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Energy Conversion in an Electromagnetic Reciprocating Motor

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ABSTRACT. Structural complexity of vibratory systems with rotary electric machines and energy losses at the intermediate stages of the multistage conversion of primary electrical energy into mechanical energy serve as an incentive to create systems with reciprocating electromagnetic motors. Significant difference of these motors from rotary electric machines is constant work in the transient electromechanical mode with a change in both the speed of armature movement and the inductances of the electric circuit, as well as the presence of elastic elements requiring periodic adjustment necessary to maintain operating conditions close to mechanical resonance; such motors had poor weight-size and energy performance. The advantage of the developed electromagnetic reciprocating motor is the increased energy performance and stability in operation, which is achieved through the simultaneous use of the phenomena of mechanical and ferromagnetic resonance. In the new construction the inductive resistance does not depend on the change in air gaps and remains constant, thereby achieving the maximum positive effect in relation to increasing efficiency and power factor. The problem of electromechanical energy conversion in the constructions of two-stroke electromagnetic reciprocating motors developed with participation of the authors is considered focusing on the increase of conversion efficiency. The theoretical bases of the conversion are proposed and the methods of graphic account of energy are introduced. *© 2019 Bull. Georg. Natl. Acad. Sci.*

Key words: vibration, electromagnetic motor, reciprocating movement, resonance, energy conversion

Sustainable development of industry and agriculture is closely linked to the elaborating of innovative methods for the intensification of technological processes, among which the vibrational methods make it possible to concentrate and use the energy efficiently. Vibrating equipment is widely used in industry and agriculture. At the same time, structural complexity of the traditional vibration systems and the energy loss at the intermediate stages of the multistage conversion of primary electrical energy into mechanical energy serve as an incentive to create systems with electromagnetic vibratory drives. This is especially preferable in those mechanisms in which the tool performs reciprocating movements, where the direct conversion of electrical energy into mechanical work of a moving part with a linear trajectory of movement allows to combine a machine-motor and a machine-tool in one block, which gives such advantages as simplification and cheapening of the entire device, increases its energy performance, improves reliability, reduces maintenance costs and at the same time electromagnetic vibration motors provide simplicity of realization of independent control of the amplitude and oscillation frequency, oscillations with the frequency over 100 Hz and high efficiency when operating at the resonance frequency [1]. Therefore, many research works are devoted to the study of electromagnetic vibratory drive with the purpose of its efficient use in technological processes, for example, in rocking conveyors, mixing and sifting of bulk materials, vibrocompaction or crushing, etc. [2]. The efficiency of these technologies is largely determined by the technical characteristics of vibratory drives, which explains their continuous improvement and the creation of new electromagnetic vibratory motors is the most promising direction, whose technical characteristics can be achieved both by developing new construction solutions and by using modern control systems, which further expands the possibilities of their application. A distinctive feature and advantage of electromagnetic vibration motors over asynchronous electric motors, which require a network with strictly maintained frequency, nominal voltage, the ratio of power supply transformer and load, is noncriticality to power quality because in linear vibratory devices a discrete conversion cycle allows using networks with any deviation of voltage and frequencies and nonconventional sources. If necessary, the parameters of the supply voltage and current pulses are easily provided by means of intermediate storage devices, such as capacitors.

An electromagnetic oscillation motor as an electromechanical energy converter can always distinguish electromagnetic system and mechanical system in its structure. Both systems are analogous to each other by their elements of two kinds of energy storage (kinetic and potential energies), and energy dissipating elements [3]. A number of constructions of electromagnetic oscillation motors were developed at the Agricultural University of Georgia and patented in more than 10 countries [4, 5], including motors with reciprocating movement [6, 7], on the basis of which agricultural conveyors, meter-mixers, etc., manufactured in the factory conditions were created. Significant difference of these motors from conventional rotary electric machines is constant work in the transient electromechanical mode with a change in both – the speed of armature movement and the inductances of the electric circuit, as well as the presence of special elastic elements (springs, strings) requiring periodic adjustment necessary to maintain operating conditions close to mechanical resonance. As a result, such vibration motors have poor weight-size and energy performance.

The results of studies of energy conversion in reciprocating motors with electromagnetic excitation are given below. Oscillatory systems of such motors are usually performed by dual-mass and the mutual oscillations occur due to the periodic transformation of kinetic energies of the masses into the potential energy of the mechanical elastic element connecting the masses, and vice versa.

Traditional methods of reducing energy losses in active materials of electromagnetic systems of vibratory motors, directed to the reduction of the active resistance of electrical circuits, energy losses in steel from eddy currents and hysteresis, are brought to a high degree of perfection. Therefore, it is necessary to find qualitatively new ways of improving their energy performance, in particular, the efficiency factor η and power factor $\cos\varphi$, mainly in the field of optimization of the process of electromechanical energy conversion. Due to the fact that this conversion is rather complicated process, the attempts of taking into consideration all the physical phenomena, including the energy conversion in ferromagnetic materials, are associated with mathematical difficulties and do not allow to establish unambiguous analytical relationships between the determining factors. At this stage, a single-phase reciprocating motor is considered and a linear approximation of the electromagnetic system is used, which is widely applied in the theory of electrotechnical devices. In addition, the character of mechanical resistance forces of the operating mechanism (mechanical characteristic) is not taken into account, which in real conditions has a significant impact on the performance of the vibratory drive.

The main advantage of the developed vibratory convertors in comparison with the existing ones is the increased energy performance and stability in operation, which is achieved through the simultaneous use of the phenomena of mechanical and ferromagnetic resonance. It is particularly difficult to maintain ferromagnetic resonance in a two-stroke electromagnetic reciprocating motor with an H-shaped core and magnetization, in the earlier construction of which [8] the inductance changed in wide range depending on the air gap distance δ and the possibility of compensating reactive energy by means of the connection of battery capacitors C parallel to the winding of the reciprocating motor. In the motor, the windings of alternating and direct current are wound on the H-shaped magnetic core, and in that half-period of the power network voltage *u(t)*, when the direction of the alternating current ***i*** coincides with the direction of direct current *I*, the attraction of corresponding armature to the core occurs. In the new construction [6], the constancy of inductive resistance is achieved by the fact that the sections of the AC windings are connected criss-cross, namely, the coils placed on each of the two upper rods are connected in series to the coils wound on the opposite lower rods (Fig. 1). As a result, at a constant current *I* in the DC bias winding, the inductances of the parallel branches of the AC winding do not depend on the change in air gaps δ_1 and δ_2 and remain constant and equal to each other at any time, thereby achieving the maximum positive effect in relation to increasing efficiency and power factor.

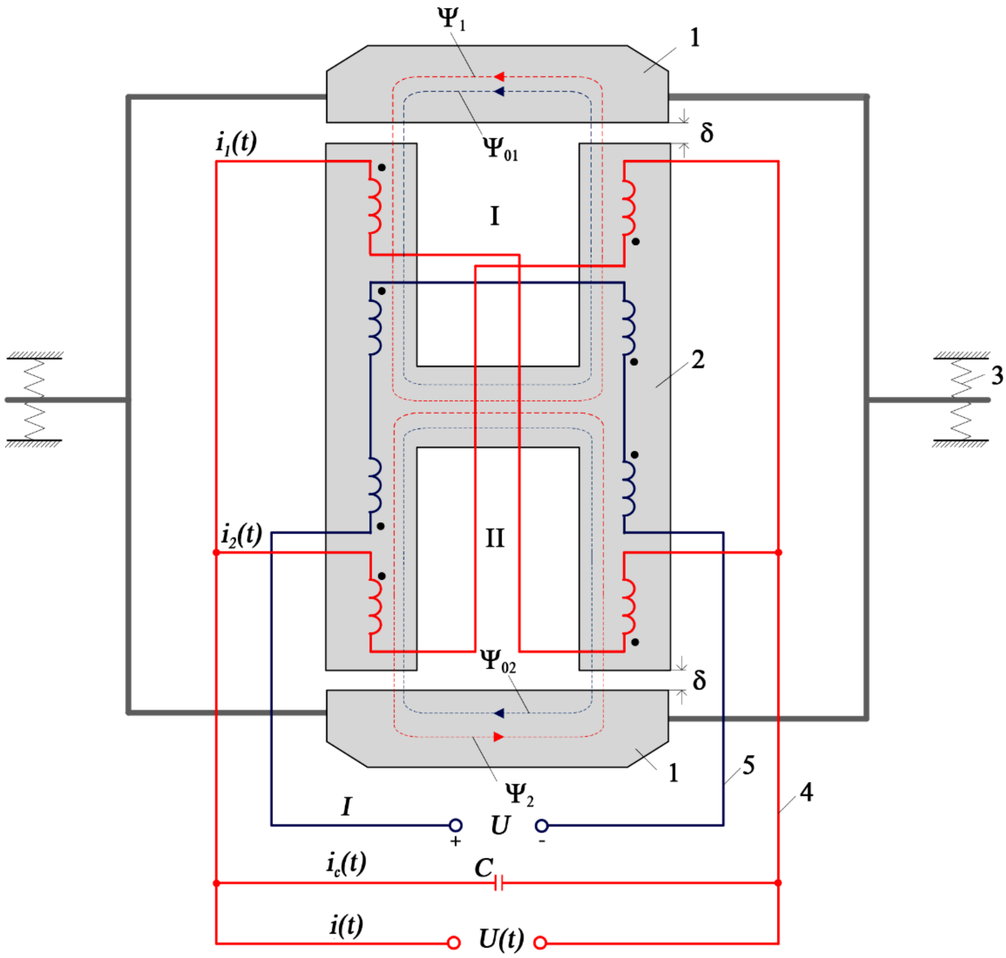

Fig. 1. Electromagnetic reciprocating motor according to [6]. 1. Armature; 2. Core; 3. Elastic elements (springs); 4. AC working circuit; 5. DC bias circuit.

Let us dwell on the energy balance equation for the single-phase two-stroke electromagnetic reciprocating motor under consideration (Fig. 1). When the armature 1 performs simple harmonic translational motions, during each half period there is an energy exchange between the electrical circuit, the mechanical system and the magnetic field, and energy conversion takes place in both directions. In a reciprocating motor, various phenomena related to energy conversion occur in parallel and simultaneously: a change of the electric field energy, electromagnetic radiation caused by a change in the electrostatic and magnetic fields, losses in the magnetic circuit, thermal losses in active resistances of the electrical circuit, losses in friction in the mechanical part, etc., and the role of various phenomena in the overall process of energy conversion is not equivalent. At an industrial frequency of 50 Hz, the energy loss due to electromagnetic radiation is insignificantly small and can be neglected [9]. The energy of the electrostatic field is also small due to the small inter-turn capacitances of the windings, and it can also be neglected. Since we are primarily interested in useful energy conversion, we can assume that there are no heat losses (active resistances of the windings are part of the resistance of the external circuit), and instead of real coils we will consider idealized coils with zero active resistance (in a real high-powered electromagnetic motor coil does not exceed 1% of the inductive); resistance, eddy current losses and hysteresis in the magnetic circuit of the device under consideration are also small and can be excluded from the analysis without specific error. In such a case, the balance equation connecting three types of energy changes in a electromagnetic reciprocating motor takes the following form [10]:

$$\Delta W_e = \Delta W_f + \Delta W_m, \tag{1}$$

where ΔW_e, ΔW_f and ΔW_m are the changes in electrical energy, field energy and mechanical energy, respectively. From equation (1), it follows that if the electric energy in a reciprocating motor exceeds the field energy, then part of the energy transfers into mechanical form; at the same time, the role of the energy stored in the magnetic field is also seen as an intermediate form of energy during the conversion of electrical energy into mechanical energy.

Ignoring the losses in active resistance, electric energy consumed by a motor

$$\Delta W_e = \int_0^t (ui - i^2 r)dt = \int_0^t eidt. \tag{2}$$

Since the main advantage of the considered reciprocating motor is the constancy of the self-inductance of the winding $L = \Psi / i$, then the known equation for changing of the electric energy, which takes place in the first-half period of the supply voltage *u(t)* (the first quadrant of Fig. 2)

$$\Delta W_e = \int_{\Psi_{11}}^{\Psi_{12}} d\Psi \tag{3}$$

can be recorded as

$$\Delta W_e = \frac{\Psi_{12}^2 - \Psi_{11}^2}{2L} = i\Delta\Psi \tag{4}$$

and for the energy stored in the magnetic field we have

$$\Delta W_f = \int_{0_1}^{\Psi_{11}} id\Psi, \tag{5}$$

which is graphically illustrated by the area $A_1 + A_2$ in Fig. 2.

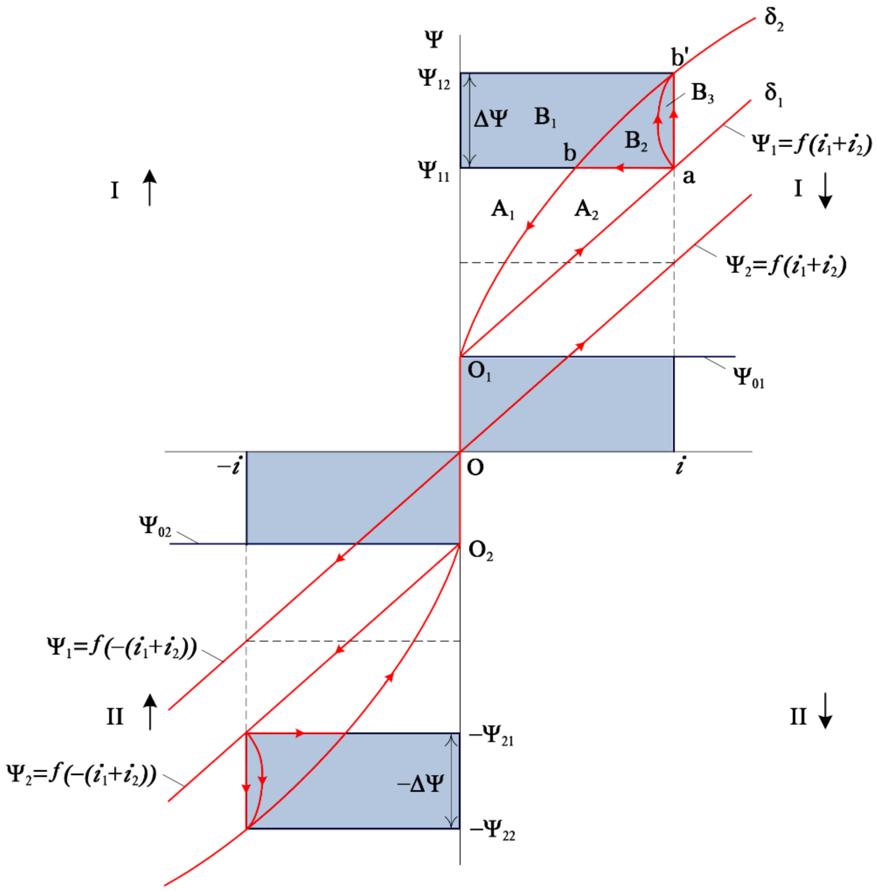

Fig. 2. Options for the state of the electromagnetic reciprocating oscillation motor.

To illustrate the process of energy conversion, we use the concept of magnetic linkage $\Psi(t)$ and consider a reciprocating motor with very low resistance; then the mathematical expression for the magnetic linkage takes the form:

$$\Psi(t) = \int_0^t u(t)dt + \Psi_{01}; \tag{6}$$

Here $u(t)$ is the given time function, therefore $\Psi(t)$ does not depend on the parameters of system and is equal to the initial value of Ψ_{01}, created by the DC bias winding.

After the alternating voltage $u(t)$ is supplied to the AC circuit (red electric circuit in the Fig. 1) of the motor, in the first half-period of the AC $i(t)$ the magnetization characteristics $\Psi = f(i)$ in magnetic circuits I and II of the motor are $\Psi_1 = f(i_1 + i_2)$ and $\Psi_2 = f(i_1 + i_2)$, respectively (red dashed lines, Fig. 1); in the second half-period the magnetic linkages change direction to the opposite $\Psi_1 = f[-(i_1 + i_2)]$ and $\Psi_2 = f[-(i_1 + i_2)]$, also variable magnetic linkages arise, which attract both halves of the armature 1 with equal forces and, therefore, the movement of the armature does not occur. After applying a constant voltage U to the bias DC I circuit (blue electric circuit in the Fig. 1), in both magnetic circuits I and II constant magnetic linkages Ψ_{01} and Ψ_{02} appear; taking into account the winding direction of the coils, in magnetic circuits I and II constant magnetic linkages Ψ_{01} and Ψ_{02} appear and armature oscillations start, since in the first and in all odd half periods of $i(t)$ in magnetic circuit I these magnetic linkages are added to the variable magnetic linkage and in the magnetic circuit II they are directed opposite and subtracted, whereby the armature begins to oscillate with the frequency of the AC current.

As can be seen from Fig. 2, application of a small positive magnetizing force, can cause a linear increase in the magnetic linkage in time to any desired level within the unsaturated zone. The graph $\Psi(t)$ depends on the specific values of the air gap δ or the law of variation δ at increasing Ψ. If we choose the origin of coordinates 0 as an initial point, where u, Ψ and i equal zero, then with the increase of magnetizing force Ψ increases along the curve piece 0_1 – a. Having reached the point a, in which the energy derived from the source and accumulated in the electromagnetic field equals the area $A_1 + A_2$, the air gap δ between the core and armature starts to decrease under the action of the force of magnetic attraction. In this case mechanical work will be done, and the flow process chart, depending on its nature, will be one of the lines ab or ab'. The final value of the field energy at point b is equal to the area $A_1 + B_1$ and the increase of the field energy is:

$$\Delta W_f = (A_1 + B_1) - (A_1 + A_2) = B_1 - A_2 \,, \tag{7}$$

and the performed mechanical work in accordance with equation (1)

$$\Delta W_m = \Delta W_e + \Delta W_f = (B_1 + B_2 + B_3) - (B_1 - A_2) = A_2 + B_2 + B_3 \tag{8}$$

is characterized by the area $A_2 + B_2 + B_3$, i.e. equals the amount by which the field energy decreased.

When reducing Ψ to zero along the path b′ - 0_1, electric energy equal to area C returns to the power network; the area B_1 is less than the amount of energy initially transmitted to the system by the amount of the executed mechanical work and every time the system passes the path 0_1 – a - b' -0_1 on the graph the energy is transferred from the electrical circuit to the field and from the field to the mechanical part; and the transfer on the return path 0_1 - b' – a - 0_1 results in the conversion of mechanical energy into electrical energy, i.e. generator mode. In the process of movement of the armature, an average force acts on it

$$F = \frac{\Delta W_m}{\Delta \delta} = \frac{A_2 + B_2 + B_3}{\delta_2 - \delta_1} = B_\delta^2 S / 2\mu_0 = \Psi(t)^2 / 2\mu_0 S \,, \text{ N} \tag{9}$$

where B_δ is the base value of magnetic induction ($B_\delta = 1$T); S is the air gap area; $\mu_0 = 4\pi 10^{-7}$ H/m is the magnetic constant. F is the negative value and strives to reduce the air gap δ. Since the strength and direction of movement are negative, the mechanical work is positive. According to the formula (9), the dependences of the thrust force on the value of the air gap at a constant value of the current i are calculated.

Since in the real electromagnetic reciprocating motors the total active resistance of the coils R is small, the current $\boldsymbol{i}$ does not remain constant and will be determined by both the active resistance and the induced electromotive force according to the equation

$$u(t) = \frac{d\Psi}{dt} + iR \,, \tag{10}$$

and, the magnetic linkage $\Psi(i,t)$ depends on both the current and the air gap, which vary with time and the current will decrease as the armature moves; thus, the process in Fig. 2 will be described not by a straight line, but by the curve ab.

The graphic method allows visual analysis of the energy balance in an electromagnetic reciprocating motor. The mechanical energy accompanying the change of the state is always equal to the area between the initial and final magnetization curves and the graph of the function $\Psi(\iota,t)$ in the transient electromagnetic process. As follows from the above mentioned, the process of energy conversion in the two-stroke electromagnetic resonant reciprocating motor under consideration is closely related to the storage of energy in a magnetic field, a capacitor battery and elastic mechanical elements. These experiments show that for an adjusted reciprocating motor, during the natural undamped frequency of oscillations ω_c is slightly higher, than the frequency of forced oscillations ω_B, the increase in bias current *I* in the DC winding causes a decrease in alternating current *i(t)* in the main winding at the expense of its reactive component and at a certain value of DC bias current *I* alternating current *i(t)* reaches its minimum value, and at the increase of the current *I* above the value 2a, the growth of alternating current begins, that is, the V curves common for a synchronous motor are obtained [11]. Fig. 3 shows the above-mentioned dependencies at different values of capacitor capacitance.

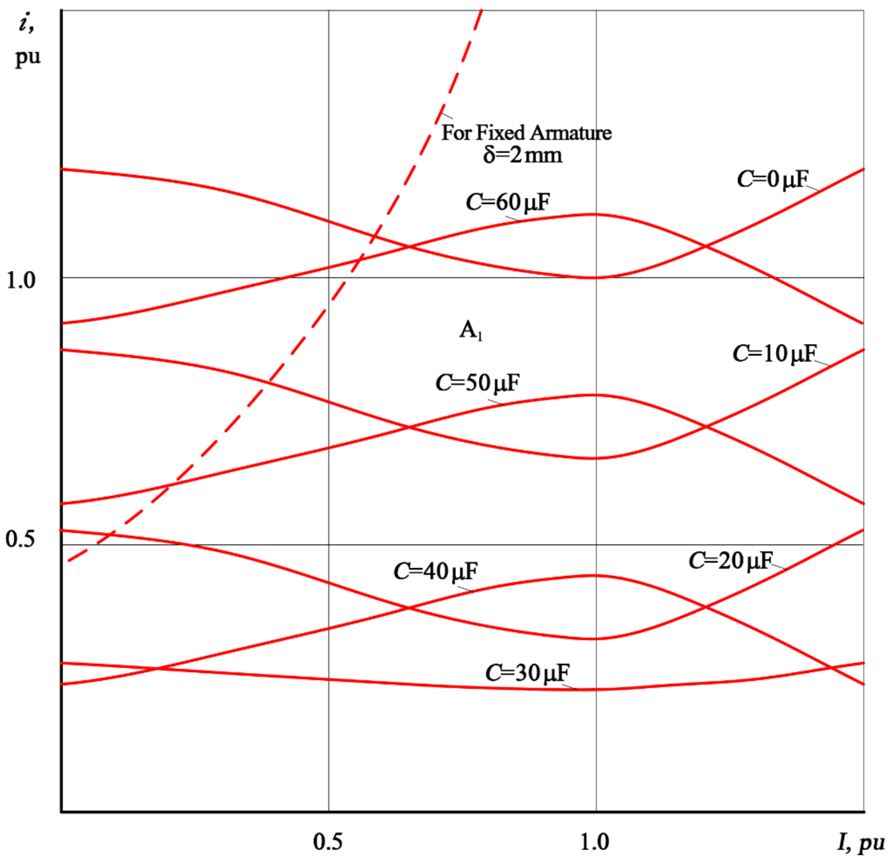

Fig. 3. V curves $i = f(I)$ of electromagnetic reciprocating motor.

Conclusion. As a result of the research, it was found that for a developed and manufactured electro-magnetic reciprocating motor, the operating mode at which $cos\varphi \to 1$ and minimal energy losses take place at maximum efficiency is provided at the point of the corresponding characteristic, which is achieved in a resonant mode when turned on in parallel with the input terminals AC capacitor with capacitance C = 30 μF (Fig. 1). In this mode, the DC bias current *I* is almost independent of the load of the electromagnetic reciprocating motor.

ელექტრომექანიკა

ენერგიის გარდაქმნა უკუქცევით-წინსვლითი მოძრაობის ელექტრომაგნიტურ ვიბრაციულ ძრავაში

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არსებობს საწარმოო მანქანების და მექანიზმების ფართო ჯგუფი, რომლებშიც ტექნოლოგიური პროცესები ხორციელდება მუშა ორგანოს ხაზოვანი ტრაექტორიის მოძრაობით. ჩვეულებრივ, ამ ტიპის მოძრაობის შესრულება ხდება როტაციული ელექტროძრავების გამოყენებით ამძრავსა და მუშა ორგანოს შორის დამატებითი მექანიკური კვანძის ჩართვით, რომელიც გარდაქმნის ბრუნვით მოძრაობას ხაზოვან მოძრაობად. ამჟამად სერიული როტაციის ელექტროძრავების ნახევარზე მეტი გამოყენებულია ისეთ მანქანებში, რომელთა მუშა ორგანოები გადაადგილდება ხაზოვანი ტრაექტორიით სწორედ ასეთი გარდაქმნის გამოყენებით. დამატებითი კვანძები ზრდიან ამძრავის გაბარიტებს და ფასს, ამცირებენ მთელი მოწყობილობის საიმედოობას, ამიტომ მიზანშეწონილი ხდება ელექტრომაგნიტური უკუქცევით-წინსვლითი მოქმედების ამძრავების გამოყენება, რომლებიც უზრუნველყოფენ მანქანა-მექანიზმის ძრავის და მუშა ორგანოს თავსებადობის ან ინტეგრაციის საუკეთესო პირობებს და ამის გამო უდავოდ პერსპექტიულია. ჩვეულებრივად ამგვარი ძრავები მუშაობენ რეჟიმებში, რომლებიც მექანიკურ რეზონანსს უახლოვდებიან, ხოლო ფერომაგნიტური რეზონანსის მიღწევა შეუძლებელი იყო საჰაერო ღრეჩოს და შესაბამისად ინდუქციური წინააღმდეგობის პერიოდული ცვალებადობის გამო. შემოთავაზებულ ელექტრომაგნიტურ ვიბრაციულ ძრავაში ელექტრული სქემის სრულყოფის შედეგად მიიღწევა ინდუქციური წინაღობის მუდმივობა, ხოლო როგორც მექანიკურ, ასევე ფერომაგნიტურ რეზონანსთან ახლო რეჟიმში მუშაობა მკვეთრად აუმჯობესებს ამძრავის ენერგეტიკულ მაჩვენებლებს. ნაშრომში განხილულია ენერგიის გარდაქმნის პროცესი ავტორების მონაწილეობით შექმნილ ელექტრომაგნიტურ ვიბრაციულ ძრავებში, სადაც უკუქცევით-წინსვლითი მოძრაობა მიიღწევა ორი, ცვლადი და მუდმივი მაგნიტური ნაკადთგადაბმულობის ურთიერთ-ქმედებით. ასეთი ტიპის ელექტრომაგნიტური ვიბრაციული ძრავებისათვის შედგენილ იქნა ენერგიის ბალანსის განტოლება და აგებულ იქნა ელექტრომაგნიტური ენერგიის მექანიკურ მუშაობაში გარდაქმნის გრაფიკული გამოსახულება. შესწავლილია დამოკიდებულება შემაგნიტების მუდმივ და მუშა ცვლად დენს შორის, მაკომპენსირებელი კონდენსატორების ბატარეის ტევადობების სხვადასხვა მნიშვნელობისათვის. ფერორეზონანსის მისაღწევად დადგინდა ცვლადი და მუდმივი დენის და ტევადობის ოპტიმალური სიდიდეები.

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