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# INFLUENCE OF ARMATURE PARAMETERS OF A LINEAR PULSE ELECTROMECHANICAL CONVERTER ON ITS EFFICIENCY

***Purpose. The evaluation of the effect of armature parameters on the efficiency of a linear pulsed electromechanical converter, taking into account the power, speed, constructive and environmental parameters. Methodology. First, the height of the electrically conductive, coil and ferromagnetic armature of a linear pulse electromechanical converter is determined, at which the highest velocity develops. An integral efficiency index is introduced, which takes into account, in a relative way, the power, speed, energy, electrical and field characteristics of the converter. Variants of the efficiency evaluation strategy are used that take into account the priority of each indicator of a linear pulse electromechanical converter using the appropriate weighting factor in the integral efficiency index. Results. A mathematical model of a linear pulsed electromechanical converter is developed. It is established that as the height of the electroconductive, coil and ferromagnetic armature increases, the force pulse increases. The greatest speed develops with the use of a coil armature, and the smallest with an electroconductive armature. In the converter with coil and ferromagnetic armature, practically the same values of the electrodynamic and electromagnetic force pulse are realized, while in the converter the electrodynamic force is 1.52 times smaller in the converter by the electrically conductive armature. It is established that with all efficiency evaluation strategies, the converter with a coil armature is the most effective, even in spite of its constructive complexity, and the converter with a ferromagnetic armature is the least effective, although it is constructively the simplest. Originality. For the first time, using the integral efficiency index, which takes into account the power, speed, energy, electrical and field indices in a relative way, it is established that with all efficiency evaluation strategies, the converter with a coil armature is the most effective, and the converter with a ferromagnetic anchor is the least effective. Practical value. The height of the electrically conductive, coil and ferromagnetic armature of a linear pulse electromechanical converter is determined, at which the highest speed develops. It is shown that when using an electrically conductive armature, the value of the electrodynamic force pulse is lower than when using a coil and ferromagnetic armature. It is established that the converter with a coil armature is the most efficient, and the converter with a ferromagnetic armature is the least effective.*** References 11, tables 3, figures 2.
*Key words:* **linear pulse electromechanical converter, mathematical model, electrically conductive, coil and ferromagnetic armature, integral efficiency index, efficiency evaluation strategy.**

***Разработана математическая модель линейного импульсного электромеханического преобразователя (ЛИЭП), описывающая быстропротекающие и взаимосвязанные электромагнитные и электромеханические процессы, проявляющиеся при перемещении якоря относительно индуктора. Показано, что при увеличении высоты электропроводящего, катушечного и ферромагнитного якорей ЛИЭП происходит увеличение импульса силы. Наибольшая скорость развивается в ЛИЭП с катушечным якорем, а наименьшая – в ЛИЭП с электропроводящим якорем. В ЛИЭП с катушечным и ферромагнитным якорями реализуются практически одинаковые значения импульса электродинамической и электромагнитной силы, а в ЛИЭП с электропроводящим якорем импульс электродинамической силы в 1,52 раза меньше. Введен интегральный показатель эффективности, который в относительном виде учитывает силовые, скоростные, энергетические, электрические и полевые показатели. Установлено, что при всех стратегиях оценки эффективности наиболее эффективным является ЛИЭП с катушечным якорем, а наименее эффективным является ЛИЭП с ферромагнитным якорем.*** Библ. 11, табл. 3, рис. 2.
*Ключевые слова:* **линейный импульсный электромеханический преобразователь, математическая модель, электропроводящий, катушечный и ферромагнитный якоря, интегральный показатель эффективности, стратегия оценки эффективности.**

**Introduction**. One of the promising devices of modern electromechanics are linear pulse electromechanical converters (LPEC) which provide a high speed of the actuator element (AE) on a short active site, and/or create powerful power pulses with little movement. LPEC are used in many branches of science and technology as electromechanical accelerators and shock-power devices [1-4].

In construction, electromagnetic hammers and perforators, devices for driving piles and anchors are used; in the mining industry – butchers, rock separators, vibrators; in geological prospecting – vibroseismic sources; in mechanical engineering – drives of mills of cold rolling of pipes, presses, hammers with a large range of impact energy; in the chemical and medical-biological industry – vibromixers and batchers. LPEC are used in magnetic pulse devices for pressing ceramics powders, cleaning containers from sticking loose materials, destroying information on digital media, etc. Such converters are used in fast-acting valve and switching devices, in testing complexes for testing response products to shock loads, in aviation and space technology, in research facilities, for example, to study micro-meteorological impacts on space or responsible ground facilities. The problem of providing high speed for high-speed electrical apparatus is topical.

A feature of considered LPECs is that they operate with a short working cycle and a shock load that multiple exceeds the load of traditional linear motors of continuous action. LPEC of induction, electrodynamic and electromagnetic types the most widely used [5]. In these converters there is an electromagnetic interaction of the movable armature with a stationary inductor excited from a pulsed source, usually a capacitive energy storage (CES). In these types of LPEC, the main difference is in the design of a movable armature, which ensures the acceleration of AE.

In the inductive-type LPEC, the electrically conducting armature (EA) is a relatively thin copper disk in which eddy currents are induced from the inductor, so that an electrodynamic repulsive force occurs between them.

In the LPEC of the electrodynamic type, the coil armature (CA) is a movable coil that is electrically connected to the inductor, i.e. it is fed by the same current, so that an electrodynamic repulsive force also occurs between them.

In the electromagnetic-type LPEC the ferromagnetic armature (FA) is a relatively thick-walled disk on which the electromagnetic force of attraction from the inductor side acts. Considering the considerable flux density of magnetic fields, it is advisable to use an external ferromagnetic shield (FS) with low electrical conductivity in the LPEC made either from a magnetodielectric or with radial cuts [6]. This shield increases the magnetic fields in the active zone of the LPEC and reduces the magnetic scattering fields which is important for closely located electronic devices and maintenance personnel.

LIEP with the types of armature under consideration provide different power and speed indicators creating different values of the flux density of magnetic scattering fields into the surrounding space. LPECs have a different mass of active elements, a constructive complexity that determines their reliability and the value of the excitation current of the inductor which is important for the electronic control system. As a consequence, for a well-founded choice of the type of LPEC armature, it is necessary to take into account many different disparate indicators.

The task of choosing the armature type for LPEC is actual. Thus, in [2], a comparative analysis of the LPEC with EA and CA is considered, and in [7] - LPEC with EA and with FA. In these works only electromechanical characteristics of the LPEC are considered, without considering the reliability of the design of the armature, the magnetic scattering fields, the interconnected electric, force, speed and mobile armature parameters and the presence of external FS.

Based on this, efficiency of the LPEC it is necessary to estimate the efficiency of the LPEC using an integrated indicator that takes into account its force, speed, power and electrical parameters, as well as the reliability of the armature design and the magnetic scattering field that negatively affects close-lying electronic devices and maintenance personnel. However, such studies have not been carried out so far, which makes it difficult to implement a reasonable and comprehensive selection of the electrically conductive, ferromagnetic or coil armature for LPEC.

**The goal of the paper** is the estimation of the influence of the parameters of the LPEC armature on its efficiency when taking into account the force, speed, constructive and environmental indicators.

**Mathematical model.** In LPEC under excitation from CES, fast interconnected electromagnetic and electromechanical processes occur when the armature moves relative to the inductor. Implementation of the mathematical model of LPEC using the theory of electric circuits does not allow to fully describe the totality of spatio-temporal processes [8]. Proceeding from this, the mathematical model of LPEC is used which is based on the finite element method.

Since these LPECs have axial symmetry, it is advisable to use a 2D mathematical model with spatially-distributed parameters [3]. To determine the electromagnetic parameters of the LPEC in the cylindrical coordinate system $\{r, z\}$, the magnetic vector potential $A$ is calculated from the equation:

$$\frac{\partial}{\partial r}\left(\frac{1}{r\mu(B)}\frac{\partial(rA)}{\partial r}\right)+\frac{\partial}{\partial z}\left(\frac{1}{\mu(B)}\frac{\partial A}{\partial z}\right)+\sigma\frac{\partial A}{\partial t}=j_n\,, \quad (1)$$

where $\mu(B)$ is the magnetic permeability depending on the magnetic flux density $B$ of the ferromagnetic material; $\sigma$ is the electrical conductivity of the armature and the inductor; $j_n$ is the current density in the active element; $n$ = 1 is the index of the inductor; $n$ = 2 is the index of the coil armature.

Components of the magnetic flux density vector are calculated by using known relations:

$$B_z=\frac{1}{r}\frac{\partial(rA)}{\partial r}\,;\; B_r=-\frac{\partial A}{\partial z}\,. \quad (2)$$

As boundary conditions the relation $n \times A = 0$ is used, where $n$ is the unit vector of the outer normal to the surface. For the ferromagnetic materials the nonlinear magnetization curve $B = f(H)$ is used.

The current in the inductor $i_1$ is described by the equation:

$$\begin{aligned}&\left(R_e+R_1\right)\cdot i_1+L_e\frac{di_1}{dt}+\frac{1}{C}\int i_1 dt+\frac{N_1}{s}\int_V\frac{dA_l}{dt}dv=0;\\&\frac{1}{C}\int_0^t i_1\cdot dt=U_0,\end{aligned} \quad (3)$$

where $R_e$ is the active resistance of the external circuit; $R_1$ is the active resistance of the inductor; $L_e$ is the inductance of the external circuit; $U_0$ is the CES charging voltage; $C$ is the CES capacitance; $N_1$ is the number of turns of the inductor; $s$ is the of the cross-section of the inductor permeated by the magnetic flux; $A_l$ is the projection of the magnetic vector potential on the direction of traversal of the contour; $V$ is the volume of the inductor.

The electrodynamic or electromagnetic forces acting on the armature are found using the Maxwell tension tensor:

$$f_z=0.5\oint_S\left[H(B\cdot n)+B(H\cdot n)-n(H\cdot B)\right]ds\,, \quad (4)$$

where $S$ is the area bounding the armature cross-section; $n$ is the unit vector of the normal to the surface of the armature.

The force pulse determining the force action on the armature from the inductor side is described by the expression:

$$F_z = \int_0^t f_z dt \,. \quad (5)$$

The velocity $v_z$ of the armature with AE along the $z$-axis is described by the equation [3]:

$$\begin{aligned}(m_2 + m_e)\frac{dv_z}{dt} = f_z(z) - k_P \Delta z(t) - k_T v_z(t) - \\ - 0.125\pi\gamma_a \beta_a D_{ex2}^2 v_z^2(t),\end{aligned} \quad (6)$$

where $m_2$ is the armature mass; $m_e$ is the AE mass; $k_P$ is the coefficient of elasticity of the buffer element, e.g. spring; $k_T$ is the coefficient of dynamic resistance; $\gamma_a$ – is the air density; $\beta_a$ is the aerodynamic resistance coefficient; $D_{ex2}$ is the outer diameter of the armature; $\Delta z$ is the value of the armature displacement.

Equations (1) – (6) describe electromechanical process in the LPEC at initial conditions: $u_c(0)=U_0$; $i_1(0)=0$; $\Delta z(0)=0$; $v_z(0)=0$, where $u_c$ is the CES voltage.

In the calculation, we assume the absence of mechanical movements (recoil) of the inductor, the deformation of the elements, and the strictly axial disposition and movement of the armature relative to the inductor.

The solution of the system (1) – (6) is obtained using the finite element method with integration over spatial variables and the improved Gear method in time integration. When moving the armature, a «deformable» mesh is used. To solve the problem, the computer model of LPEC was developed in the software package *Comsol Multiphysics* which allows adaptively changing the mesh and monitoring errors when working with various numerical solvers [9]. The estimated time step automatically is varied depending on the convergence conditions and the error indices of the solutions obtained. The solution of the system of equations is performed using the BDF (*backward differentiation formula*) method with fixed time step, irregular mesh and using the PARDISO solver.

**The main parameters of the LPEC.** Let's consider LIPEC with electrically conductive, coil and ferromagnetic armature, and unchanged dimensions. LPEC has a coaxial configuration and contains a FS covering the inductor from the end and outer sides [6]. The armature is made in as a flat disk, one side of which faces the inductor, and the second one interacts with the AE. The main parameters of the LPEC are:

*Inductor*: outer diameter $D_{ex1}$=100 mm, inner diameter $D_{in1}$=10 mm, section of copper bus $a \times b$=1.8×4.8 mm$^2$, the number of turns of the bus $N$ = 46;

*FS*: the height of the disk base $H_{3a}$=8 mm, the outer diameter of the shell $D_{ex3b}$=118 mm, the inner diameter of the shell $D_{in3b}$=102 mm.

*CES*: capacitance $C$=2850 μF, voltage $U_0$=400 V. The electronic system forms an aperiodic pulse of excitation of the inductor using an inverse diode [5].

Weight of the AE $m_e$=0.5 kg.

The EA is made as a massive disk of technical copper, and the CA and FA are made of a magnetodielectric with the magnetic properties of steel Ст.10. The CA and inductor are made with the same geometric parameters and are wound with a copper bus.

Table 1 shows the differing parameters of the LPEC elements due to the type of armature.

**Influence of armature height on LPEC indicators.** Electromechanical characteristics of the LPEC with EA, CA, and FA are presented in [10]. We consider the influence of the height of the armature of these types on the LPEC on the maximum velocity $V_m$ and the valueof the impulse of the electrodynamic or electromagnetic force acting on the armature. Despite the different structure of the movable armature in the converters under consideration, they can realize different heights while preserving the remaining parameters. The height of the EA and the FA is determined by the height of the copper and ferromagnetic disks, respectively. The height of the CA is determined by the width of the bus with an unchanged number of its turns.

Table 1

Different LPEC parameters

| Indicator, designation, unit | LPEC armature type | | |
|---|---|---|---|
| | CA | FA | EA |
| Inductor height, $H_1$, mm | 5 | 10 | 10 |
| Armature outer diameter, $D_{ex2}$, mm | 100 | 118 | 100 |
| Armature inner diameter, $D_{in2}$, mm | 10 | 0 | 6 |
| Armature height, $H_2$, mm | 5 | 5 | 2.5 |
| Initial distance between inductor and armature, $\Delta z_0$, mm | 1 | 5 | 1 |
| Armature mass, $m_2$, kg | 0.345 | 0.535 | 0.205 |
| FS shell height, $H_{3b}$, mm | 24 | 21 | 24 |

The cross-section of the inductor bus remains unchanged. We introduce a dimensionless geometric parameter characterizing the height of the armature:

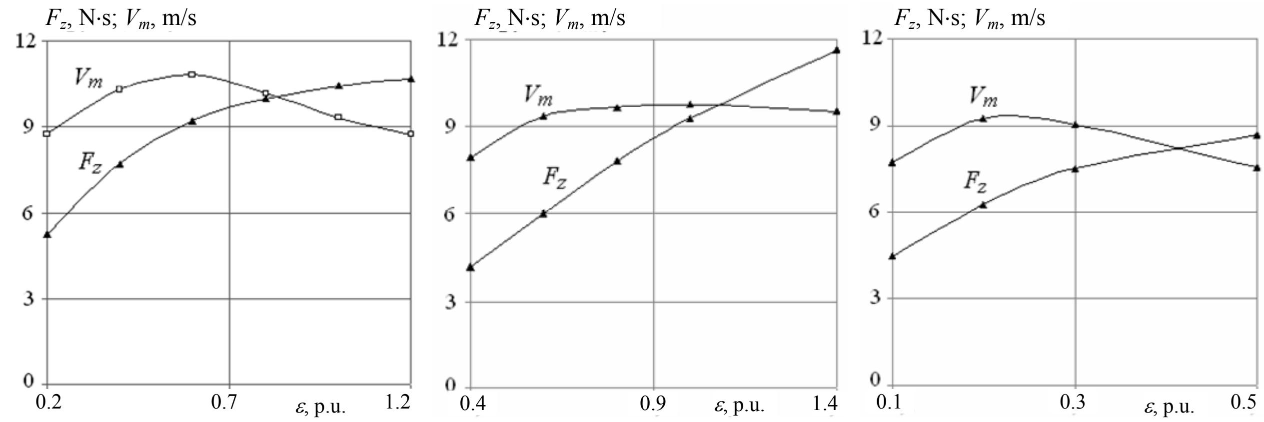
$$\varepsilon = \frac{H_2}{H_1} \,. \quad (7)$$

Let's consider the range of the height variation of armature, in which the maximum speed of the armature with the AE $V_m$ is located (Fig. 1). When the height of the armature is increased, an increase in the force impulse $F_z$ occurs in all LPECs. When the geometric parameter $\varepsilon$ of the CA is changed from 0.2 to 1.2, the value of the force impulse $F_z$ increases by a factor of 2.03.When the geometric parameter $\varepsilon$ of the FA changes from 0.4 up to 1.4, the value of $F_z$ increases by a factor of 2.52. And when the parameter $\varepsilon$ of EA changes from 0.1 to 0.5, the value of $F_z$ increases by 1.94 times. Thus, with increasing the height of the considered types of the armature in the LPED, the value of the electrodynamic force impulse $F_z$ increases, but in different degrees.

With an increase in the height of the armature, an increase in its mass also occurs. This causes that, the maximum speed of the armature with AE $V_m$ on the specified height has a more complex dependence. The maximum values of the speeds of the types of LPEC armature considered are realized at different heights, which is the most rational for them. The least low, from this point of view, is the EA ($H_2$=2.2 mm), and the highest is the FA ($H_2$=10.5 mm). In the CA, the maximum speed is realized at the armature, the rational height of which is $H_2$=6.1 mm.

In Table 2 shows the values of the force impulse $F_z$ and the maximum armature speed $V_m$ at a rational height, which is represented as a geometric parameter $\varepsilon$. As follows from the obtained results, at a rational height of the armature, the fastest speed takes place in the LPEC with CA, and the smallest one in the LPEC with EA. In the LPEC with CA and FA, practically the same values of the electrodynamic and electromagnetic force impulse are realized, while in the LPEC with EA the electrodynamic force pulse is 1.52 times smaller.

Fig. 2 shows the distribution of the magnetic flux density at the moment of the maximum force in the LPEC with different types of armature. In the LPEC with EA, the greatest magnetic flux density takes place in the gap between the inductor and the armature. At the same time, on the outer surface of the armature the field is almost completely shielded. In the LPEC with CA, the greatest magnetic flux density appears between the armature and the inductor, over which the same current flows. In this case, the magnetic field partially extends beyond the surface of the armature. In the LPEC with the FA, the maximum magnetic flux density occurs in the inner cylindrical core, which is covered by an inductor. In this case, a considerable magnetic flux density of the scattering field is observed.




*a* *b* *c*

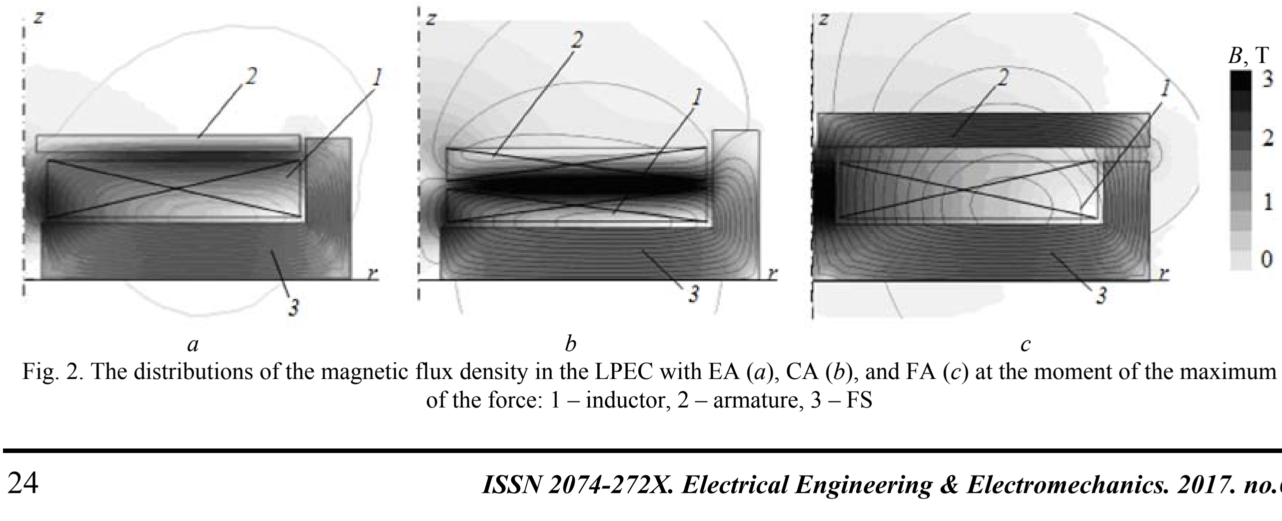
Fig. 1. The change in the moment of the force $F_z$ and the maximum velocity $V_m$ of the armature with AE as a function of the value of the parameter $\varepsilon$ for: CA (*a*), FA (*b*), and EA (*c*)

Table 2

The $F_z$ and $V_m$ values for the LPEC with different types of armaturefor a rational value of the parameter $\varepsilon$

| Armature type | $\varepsilon^*$, p.u. | $F_z$, N·s | $V_m$, m/s |
|---|---|---|---|
| EA | 0.22 | 6.1 | 9.32 |
| CA | 0.61 | 9.3 | 10.82 |
| FA | 1.05 | 9.3 | 9.75 |

As calculations show that electromechanical processes occur most rapidly in the LPEC with CA, and the current in the inductor and the electrodynamic forces take the greatest values. In the LPEC with FA, electromechanical processes proceed most slowly, and the maximum value of the electromagnetic forces here is the smallest. The velocities of the LPEC with CA and EA, where the electrodynamic repulsive forces act, after a sharp initial increase practically do not change. In LPEC with FA, where the electromagnetic force of attraction acts, the indicated speed constantly increases until the moment of the armature collision with the FS.




*a* *b* *c*

Fig. 2. The distributions of the magnetic flux density in the LPEC with EA (*a*), CA (*b*), and FA (*c*) at the moment of the maximum of the force: 1 – inductor, 2 – armature, 3 – FS

**Evaluation of the efficiency of LPEC.** To evaluate the LPEC with different types of armature, having a rational height at which the fastest armature speed with AE takes place, we introduce the integral efficiency indicator $K^*$ [11]. This indicator in a relative form takes into account the force, speed, power, electrical and field (magnetic flux density of the field of scattering) indicators:

$$K^* = \beta\left(\alpha_1 f_{zm}^* + \alpha_2 V_m^* + \alpha_3 W_{kin}^* + \frac{\alpha_4}{j_{1m}^*} + \frac{\alpha_5}{B_{ex}^*}\right), \quad (8)$$

where $j_{1m}$ is the maximal current density in the inductor, $f_{zm}$ is the maximum value of the force acting on the moving armature from the side of the inductor, $V_m$ is the maximum value of the speed of the armature with AE, $W_{kin}$ is the kinetic energy of the LPEC, $B_{ex}$ is the averaged value of the magnetic flux density of the field of scattering, $\beta$ is the armature reliability factor, $\alpha_j$ are the weight factors of the corresponding LPEC indicators satisfying the relation:

$$\sum_{j=1}^{5} \alpha_j = 1 \,. \quad (9)$$

The averaged value of the magnetic flux density of the field of scattering $B_{ex}$ is calculated on the contour located at a distance $2H_1$ from the lower end and side sides and at a distance $4H_1$ from the upper side of the inductor.

All LPEC indicators are normalized with respect to the LPEC with EA and marked with asterisks. Thus, the integral indicator of the efficiency of the LPEC with EA $K^*$=1.

We use the reliability factors for the FA $\beta$ = 1.2, for the EA $\beta$ = 1, for the CA $\beta$ = 0.8. The increased reliability of the FA is due to the design of a massive ferromagnetic disk. The lower reliability of the EA is due to the cdesign of a thin-walled copper disk that is less stable to electrodynamic forces. Even lower reliability of the CA is due to the presence of a movable contact between the inductor and the armature, which is made in the form of a multi-turn coil compounded with epoxy resin.

Let's consider several variants of the strategy for assessing the efficiency of the LPEC (Table 3). The priority of the LPEC indicator is estimated by the value of the corresponding weighting coefficient $\alpha_j$.

Table 3

Variants of the evaluation strategy and the values of the integral indicator of the efficiency of the LPEC with FA and with CA, p.u.

| Variant | $\alpha_1$ | $\alpha_2$ | $\alpha_3$ | $\alpha_4$ | $\alpha_5$ | $K^*$ (with FA) | $K^*$ (with CA) |
|---|---|---|---|---|---|---|---|
| I | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.703 | 1.518 |
| II | **0.4** | 0.15 | 0.15 | 0.15 | 0.15 | 0.656 | 1.556 |
| III | 0.15 | **0.4** | 0.15 | 0.15 | 0.15 | 0.676 | 1.335 |
| IV | 0.15 | 0.15 | **0.4** | 0.15 | 0.15 | 0.720 | 1.474 |
| V | 0.15 | 0.15 | 0.15 | **0.4** | 0.15 | 0.829 | 1.218 |
| VI | 0.15 | 0.15 | 0.15 | 0.15 | **0.4** | 0.631 | 2.004 |
| VII | **0.35** | 0.1 | 0.1 | 0.1 | **0.35** | 0.584 | 2.043 |
| VIII | 0.1 | **0.35** | 0.1 | 0.1 | **0.35** | 0.605 | 1.822 |

In the variant of strategy VII in which the highest priority is given to the amplitude of the force acting on the armature and the value of the magnetic flux density of the scattering field, the efficiency of the LPEC with the FA is the smallest, and the efficiency of the LPEC with CA is the largest. In the variant of strategy V in which the highest priority is given to the value of the inductor current pulse, the efficiency of the LPEC with FA is greatest, and the efficiency of the LPEC with FA is the smallest although it is constructively the simplest.

Thus, for all efficiency assessment strategies, the LPEC with CA is the most effective, even in spite of its constructive complexity, and the LPEC with FA is the least effective, although it is constructively the simplest.

**Conclusions.**

1. A mathematical model of the LPEC has been developed which describes fast and interconnected electromagnetic and electromechanical processes manifested when the armature moves relative to the inductor which is excited by the CES.
2. It is shown that as the height of the electrically conducting, coil and ferromagnetic armature of the LPEC increases, the force impulse increases.
3. The greatest speed takes place in LPEC with CA, and the smallest one in LPEC with EA. In the LPEC with CA and FA, practically the same values of the electrodynamic and electromagnetic force impulse are realized, while in the LPEC with EA the electrodynamic force impulse is 1.52 times smaller.
4. Using the integral efficiency indicator which takes into account in a relative way the force, speed, power, electrical and field indicators, it is established that for all evaluation strategies the LPEC with CA is most effective, even in spite of its constructive complexity, and the LPEC with FA is the least efficient, although it is constructively the simplest.

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