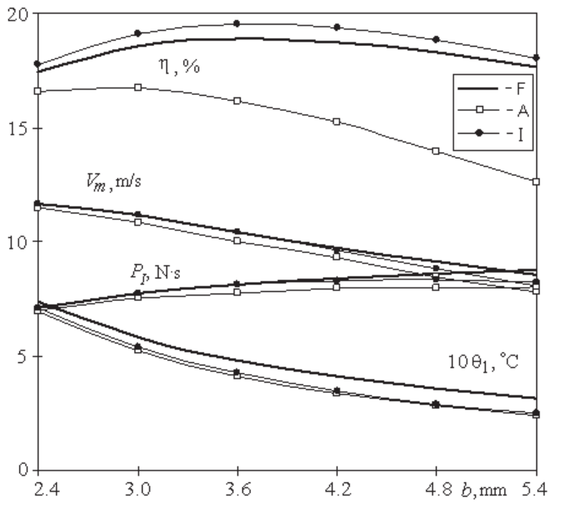

Fig. 5. The dependence of width of the LPEC copper bus b windings on its electromechanical and thermal performance

θ_1. With an increase in the width of the copper bus b the maximum speed V_{zm} and the excess of the temperature of the inductor winding θ_1 decrease, and the EDF pulse P_I increases.

With an increase in the width of the copper busbar windings b, the influence of pulsed excitation manifests itself to a greater extent for the maximum speed V_{zm}, the EDF pulse P_I and the efficiency η. The highest values of the maximum speed V_{zm} and the EDF pulse P_I arise when the windings are excited by a damped current pulse, and the lowest values when excited by an aperiodic pulse. Similar dependences are manifested for the temperature of the inductor winding θ_1. When excited by aperiodic and half-wave current pulses, the temperature rises of the IW θ_1 are almost identical.

The efficiency dependence η on the width of the copper bus b has a more complex dependence. With a half-wave excitation current pulse, the maximum value of the efficiency $\eta = 19.5$ % is realized at $b = 3.6$ mm, with a vibrationally damped excitation pulse the maximum value of the efficiency $\eta = 18.9$ % is realized at $b = 3.4$ mm, and with an aperiodic excitation pulse the maximum value of the efficiency is $\eta = 16.7$ % realized at $b = 3.0$ mm. For the narrowest ($b = 2.4$ mm) and widest ($b = 5.4$ mm) copper busbars from the considered series, the converter efficiencies are almost the same when excited by half-wave and vibration-damped current pulses. When excited by an aperiodic current pulse and the widest copper bus, the efficiency decreases by 28 % compared to the narrowest bus.

Excitation of the LPEC with a recharge backed up aperiodic impulse makes it possible to use a reduced capacitance for the main CES, and a reduced charge voltage U_1, for the recharge backed up CES, which increases the reliability of the entire CES. Since the energy of the main CES for the LPEC with oscillatory-damped, half-wave and aperiodic pulses of the excitation current was $W_0 = 250$ J, we will use the same total energy of CES for the LPEC when excited by an aperiodic current pulse with recharge. In this converter, the excitation of the windings begins with the main CES with the parameters $U_0 = 500$ V, $C_0 = 1000$ μF, $W_0 = 125$ J. And when the voltage is reduced to a value of U_1, a recharge CES with parameters U_1, C_1 is connected. Wherein, the energy of the recharge CES $W_1 = 125$ J is the same as the energy of the main CES.

Fig. 6 shows the electromechanical characteristics of the LPEC excited by an aperiodic current pulse with recharge at various values of the recharge CES voltage U_1.

The windings of this converter are wound with a copper bus of average width $b = 3.6$ mm of the row in question. When a recharge CES with a voltage of $U_1 = 450$ V ($C_1 = 1234.5$ μF) is connected, the amplitude of the current density in the windings is lower than when using the above pulsed excitations by 2.6 %, and at $U_1 = 250$ V ($C_1 = 4000$ μF) it decreases by 18 %. When the voltage U_1 decreases from 450 V to 250 V, the amplitude of the EDF F_{zm} decreases by 31.5 %; however, due to the delay of electromagnetic processes, the pulse of the EDF P_I increases slightly (by 3 %) rather than decreasing. In this case, the efficiency η of the converter increases by 8.2 %. In general, as the analysis shows, in the LPEC excited by an aperiodic current pulse with recharge, the dependence of the electromechanical and thermal indicators on the width of the copper bus b is the same as when the converter is excited by an aperiodic current pulse.

Let us consider the influence of the voltage of the recharge CES U_1 on the electromechanical and thermal indicators of the LPEC (Fig. 7).

With a decrease in voltage U_1 from 500 to 200 V and therefore with an increase in the capacitance of the recharge CES, the maximum current density in the windings j_m decreases by 20.7 %, and the amplitude of the EDF F_{zm} – by 47.5 %. However, due to the fact that when the voltage U_1 decreases, the electromagnetic processes drag out, and the magnitude of the EDF pulse P_I practically does not change. Moreover, with a decrease in voltage U_1 in the considered range (500–200 V),

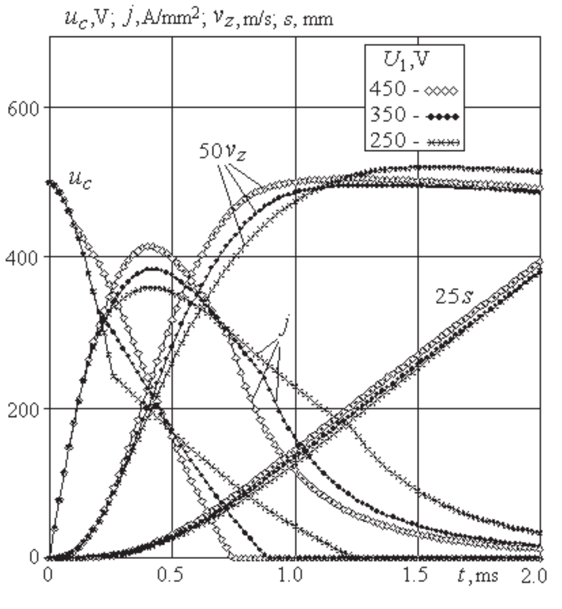

Fig. 6. Electromechanical characteristics of the LPEC excited by an aperiodic current pulse with recharge

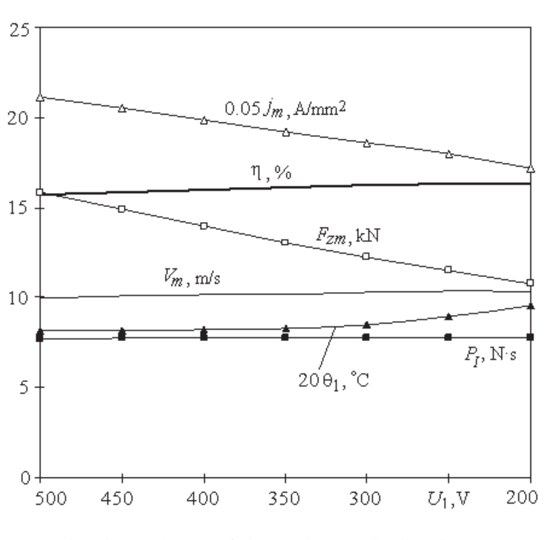

Fig. 7. The dependence of the recharge CES voltage U_1 on the electromechanical and thermal indicators of the LPEC

the maximum speed V_m and efficiency η increase by 3.7 and 3.9 %, respectively, and the temperature rise of the inductor winding θ_1 increases by 17 %.

Integrated LPEC effectiveness evaluation. For an integrated assessment of the influence of pulse excitation on the efficiency of the LPEC, we introduce a complex criterion

$$K^* = \beta\left(\frac{\alpha_1}{i_m^*} + \frac{\alpha_2}{m^*} + \frac{\alpha_3}{\theta_1^*} + \alpha_4 P_I^* + \alpha_5 \eta^* + \alpha_6 V_{zm}^*\right), \qquad (20)$$

where α_k stands for weight coefficients that take into account the relative amplitudes of the excitation current $i_m(\alpha_1)$, the windings mass $m(\alpha_2)$, the inductor winding temperature exceeds $\theta_1(\alpha_3)$, the magnitude of the EDF pulse $P_I(\alpha_4)$, the efficiency $\eta(\alpha_5)$ and the maximum speed $V_{zm}(\alpha_6)$; β is the LPEC reliability coefficient.

Wherein

$$\sum_{k=1}^{6} \alpha_k = 1. \qquad (21)$$

All indicators of the LPEC are presented in a dimensionless form and are marked*. As a basic option, we use the LPEC, whose windings are wound with the narrowest copper bus ($b =$ $= 2.4$ mm) from the considered series, and vibration-damped current pulse excitation.

We consider that the LPEC reliability coefficient upon excitation by a vibrationally damped pulse is $\beta = 1$. Based on expert estimates, we assume for the LPEC when excited by a unipolar pulse $\beta = 1.1$, for the LPEC when excited by an aperiodic pulse $\beta = 1.2$, for the LPEC when excited by an aperiodic pulse with feed $\beta = 1.15$. The increased reliability of these LPECs is due to a simpler electronic circuit and the use of polar electrolytic capacitors for the CES when excited by an aperiodic current pulse.

Consider three options of the strategy for evaluating the effectiveness of the LPEC. The priority of the indicator is estimated by the value of the corresponding weight coefficient α_k. Strategy option I evaluates the LPEC by force – the highest priority ($\alpha_4 = 0.5$) is given to the EDF impulse P_I. Strategy option II evaluates the LPEC by speed indicators – the highest priority ($\alpha_6 = 0.5$) is given to the maximum speed value V_{zm}. Strategy option III evaluates the quality of the LPEC's work – the highest priority ($\alpha_5 = 0.5$) is given to the efficiency η. Moreover, all other k^{th} parameters of the converter are evaluated equally ($\alpha_k = 0.1$).

Table shows in relative form the values of the complex efficiency criterion K^* LPEC, excited by various current pulses. When the LPEC is excited by an aperiodic pulse with recharge, we use the main CES with parameters $U_0 = 500$ V, $C_0 = 1000$ μF and the recharge CES with parameters $U_1 = 250$ V, $C_1 =$ $= 4000$ μF. For all variants of the evaluation strategy, the worst case scenario is the basic version of the LPEC. In terms of force, the most effective is a converter excited by an aperiodic pulse with recharge, the windings of which are wound with a copper bus of the greatest width ($b = 4.8$ mm) of the series in question. Note that for any excitation pulses, an increase in the width of the copper busbar of the windings increases the power indicators of LPEC.

In terms of speed, the most efficient is the converter, which is also excited by an aperiodic pulse with recharge, but whose windings are wound with a medium-width bus ($b = 3.6$ mm). In terms of quality of work, the most appropriate is a converter excited by an aperiodic current pulse, the windings of which are wound with a copper bus width ($b = 3.6$ mm).

Among almost all variants of the evaluation strategy, the highest indicators are those of the LPEC, whose windings are excited by an aperiodic current pulse with recharge, and the worst indicators are LPEC, whose windings are excited by an oscillating-damped pulse.

Table

The values of the complex performance indicators K^* of the LPEC for various variants of the strategy, p.u.

Excitation current pulse	b, mm	Strategy option		
		I	II	III
Vibration damped	2.4	1.0	1.0	1.0
	3.6	1.188	1.004	1.080
	4.8	1.326	1.002	1.109
Unipolar	2.4	1.097	1.104	1.112
	3.6	1.293	1.121	1.221
	4.8	1.519	1.126	1.268
Aperiodic	2.4	1.180	1.188	1.171
	3.6	1.360	1.181	**1.339**
	4.8	1.495	1.181	1.218
Aperiodic with recharge	2.4	1.153	1.135	1.127
	3.6	1.669	**1.229**	1.282
	4.8	**1.752**	1.217	1.279

Conclusions. The results of the study are the basis for the development of electronic circuits for power supplies of linear pulse converters of electrodynamic type. A numerical model of a linear pulse converter of an electrodynamic type has been developed, which uses the concentrated parameters of the fixed inductor winding and the moving armature winding. The numerical model takes into account interconnected electromagnetic, mechanical and thermal processes, presenting their solutions in a recurring form.

The influence of the current pulse – vibrational-damping, half-wave, aperiodic, and aperiodic with recharge on the characteristics and performance of LPEC has been established.

A comprehensive criterion for the LPEC efficiency was introduced, which takes into account in a relative form the amplitude of the excitation current, the mass of the windings, the temperature of the inductor winding, the magnitude of the EDF pulse, the efficiency, and the maximum speed for a given reliability coefficient. It has been established that in terms of force and speed indicators, the most effective is a converter excited by an aperiodic pulse with recharge, while a converter excited by an aperiodic pulse is the most effective in terms of performance quality.

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Вплив імпульсного збудження на електромеханічні показники лінійного імпульсного перетворювача електродинамічного типу

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Мета. Дослідження впливу імпульсного збудження обмоток індуктора та якоря, сформованого електронною схемою джерела живлення з ємнісним накопичувачем енергії (ЄНЕ), на швидкісні й силові показники лінійного імпульсного перетворювача електродинамічного типу (ЛІПЕТ).

Методика. На базі розробленої математичної моделі досліджено вплив імпульсного збудження – коливально-загасаючого, однонапівперіодного, аперіодичного та аперіодичного з підживленням, на характеристики й показники роботи ЛІПЕТ. Математична модель ЛІПЕТ, використовуючи зосереджені параметри обмотки індуктора та обмотки якоря, ураховує взаємозалежні електромагнітні, механічні та теплові процеси, представляючи їх рішення в рекурентному вигляді.

Результати. Встановлено, що імпульсне збудження ЛІПЕТ незначною мірою впливає на максимальну швидкість, імпульс електродинамічних зусиль (ЕДЗ) і перевищення температури обмотки індуктора. Найбільші значення максимальної швидкості та імпульсу ЕДЗ виникають при збудженні коливально-загасаючим імпульсом струму, а найменші значення – при збудженні аперіодичним імпульсом. Збудження ЛІПЕТ аперіодичним імпульсом з підживленням дозволяє використовувати для підживлювального ЄНЕ знижену напругу заряду. Зі зменшенням цієї напруги та при збереженні енергії ЄНЕ амплітуда ЕДЗ зменшується на 31,5 %, однак за рахунок затягування електромагнітних процесів імпульс ЕДЗ зростає на 3 %, а ККД підвищується на 8,2 %.

Наукова новизна. Уведено комплексний критерій ефективності ЛІПЕТ, що враховує у відносному вигляді амплітуду струму збудження, масу обмоток, перевищення температури обмотки індуктора, величину імпульсу ЕДЗ, ККД і максимальну швидкість при заданому коефіцієнті надійності. За допомогою цього критерію встановлено, що по силовому впливу й по швидкісним показниками найбільш ефективним є перетворювач, що збуджується аперіодичним імпульсом струму з підживленням, а за якістю роботи найбільш ефективним є перетворювач, що збуджується аперіодичним імпульсом.

Практична значимість. Встановлено вплив ширини мідної шини і відповідних їй висот обмоток індуктора та якоря на швидкісні й силові показники ЛІПЕТ при використанні коливально-загасаючого, однонапівперіодного, аперіодичного та аперіодичного з підживленням імпульсів збудження.

Ключові слова: *лінійний імпульсний перетворювач електродинамічного типу, комплексний критерій ефективності, імпульс струму збудження*

Влияние импульсного возбуждения на электромеханические показатели линейного импульсного преобразователя электродинамического типа

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Цель. Исследование влияния импульсного возбуждения обмоток индуктора и якоря, формируемого электронной схемой источника питания с емкостным накопителем энергии (ЕНЭ), на скоростные и силовые показатели линейного импульсного преобразователя электродинамического типа (ЛИПЭТ).

Методика. На базе разработанной математической модели исследовано влияние импульсного возбуждения – колебательно-затухающего, однополупериодного, апериодического и апериодического с подпиткой, на характеристики и показатели работы ЛИПЭТ. Математическая модель ЛИПЭТ, используя сосредоточенные параметры неподвижной обмотки индуктора и подвижной обмотки якоря, учитывает взаимосвязанные электромагнитные, механические и тепловые процессы, представляя их решения в рекуррентном виде.

Результаты. Установлено, что импульсное возбуждение ЛИПЭТ незначительно влияет на максимальную скорость, импульс электродинамических усилий (ЭДУ) и превышение температуры обмотки индуктора. Наибольшие значения максимальной скорости и импульса ЭДУ возникают при возбуждении колебательно-затухающим импульсом тока, а наименьшие – при возбуждении апериодическим импульсом. Возбуждение ЛИПЭТ апериодическим импульсом тока с подпиткой позволяет использовать для подпиточного ЕНЭ пониженное напряжение заряда. С уменьшением этого напряжения и при сохранении энергии ЕНЭ амплитуда ЭДУ уменьшается на 31,5 %, но за счет затягивания электромагнитных процессов импульс ЭДУ возрастает на 3 %, а КПД – на 8,2 %.

Научная новизна. Введен комплексный критерий эффективности ЛИПЭТ, учитывающий в относительном виде амплитуду тока возбуждения, массу обмоток, превышение температуры обмотки индуктора, величину импульса ЭДУ, КПД и максимальную скорость при заданном коэффициенте надежности. При помощи этого критерия установлено, что по силовому воздействию и по скоростным показателям наиболее эффективным является преобразователь, возбуждаемый апериодическим импульсом тока с подпиткой, а по качеству работы – преобразователь, возбуждаемый апериодическим импульсом.

Практическая значимость. Установлено влияние ширины медной шины и соответствующих ей аксиальных высот обмоток индуктора и якоря на скоростные и силовые показатели ЛИПЭТ при использовании колебательно-затухающего, однополупериодного, апериодического и апериодического с подпиткой токовых импульсов.

Ключевые слова: *линейный импульсный преобразователь электродинамического типа, комплексный критерий эффективности, импульс тока возбуждения*

Recommended for publication by H. M. Suchkov, Doctor of Technical Sciences. The manuscript was submitted 04.10.19.