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ABSTRACT

of the dissertation for the degree of Doctor of Philosophy

USAGE OF ELECTROMAGNETIC VIBRATING FEEDER WITH LOW MECHANICAL FREQUENCY FOR ELECTROMECHANICAL COMPLEXES

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Urgency of the topic and degree of usage

In multiple sectors, vibration devices are commonly used in the transportation of finished products, their orientation, mixing, accelerating chemical reactions, and other such operations. Because vibration devices are utilized in various sectors of the economy, they have very diversified construction and operational capabilities across a wide power range. The criterion of technological processes for vibration devices is that their mechanical frequency is within the appropriate interval and that the system operates reliably within this interval.

Diverse vibrating devices are utilized in technical processes in various areas of industry, depending on the mechanical frequency and operating amplitude, as well as their control interval. In such devices, the high and low mechanical frequency values shift substantially depending on the intent of the device. The usage of a low mechanical frequency range (up to 20 Hs) is crucial in some technological processes. At this time, there is a growing demand for vibrating feeders with mechanical systems that work at low frequencies. As well as ensuring that mechanical oscillations are in the low frequency range, such devices must meet adequate power requirements.

In vibration devices that operate at low mechanical frequency range, single-phase electromagnetic vibrating feeders (EVF) are mainly utilized as an impactor. It is difficult to achieve the thrust required or power required with such existing devices. To obtain the requisite power, it is considered appropriate to use a three-phase EVF. In this regard, there is a requirement to develop three-phase one or two-stroke vibrating feeders that meet manufacturing standards.

It is prominent that contemporaneous three-phase low mechanical frequency electromagnetic type vibrating feeders electromagnet cores are made of electrotechnical steel supplier plate. The most common of these devices, which use a capacitor coupled in series or parallel with other capacitors in accordance with the electromagnet's circuit, operate on the resonance of voltages or currents. The stability of the system when such devices are in use depends on maintaining the electrical and mechanical systems' specific frequencies at or near one another. It is obvious that during a process, the specific frequency of a mechanical system varies depending on mass while the specific frequency of an electrical system essentially stays the same. As a result, the vibration device's electromechanical system operates in an unstable manner. Expanding the frequency interval of the amplitude-frequency characteristic of the electric system is a better solution to address this shortcoming. It should be noted that the frequency interval is very small due to the steepness of the amplitude-frequency characteristic at the required value of the power of the vibro-effector whose core is assembled from ordinary electrical steel sheets. It is considered acceptable to prepare the electromagnetic core material by making the necessary adjustments to its construction in order to increase the frequency interval and, as a result, to ensure the stable operation of the system. The equipment's primary objective is to have the simplest feasible structural design while also being as resistant to different detrimental impacts of the environment in where it is positioned as possible. To derive the expressions of the magnetic system of the EVF, electromechanical analogies are employed in accordance with the foregoing. As voltage fluctuations quickly alter the electrical system's specific frequency in such devices, the inductance of the coil of the electromagnet, which is very sensitive to voltage changes, upsets the device's stable operation.

The present scientific and technical literature sufficiently covers vibration devices with a core made of common electrotechnical steel. In this field, Nitusov Y.E., Babichev A.P., Je-Hoon Kim, Sang-Hyun Jeong, Guliyev Z.A., Gasimov R.A., Babayev I.S., Jafarov S., Huseynnov R.A. and others have conducted research. The challenges of implementing appropriate structural adjustments and conducting theoretical-practical research to increase the frequency range and guarantee successful management, however, have not been thoroughly addressed in the evaluated works. The steepness of the amplitude-frequency characteristic at the required amount of the power of the vibrator, whose core is constructed from standard electrotechnical steel sheets, results in a very tiny frequency interval.

It is deemed appropriate to prepare the electromagnetic core by making the necessary adjustments to the material in order to widen the frequency range and guarantee the system's steady operation. These devices' unstable performance is disrupted by the inductance of the coil of the electromagnet, which is extremely sensitive to voltage variations when the electrical system's specific frequency changes quickly. The fact that dissertation work is devoted to solving these and other previously mentioned problems makes it **pertinent**.

The object and subject of the research. It is intended to conduct continuous, periodic active and passive experimental studies in the fields of medicine, light industry, oil drilling, vibro-drilling, vibro-diagnostics, vibro-sieve, etc. using mathematical models, algorithms, management systems, and control systems.

The subject of the research is the construction, theoretical model and application of the three-phase two-stroke low mechanical frequency electromagnetic vibrating device intended for the implementation of technological processes in various fields of the industry.

The intentions and objectives of the research. The primary objectives of the dissertation work include a theoretical-practical analysis of the electromagnetic system parameters of the three-phase low mechanical frequency vibrating feeder (TPEMVF) and the development of a new two-stroke vibration device, expanding the TPEMVF's functional capabilities, developing a mathematical model and calculating the traction characteristics, and resolving issues with experimental research and the use of the device in production.

The following issues will be researched in order to find solutions to the problems:

1. Analyses of modern low mechanical frequency TPEMVF's and their electromagnetic and mechanical properties, either separately or in combination.
2. Theoretical study of TPEMVF.
3. Obtaining the mathematical model of the TPEMVF as well as the extension characteristics.
4. Experimental study of TPEMVF.

Scientific innovation.

The dissertation's scientific novelty consists of a theoretical-practical study of the electromagnetic system parameters of a three-phase low mechanical frequency vibrator, the development of a new two-stroke vibration device with increased functional capabilities, the construction of its mathematical model, the acquisition of thrust characteristics, and effective control.

The scientific novelty of the work consists of the following scientific results:

1. Analytical expressions of induced currents of TPEMVF were obtained.
2. The extension force of TPEMVF was determined by the analytical method.
3. The methodology of obtaining the characteristics of the TPEMVF draft has been developed.
4. The electromagnetic system of TPEMVF was studied according to the quality factor.

Defended primary provisions are as follows:

1. The current state of the problem is an examination of three-phase two-stroke low mechanical frequency acquisition methods.
2. Justification for using standard electrotechnical steel sheets as the core of TPEMVF in new formation.
3. Theoretical study of two-stroke electromagnetic type vibration device.
4. Obtaining the mathematical model of the two-stroke TPEMVF.
5. Analytical determination of the extension characteristic of TPEMVF.
6. Selection and experimental study of the formation of TPEMVF.

Justification and consistency of results. The research is based on electromechanics equations, calculation methods, electromechanical analogy methods, and electromagnetic field theory. The compatibility of experiments conducted in laboratory and industrial situations confirms the key theoretical assumptions and findings.

Theoretical and practical importance of research. The mathematical models and theoretical assumptions developed in the research allow for a more complete examination of the many modes of the two-stroke TPEMVF, ensuring stability and effective control, constructing a design methodology, and optimizing the characteristics of its operational part.

The two-stroke device developed as a result of the dissertation work was applied to the double sieve used in the separator to clean the product from mechanical mixtures (separate it into fractions), to the separator device used in the flour grinding mill of "Ineks LTD" LLC to select grain varieties, and to empty the finished product from the reservoir.

Approbation of work.

The results of the dissertation work have been appropriately reported and successfully discussed in organizations that fit the current criteria.:

- Republican Scientific Conference dedicated to the International Year of Chemistry (Sumgait June, 2011);
- Modern problems of energy. Republican scientific conference (Sumgait December, 2011);
- CAD and modeling in modern electronics (Bryansk, 2019);
- Modern problems and development prospects of electric energy. International scientific and technical conference (November, 2022, Baku).

The structure and scope of the work.

The dissertation consists of an introduction, four chapters, a bibliography and an appendix. The total volume of the work consists of 204 pages, including 189 pages of the main text, 56 figures, and a 129-title bibliography. The dissertation work has a total of 245007 number of marks, which include: Introduction - 21213 n.m., Chapter 1 - 37686 n.m., Chapter 2 - 33325 n.m., Chapter 3 - 48597 n.m., Chapter 4 - 37347 n.m., and Conclusion - 3110 n.m. Total text part count: 183973 n.m.

Publications.

The dissertation's main findings were presented in 17 scientific works, 12 of which were articles (5 of which were published abroad), 5 of which were published in materials of important International and Republican conferences (1 of which was published abroad), and 1 article was published in a journal indexed in the Scopus database.

GENERAL CHARACTERISTICS OF THE WORK

In the introduction, the relevance of the topic is justified, the goals and tasks of the research are defined, the scientific novelty of the work, its practical importance, and the important propositions defended are explained, and the brief content of the main sections of the dissertation is provided.

In chapter one, the analysis of the main indicators of the current electromagnetic type two-stroke three-phase low mechanical frequency electromagnetic vibration feeder (TPEMVF), the general state of the calculation of the parameters of the electromagnetic system, the functional characteristics of the applied TPEMVF and the main purpose of the dissertation were considered.

According to the research, it was found that the capacitance-inductance operating principle of the TPEMVF`s based on voltage resonance allows for a wide range of mechanical frequency adjustment, while the existing two-stroke, three-phase EVF consist of an electromagnet and an anchor and are attached to the body of the influencing device with the help of an elastic spring system. products made up of a series circuit.When the armature is dragged by the electromagnet during resonance, the air gap between the armature and the electromagnet diminishes, and the inductance practically changes. As a result, the inductive resistance of the magnetic coil differs from the resistance of the capacitor, and the system's resonance condition is disrupted. As a result of the research, it was determined that the steel core of the existing TPEMVF is assembled from ordinary electrotechnical steel sheets. The inductance of such influencing electromagnets is particularly sensitive to voltage variations, resulting in the phenomena of ferroresonance in the TPEMVF circuit and worsening of its output characteristics.

The working principle of the most widely used of such devices is based on the resonance of voltages or currents, devices that work with a series or parallel capacitor connected circuit according to the circuit of the electromagnet. The frequency interval is quite narrow due to the steepness of the amplitude-frequency characteristic at the needed value of the power of the vibrator, whose core is assembled from conventional electrical steel sheets.

As a result, the present single-phase and three-phase low mechanical frequency electromagnetic vibrating feeder (LMF EVF) have the following flaws:

1.In single and three-phase LMF EVF, the goal of smooth adjustment of the frequency in a wide range is not effective enough.

2. Since the working principle of those LMF EVF is based on the resonance of voltages, the steepness of the resonance curve is high due to improper selection of the material of the core used in them, which often causes the stable operation mode of the device to be disturbed.

3. The computation of the magnetic system characteristics of one- and three-phase LMF EVF is mainly done by empirical methods and does not meet many requirements in their present design work at the required level.

4. The voltage dependency of the electromagnetic parameters of the LMF EVF, as well as the inductance and capacitance of the oscillation circuit, has not been thoroughly examined in any of the currently available sources.

5. Issues such as expanding the functional capabilities of single and three-phase LMF EVF electric motors, enhancing their properties, and increasing efficiency have not been widely studied.

6. Existing AMT EVT production technology is difficult.

The frequency and amplitude of mechanical oscillations can be adjusted in the following ways:

1) regulation of the voltage feeding the coils of electromagnets (with an autotransformer);

2) changing the intensity of the current in the electromagnet (by reducing the active resistance);

3) changing the pulling force of the electromagnet by adjusting the air distance between the anchor and the core;

4) increasing the magnetic flux (changing the number of

windings in the windings);

5) changing the phase angle (changing the capacity of the capacitor);

The settings of the following parts and systems can be changed to tune the vibrating unit to resonance:

1) moments of inertia of the transverse section of the springs;
2) the working length of the transfer;
3) mass of the system or total moment of inertia;
4) changing the number of working rings of springs.

In addition to the ferro resonance aforementioned, it has been found that it is preferable to make the material of the electromagnetic core from special steel in order to broaden the frequency interval and, as a result, assure the system's stability.

Three-phase two-stroke vibration devices can be structurally composed of a combination of three single-phase windings in the shape of Ш. In this case, a circuit is installed on each rod, which is then built according to a specific scheme and connected to a three-phase network. Here the rods are placed on a plane. The magnetic circuit of such a device possesses magnetic asymmetry.

Despite the asymmetry in the magnetic system, the extension force acting on the armature written as

$$\dot{F} = \dot{F}_A + \dot{F}_B + \dot{F}_C \tag{1}$$

In here $\dot{F}_A, \dot{F}_B, \dot{F}_C$ –is the drag force corresponding to the modulus of the energy generated by the magnetic fluxes of the individual phases. The extension force expression corresponding to each phase is frequency-independent and variable with double frequency ω_k and ω_{k-1} harmonics corresponding to the sum and difference of frequencies are obtained so that of these (ω_k-ω_{k-1}) is transmitted to the output of the organizing vibration device, which varies with the angular frequency. As a result, the frequency of the auto-oscillation created by the gadget is determined by the given frequency difference.

To address the aforementioned inadequacies, the issue of developing an electromagnetic three-phase two-stroke TPEMVF with a core assembled from unique steel sheets was researched and solved in the following directions:

1. Analysis of the modern two-stroke TPEMVF according to its electromechanical parameters.
2. Theoretical study of the two-stroke TPEMVF, taking into account its constructive structure.
3. Construction of the mathematical model of the three-phase EVF and extraction of the draft characteristic.
4. Justification of the selection of the core of the two-stroke TPEMVF from special electrotechnical steel sheets.
5. Experimental research and application of two-stroke TPEMVF in production.

The results of the first chapter are reflected in works [4, 14, 15].

Chapter two examines the electromagnetic system of the low mechanical frequency three-phase special electrotechnical steel core EVF, the theoretical determination of the electromagnetic parameters of the two-stroke EVF, and the analytical expression of the traction force it can generate.

It is known that when special steel sheets are chosen for the electromagnetic core, a surface effect phenomenon occurs in the core, necessitating additional theoretical studies and the use of new methods of calculating the parameters of two-stroke TPEMVF in order to ensure the device's normal operation in the required power and frequency interval. For example: Current of phase A - i_A current the following expression can be written for:

$$i_A = i_{1A} + i_{2A} = \sqrt{(B_{11}+B_{21})^2 + (B_{12}+B_{22})^2}\sin(\omega t + \varphi_{4A}) + \\ + \sqrt{B_{23}^2 + B_{24}^2}\sin(3\omega t + \varphi_{5A}) \tag{2}$$

The obtained expression meets the practice requirement with an error of (8-10 %). For the other phases, i.e., phases B and C, the following expressions were obtained accordingly:

$$i_B = \sqrt{(N_{11}+N_{21})^2 + (N_{12}+N_{22})^2}\sin(\omega t + \varphi_{4B}) + \\ + \sqrt{N_{23}^2 + N_{24}^2}\sin(3\omega t + \varphi_{5B}) \tag{3}$$

$$i_C = \sqrt{(M_{11}+M_{21})^2 + (M_{12}+M_{22})^2}\sin(\omega t + \varphi_C) + \\ \sqrt{M_{23}^2 + M_{24}^2}\sin(3\omega t + \varphi_{5C}) \tag{4}$$

At the same time, it was discovered that when these devices are investigated using Maxwell's equations, the mathematical expressions obtained during their integration allow for more accurate conclusions. In relation to the foregoing, the approach of electromechanical analogies was utilized to derive the expressions of the mathematical models characterizing the magnetic system of the two-stroke TPEMVF. The inductance of the winding of the electromagnetic core in this type of equipment is particularly sensitive to voltage changes, causing the equipment's stability to be disrupted due to the quick change of the electrical system's specific frequency.

The main electrical scheme of the studied two-stroke TPEMVF is shown in figure 1. Each of the electromagnet fed from a three-phase voltage source is the electromagnetic system of the device's balancing equations are expressed in the form of a system of integrodifferential equations, with a capacitor C linked in series to the phase loop, active resistances r, inductances L, and mutual inductances M between the phases. Certain transformations were applied to the received equations, and it was assumed that the amplitude values of the currents passing through the phases are identical to each other:

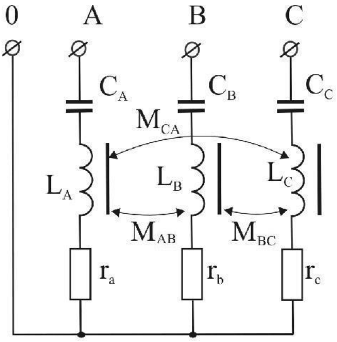


Figure 1. Principal of TPEVF

$$\begin{cases} \dot{I}_A\left(r + j\dot{X}\right) + j\dot{X}_m\dot{I}_B + j\dot{X}_m\dot{I}_C = \dot{U}_A, \\ \dot{I}_A j\dot{X}_m + \dot{I}_B\left(r + j\dot{X}\right) + \dot{I}_C j\dot{X}_m = \dot{U}_B, \\ \dot{I}_A j\dot{X}_m + \dot{I}_B j\dot{X}_m + \dot{I}_C\left(r + j\dot{X}\right) = \dot{U}_C \end{cases} \tag{5}$$

- It should be mentioned that the device's phase loops have an equal number of windings. Furthermore, the cost of the capacitances of the capacitors linked in series with the phases is likewise the same. The following analytical conclusions can be reached by analyzing the obtained expressions for various phase currents under such conditions:

- The time variation of the investigated quantities in steady state is non-sinusoidal, which is related to the magnetic system's significant nonlinearity;
- The nominal value of the current surpasses one established at the start of the switching operation, which is explained by the magnetic saturation of the electrotechnical steel.
- The oscillations' non-sinusoidal character has a significant impact on the lowest value of the air distance.

As a result, the linearity of oscillations must be ensured in order to assist the selection of the minimum air distance and preserve its value within reasonable ranges. By ensuring the minimum value of the air distance, it is possible to obtain a greater electromagnetic pulling force with minimal energy losses, which is performed by the correct selection of the parameters of the core, anchor and windings of the electromagnet.

Taking into account the cyclic current losses generated in the core of the magnetic system of the two-stroke TPEMVF consisting of steel sheets analytical expressions for the complex form of total resistance corresponding to each phase were obtained and for the state of resonance in the phases of the system, its characteristics depending on the quality factor were determined.

Theoretical-practical studies on two-stroke TPEMVF revealed that, from two strokes, theoretical-practical operations performed on one can be attributed to both strokes if the electrical parameters (U_A, U_B, U_C and I_a, I_b, and I_c) in a two-stroke three-phase system form 120° symmetry with each other. At the same time, since the winding with the same number of windings is utilized in all three phases, the inductances of the phase windings will be the same. Nonetheless, the electromagnetic field theory is used to calculate the magnetic losses resulting from inter-cycle mutual probable periodic current losses, which are directly proportional to the current value. The length of the air gap in the magnetic flux's passage determines the electromagnetic losses on both cycles, so the air gap in the magnetic flux's path in the constructed two-stroke, three-phase vibrating device may differ, but only slightly.

Examination of the derived formulas for various phase currents reveals that:

- Due to the significant nonlinearity of the magnetic system, the time variation of the studied values in the steady state is non-sinusoidal in character;
- The saturation of the steel in the electromagnets explains why, at the start of the switching operation, the nominal value of the current is greater than the nominal value;
- The minimal value of the air distance is significantly impacted by the oscillations' non-sinusoidal character.

Therefore, it is vital to maintain the linearity of oscillations in order to assist the selection of the minimum air distance and to keep its value within reasonable limits. A higher electromagnetic pulling force with less energy loss can be achieved by maintaining the smallest air distance. This is accomplished by carefully choosing the electromagnet's core, anchor, and winding characteristics. The effects of periodic current loss continue to exist concurrently.

As a result, the final equations acquired enable one to ascertain how the voltage provided to the circuit's input depends on the particular inductance and frequency variation. It is known from the course of theoretical foundations of electrical engineering that during resonance, the inductive resistance is compensated by the capacitive resistance, thus the circuit consists of just active (R) resistance. This frequency, which is around three times lower than the frequency of the feeding voltage, is obtained in vibration devices and is similar to the particular frequency of the mechanical system. On the other hand, when β is $\omega > \omega_0$ the frequency change is positive,when is $\omega < \omega_0$ it is negative. When $\omega = 0$, at the $\beta = -1$ resonance frequency $\beta = 0$.

The review of the quality factor's dependency on the impedance of one phase of the three-phase system reveals that, When the core of the TPEMVF is made of special steel sheets with low magnetic permeability, the quality factor of its phases decreases and as a result, the frequency response band broadens in the frequency response. As the quality factor Q_a is higher, the steepness of the characteristic is relatively high. As a result, the three-phase vibrator operates normally across the entire frequency range. However, $Q_a = 10$, 100 and higher pricing, the typical working mode is disturbed.

As devices are utilized in a variety of industries, industrial vibration devices have a very broad power range, diverse constructions and functions, and varied impact ways. Transportation, scheduling, blending, arranging, quickening, and so forth in the instruments and apparatuses that supply these technological processes, vibrating devices play a significant role as power elements. Since these gadgets are utilized as power elements, as was previously discussed, it's critical to ascertain their traction force and traction force components.

The maximum value of the amplitude of the extension force for the full period of the sinusoid defined as:

$$F = F_m \cdot \sin \frac{2\pi}{T} t \qquad (6)$$

Here, *m*- is transition scale to the power; F_m – is the maximum amplitude of the signal; *T*- is the complete period of the sinusoidal signal; *t* – is the actual rate of the time

Modulus of final extension force F is defined as:

$$F_m = \sqrt{F_0^2 + F_{1m}^2 + F_{2m}^2 + F_{3m}^2 + F_{4m}^2 + F_{5m}^2 + F_{6m}^2 + F_{7m}^2} \qquad (7)$$

Determining the traction force and traction force components of these devices is crucial because, as was previously noted, they are used as power elements. Simultaneously, the force expression that is obtained encompasses all the parameters of the TPEMVF and facilitates the determination of its output characteristics.

The results of the second chapter are reflected in works [1-3, 6, 10, 17].

In the **chapter third**, the electrotechnical steel core of a three-phase two-stroke electromagnetic vibration device is chosen from available materials based on the change of the magnetic field voltage over a large range (figure 2). Research has shown that in steel-2, and cast iron-C of the magnetic field voltage H=11A/m and H=16 A/m

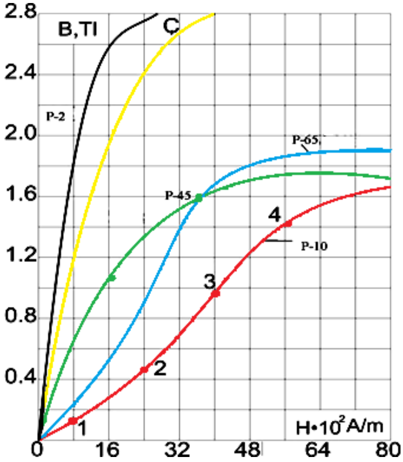


Figure 2. Various steelsmagnetization curves

the process of saturation occurs in the rate. And this Limits the variation interval of the TPEMVF according to the magnetic field voltage. The Ш-shaped steel core TPEMVF manufactured of this material may operate normally in both light and strong magnetic fields. At the same time, it may be appropriate to utilize steel-2 and cast iron as the material of the vibration device's core since additional high harmonics are formed in the affected loop at high magnetic field voltage values. As a result of comparative analysis of steel-10, steel-45 and steel-65 materials, electrotechnical steel-10 material was selected and at this time it was noted that for the two-stroke TPEMVF, such a mode should be chosen so that no additional dynamic effects arise.

Let's begin to discuss steel-10 substance. This material's magnetization curve exhibits nonlinearity both before and after the value of H=48 *A/m*. The magnetic flux created in the core is likewise non-sinusoidal due to both received nonlinearities, which lowers the vibration device's dependability. The expression of the curve shown in the figure as a binomial must be described in order to ascertain the frequency and amplitude of harmonics resulting from nonlinearity in this material. Assume that the part of the steel-10 curve corresponding to the weak area

$$B = a_1 H_1 + a_2 H_A^2 + a_3 H^3 + a_4 H^4 \tag{8}$$

described as a binomial. Here, a_1, a_2, a_3, a_4 are constant coefficients. The experimentally acquired curve for steel-10, depicted in the image, is utilized to determine these coefficients. As illustrated in Figure 3.1.1, that curve is approximated by four points. The following system of equations is produced if we write an equation for every point:

$$\begin{cases} B_1 = a_1 H_1 + a_2 H_1^2 + a_3 H_1^3 + a_4 H_1^4, \\ B_2 = a_1 H_2 + a_2 H_2^2 + a_3 H_2^3 + a_4 H_2^4, \\ B_3 = a_1 H_3 + a_2 H_3^2 + a_3 H_3^3 + a_4 H_3^4, \\ B_4 = a_1 H_4 + a_2 H_4^2 + a_3 H_4^3 + a_4 H_4^4 \end{cases} \qquad (9)$$

From the solution of this system of equations a_1, a_2, a_3, a_4 coefficients are determined. H_1=800*A/m*, H_2=2400*A/m*, H_3=4000*A/m*, H$_4$=5600*A/m*, B_1=0,1*Tl*, B_2=0,5*Tl*, B_3=1,05*Tl*, B_4=1,4*Tl*. *B* and *H* After calculating and considering their values in expressions (8) and (9) the coefficients have the following values:

$a_1 = 8{,}411415 \cdot 10^{-5}; a_2 = 4{,}785244 \cdot 10^{-8}; a_3 = 5{,}289282 \cdot 10^{-12}; a_4 = -1{,}525835 \cdot 10^{-15}$

Considering these values in the formulation (9), $H = H_m \sin \omega t$ assuming that $B = f(H)$ The resulting dependence has the trigonometric form shown below:

$$B = a_1 H_m \sin \omega t + a_2 H_m^2 \sin^2 \omega t + a_3 H_m^3 \sin^3 \omega t + a_4 H_m^4 \sin^4 \omega t \qquad (10)$$

Here, the following expression is produced by transforming trigonometric functions:

$$\begin{aligned} B = {} & \frac{1}{2} H_m^2 \left(a_2 + \frac{3}{4} a_4 H_m^2 \right) + H_m \left(a_1 + \frac{3}{4} a_3 H_m^3 \right) \sin \omega t - \\ & - \frac{1}{2} H_m^2 \left(a_2 + a_4 H_m^2 \right) \cos 2\omega t - \frac{a_3 H_m^3}{4} \sin 3\omega t + \frac{1}{8} a_4 H_m^4 \cos 4\omega t \end{aligned} \qquad (11)$$

Expression (11) shows that when the vibrating device's steel-10 core is used, the magnetic induction changes non-sinusoidally when the magnetic field voltage varies in accordance with the sinusoidal rule because of the nonlinearity of its magnetization curve and the composition of this non-sinusoidal is obtained from the constant component, the first, second, third and fourth harmonics. The vibration device's operating mode is altered when a stable amount of magnetic induction is present because it causes the core's magnetization characteristic to move parallel to itself in the direction of the *B* axis. High frequency harmonics are rapidly eliminated by the gadget because it is low frequency tuned. The constant organizer's impact endures, nevertheless, because it is near the low frequency. The impact of the fixed organizer on the vibration device's operating mode is eliminated when the series capacitance is introduced to the influence circuit of the low-frequency vibration device. Therefore, it is deemed reasonable to accept that electrotechnical steel-10 was used to make the material for the two-stroke TPEMVF core. Following that, the question of figuring out the TPEMVF 's traction force could be addressed.

To determine the electromagnetic drag force and the components of the drag force of the TPEMVF, for the average value of the drag force of the three phases together the expression

$$F_{or} = \frac{9}{4} \cdot \frac{U_m^2}{r^2} \frac{1}{1+Q^2\beta^2} \cdot \frac{dL_A}{d\delta} = F_0 \frac{1}{1+Q^2\beta^2} \ . \tag{12}$$

was obtained. The dependency of the inductance on the air gap distance of the electromagnetic extension force of the TPEMVF is presented here for the sake of relative simplification of the analytical limit.

$$L_A = \frac{K_{hA}}{1+K_1\delta} \tag{13}$$

Here, $K_1 = \frac{3\mu}{3h+2d}$, $K_{hA} = \frac{W^2\mu\mu_0 a_1 b_1}{3h+2d}$; a_1, b_1, h and d - are the geometric dimensions of the nucleus.

$L_A = f(\delta)$ curves constructed according to expressions (11) and (12) are approximated by a simpler polynomial in the working zone:

$$L_A = m_0 + m_1\delta + m_3\delta^2 + m_6\delta^3 \tag{14}$$

Here, m_0, m_1, m_3, m_6 - are approximation coefficients.

The time-dependent variation of δ is a constant complex and the sum of two harmonics, namely:

$$\delta = \delta_0 + \delta_{1m} \sin \Omega t + \delta_{2m} \sin 2\Omega t \tag{15}$$

Here, Ω- is the frequency of mechanical oscillations. Taking this into account, the following expression for the mechanical traction force of the device was calculated from the experiment results:

$$F = F_m \sin \frac{k\omega}{n+1} \cdot \tag{16}$$

Here, F_m - the amplitude of the equivalent extension force; k=2,6,10 -

the coefficient indicating how many times the pure electric frequency harmonics exceed the mains frequency in the computed power expression, $n = 1 \div 5$-the frequency of the attraction force of the electromagnet is the number of harmonics equal to the mechanical frequency.

The amplitude of the equivalent extension force F_m for the given specific situation can be expressed as follows:

$$F_m = \frac{U_m^2}{24} \cdot \frac{1 + a^2 + a^4}{2r^2 + b^2} \cdot \sqrt{\sum_{n=1}^{6} D_n^2 + b_1^2 + b_2^2 + b_3^2 + a_1^2 + a_2^2 + a_3^2} \qquad (17)$$

Here

$$b_1 = \frac{1}{2}\sqrt{B_1^2 + B_2^2} \;; \quad b_2 = \frac{1}{2}\sqrt{B_3^2 + B_4^3} \;; \; b_3 = \sqrt{B_4^2 + B_5^2} \;;$$

$$a_1 = \frac{K}{2}\sqrt{A_1^2 + A_2^2} \;; \; a_2 = \frac{K_1}{2}\sqrt{A_3^2 + A_4^2} \;; \; a_3 = \frac{K_1}{2} A_5 \,.$$

The derived traction force expression (13) comprises all of the parameters of the two-stroke TPEMVF device and enables for the determination of its output characteristics. The two-stroke TPEMVF (figure 3) consists of a fixed base 1, arc-shaped cores 2,3 and 4 and loops 5,6 and 7 located on the cores, plates 8, two pairs of nuts 9,10, 11,12,13 for fastening the latter to the elastic system. It consists of 14 springs, 15 rigid elements, 16, 17 working bodies, 21 cables connecting the working bodies with 19 anchors, 18, 20 guides (rollers) and 22 metal strips to which the rollers are attached. TPEMV works as follows. A three-phase electromagnet 8 connected to an alternating current source attracts the armature, springs 11, 13 are compressed during the downward movement of the anchor and springs 12 and 14 are released accordingly.

The latter are slightly released from the compression applied to them. Springs 11, 13 are deformed under the influence of load M18 and this deformation remains in the same direction. Deformation received by springs 11, 13 from mass load M18 remains in the same direction during the work process and corresponds to the direction of extension force. Springs 12 and 14 undergo additional deformation due to the action of M16 and M17 operational parts and these springs are freed from that deformation to a certain extent when the anchor is pulled by the electromagnetic.

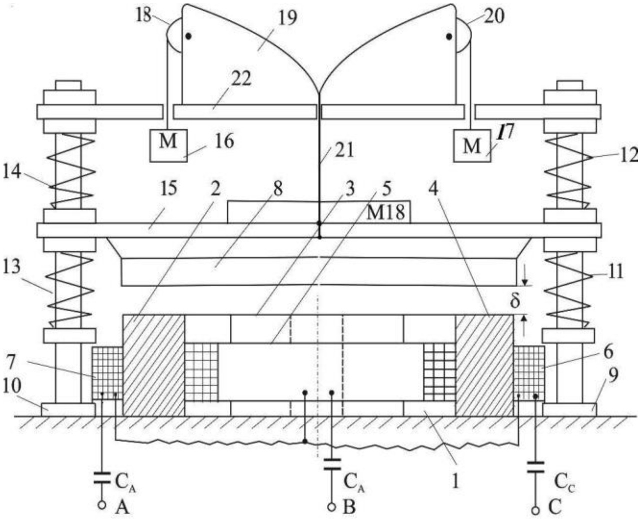


Figure 3. Physical model of three-phase EVQ

The mass of M18 and the gravity of the anchor with the help of 21 cables, balances with a certain part of the M16 and M17 loads and thus the degree of compression of the springs 11, 13 decreases and always remains constant in the working process. The compression process occurs in the current state of the anchor due to the influence of loads M16 and M17 on springs 12 and 14, and the tension process occurs due to the effect of load M18 and the gravity of the anchor. This process remains unchanged while the device is running.

When the anchor spring system is pushed up, the top springs are deformed further, while the lower springs are freed from the distortion induced by the nuts. The upper and lower springs are also distorted once per period as a result of this. This procedure is repeated in the following steps.

The lower springs are freed from the strain brought on by the nuts when the anchor is pulled up, while the top springs undergo extra deformation. As a result, once every period, the upper and lower springs are extra distorted. In the steps that follow, this procedure is repeated. Considering all of the aforementioned, figure 3.3.2 depicts the TPEMVF replacement strategy.

In the figure, mechanical springs and loads are symmetric with respect to the y and x coordinate axes and can be described as

$$M_1 = \frac{M_{16} + M_{17} - M_{18} - M_e}{2} \quad \text{and}$$

$$M_2 = \frac{M_{18} + M_e - M_{16} - M_{17}}{2}$$

Amplitude values and phase shift angles of the currents flowing from the branches are written as follows:

$$I_{mL1} = \sqrt{\left(I_{2a} - I_{3a}\right)^2 + \left(I_{2p} - I_{5p}\right)}\ ;\ \ \varphi_{L1} = arctg\,\frac{I_{2p} - I_{5p}}{I_{2a} - I_{5a}} \tag{18}$$

$$I_{mL2} = \sqrt{\left(I_{3a} - I_{1a}\right)^2 + \left(I_{3p} - I_{1p}\right)}\ ;\ \ \varphi_{L2} = arctg\,\frac{I_{3p} - I_{1p}}{I_{3a} - I_{1a}} \tag{19}$$

$$I_{mL\ell} = \sqrt{\left(I_{1a} - I_{5a}\right)^2 + \left(I_{1p} + I_{5p}\right)}\ ;\ \ \varphi_{L\ell} = arctg\,\frac{I_{1p} + I_{5p}}{I_{1a} + I_{5a}} \tag{20}$$

$$I_{mR1} = \sqrt{\left(I_{2a} + I_{4a}\right)^2 + \left(I_{2p} + I_{4p}\right)}\ ;\ \ \varphi_{R1} = arctg\,\frac{I_{2p} + I_{4p}}{I_{2a} + I_{4a}} \tag{21}$$

$$I_{mR2} = \sqrt{\left(I_{3a} - I_{4a}\right)^2 + \left(I_{3p} - I_{4p}\right)}\ ;\ \ \varphi_{R2} = arctg\,\frac{I_{3p} - I_{4p}}{I_{3a} + I_{4a}} \tag{22}$$

Using the method of electromechanical analogies of the two-stroke TPEMVF, we obtain the following expressions for elastic forces and gravity forces of loads:

$$\begin{aligned}
&F_1 = F_{1m}\sin\left(\omega_\nu t + \varphi_{f1}\right) = \sqrt{F_{1a}^2 + F_{1p}^2}\,\sin\left(\omega_\nu t + \varphi_{f1}\right);\\
&F_2 = F_{2m}\sin\left(\omega_\nu t + \varphi_{f2}\right) = \sqrt{F_{2a}^2 + F_{2p}^2}\,\sin\left(\omega_\nu t + \varphi_{f2}\right);\\
&\varphi_{f1} = arctg\,\frac{F_{1p}}{F_{1a}}\ ;\ \ \varphi_{f2} = arctg\,\frac{F_{2p}}{F_{2a}}\ ;\\
&F_3 = F_{3m}\sin\left(\omega_\nu t + \varphi_{f3}\right) = \sqrt{F_{3a}^2 + F_{3p}^2}\,\sin\left(\omega_\nu t + \varphi_{f3}\right);\\
&\varphi_{f3} = arctg\,\frac{F_{3p}}{F_{3a}}\ ;
\end{aligned} \tag{23}$$

Thus, the length of the spring-elastic system of the two-stroke TPEMVF changes depending on the time in the working process according to the sum of the two forces. The time-dependent harmonic oscillator with angular frequency governs the variable part of these forces. Building simulation models of a three-phase two-stroke electromagnetic vibration device's electric circuit provides for a more complete analysis of the processes that occur in that device. The SimPowerSystems part of the Simulink program was utilized in the study for this purpose, and the electric circuit was simulated for a single-phase and subsequently a three-phase electromagnet.

Figures 4 and Figure 5 illustrate the schematic of one of the simulation models as well as the output signal change curve.

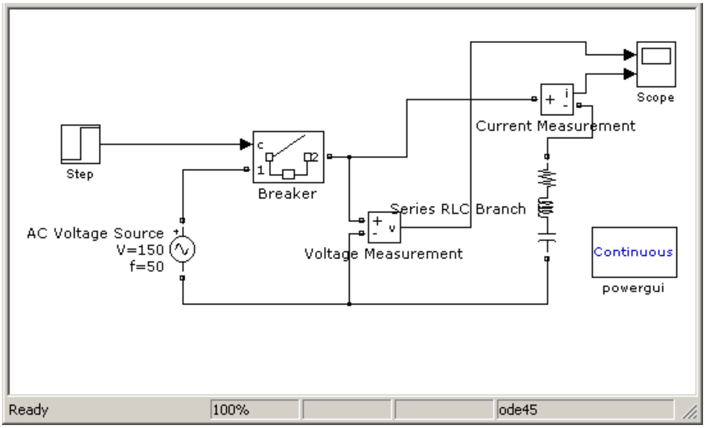


Figure 4. Improved simulation model of Single-Phase circuits

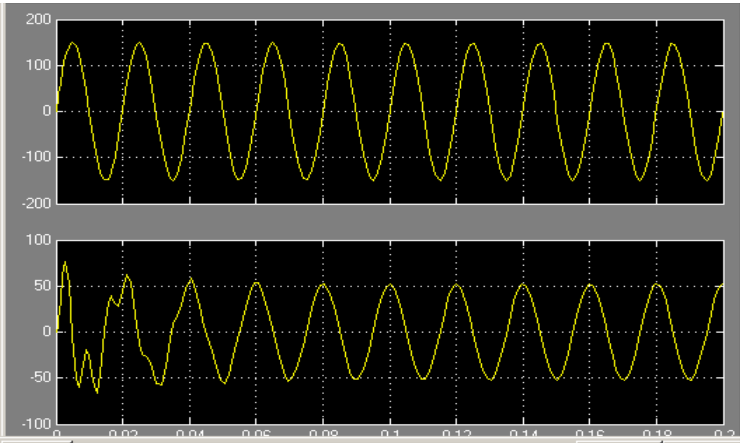


Figure 5. Form of voltage and current

Using simulation models, simply construct a circuit corresponding to the vibration device's comparable replacement electric circuit, to compare theoretical research with the findings of computer experiments performed by simulating processes at various values of the variables, enables the study of the effect of this or that variable on the operation of the device based on the processing of a large number of simulation results.

The results of the third chapter are reflected in works [8, 9, 11-13].

In chapter four Information on the experimental research of TPEMVF and its manufacturing application experiments and tests carried out on TPEMVF which core is made of specially selected electrotechnical steel sheets, the conclusions of the management, theoretical circuits model, and thermal report are presented.

A program of experimental research was designed in order to validate the theoretical studies, and it was carried out by measuring the frequency and amplitude of vibrations of the vibrating device in different modes, the traction force, and the used power. For the test, a three-phase autotransformer, measuring instruments, and a laboratory model was used. Dependencies of the resonant inductance in the phases of the electromagnetic system of the two-stroke TPEMVF on air distance and voltage, experimentally deduced to the δ=(0,25-5) mm interval, the adequate voltages of seriesconnected capacitors to the phases are determined. The device's efficiency is demonstrated by the fact that the frequency and amplitude of the low mechanical frequen-cy oscillations pro-duced by it are within the required limits was demonst-rated, by heat loss minimization, appropriate size and volume, easy mode adjustment, and the ability to perform in a wide voltage range was determined.

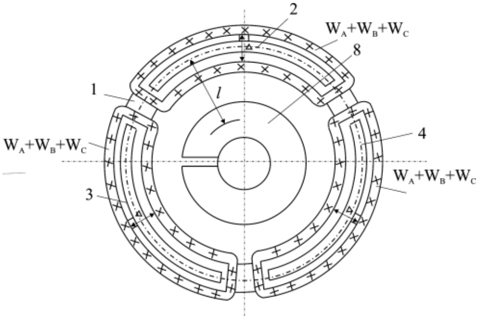


Figure 6. Placement of phase loops in the magnetic system

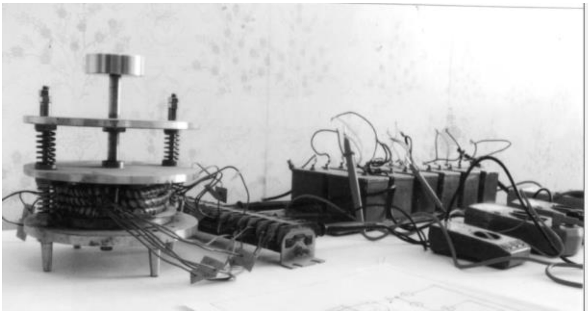


Figure 7. Picture of the experimental vibration device.

While the core is comprised of precisely selected electrotechnical steel sheets, the magnetic system indicated in figure 6 is obtained. The following formula was calculated using the three-phase device's equivalent replacement scheme, which permits determining the device's traction force based on its magnetic resistance:

$$F = 6W^2 I_m \frac{R_{11}^1}{R_{11}^2}\left[\left(\frac{dI_m}{dx} - \frac{I_m}{R_{11}} \cdot \frac{dR_{11}}{dx} + \frac{I_m}{2R_{11}^1}\frac{dR_{11}^1}{dx}\right)\right] \qquad (24)$$

To validate the results obtained using the developed mathematical model, an experimental model of the vibration two-stroke TPEMVF device (Figure 7) was created, and experiments were performed at various voltages.

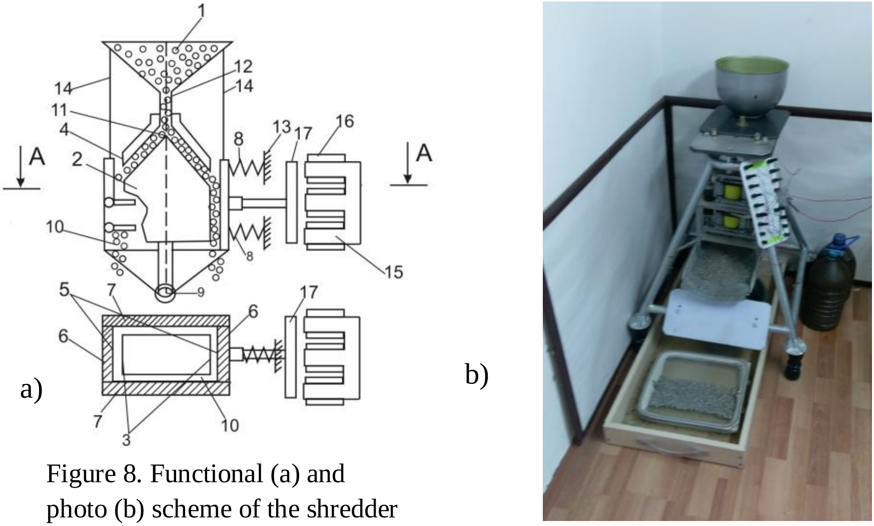
The theoretical and experimental values of EVF parameters express that the initiated device meets all the above-mentioned requirements and its efficiency is comparable to the efficiency indicators of vibrating electromagnetic transmission devices designed for use in electromechanical complexes. The vibratory element of the supplied shredding machine is relatively simple and fully fits the standards for the completed product's shredding quality.

Figure 8 shows the functional scheme (a) and photo view of the grain and granular materials shredder TPEMVF that was created using the aforementioned judgments.

The crusher consists of 1 - cargo hopper, 3 - two working faces, 2 - hammer, 4 - oscillator located inside the part and 9 - connected to the axle. 4 - consists of moving and immovable covers with the part, 5, 6 covers and 7 - side wall. 2 - the crushing cover of the hammer and 4 - form two crushing chambers 10 - of the part. 2 - in the upper middle part of the hammer, a branching channel - 11 is opened, which connects it with the crushing chamber 11. The upper section of the channel 12 is connected to the cargo hopper 12 with a corrugated hose 12.

The crushing apparatus 2 - comprises of two cargo hoppers and 2 working faces, 3 covers, 2 hammers, and 4 oscillators are all situated in the lower half of the part and linked to axis 9. Together with the parts, 4—which moves alongside it and is made up of covers 5, 6, and a side wall—2, the upper covers with a hammer, and 4—form the crushing chamber 10.

An electromagnetic three-phase vibrator and two 8-elastic springs are attached to the fixed face of the body on the same side. 14 ropes support 4-hull on all four sides as it hangs from 1-cargo hopper. 15 - The cargo hopper is joined to the vibrator.



a)

b)

Figure 8. Functional (a) and photo (b) scheme of the shredder

The shredder uses the following technological procedure. The initial material is added to the loading hopper 1, and the same material flows into the crusher 11's channel through the aid of a hose 12. There, it is dispersed equally and enters the two shredders 10, where it is crushed, working with 13 electromagnetic vibrators, it vibrates its 4 bodies in a straight line and on a horizontal plane. The hammer 2 oscillates in the opposite phase to the body 4's oscillation, crushing the granular material by striking it alternatively. Springs-8 linked to the moving body - 4, electromagnetically remove the created dynamic load and adequately minimize the noise (hum) of the unit in addition to moving the body back to the output position. 15 - By evenly distributing the shredder's load to the body, an electromagnetic vibrator ensures the gadget will operate steadily. The apparatus was used to empty the final product from the reservoir and choose grain in the "İneks LTD" LLC flour mill.

The results of the fourth chapter are reflected in works [5, 7, 16].

MAIN RESULTS OF THE WORK

The dissertation focuses on theoretical-experimental study, control, design, structural development, and implementation of a low mechanical frequency three-phase two-stroke electromagnetic vibration device. During the solution of this problem, the following results were obtained:

1. In accordance with an overview of available resources, the latest version of three-phase low mechanical frequency electromagnetic vibration devices commonly used in electromechanical complexes has been thoroughly analyzed; their primary characteristics, the current state of calculating their electromechanical parameters, and existing problems related to theoretical research, design, and management have been identified

2. It has been defended to make the core of TPEMVF using standard electrotechnical construction steel, and it was deemed appropriate to make the core from P-10 steel, so a theoretical-analytical study of the magnetic system of EVF was performed, equations with two sets of variable coefficients were obtained for each phase, and their solution was given, and the harmonics of the instantaneous values of each phase current were determined.

3. The electromagnetic system of the low mechanical frequency TPEMVF was studied using the quality factor corresponding to the resonance mode of its electric circuit, taking into account the current losses in the magnetic circuit, the expressions containing the complete electrical resistance of the phases are determined and on

the basis of these expressions, the characteristic of the ratio of the current values of the phase currents to its resonance current was determined. Based on the observed features, it was discovered that the steepness of the system's resonance curve reduces as the value of the quality factor lowers. The value of the coefficient of quality Q_a=4; when it's 10 and 100 characteristics obtained in the intended low frequency range (below 20 Hs) is taken practically parallel to the line ω/ω_0 and which makes it appropriate to use P-10 brand steel in the preparation of the core.

4. A mathematical model was created by modeling the corresponding electrical circuit for the low mechanical frequency three-phase EVF using the system of electromechanical analogies and the device's operational parameters and output characteristics. The three-phase vibrator's processes are accurately and completely reflected by the features and report outcomes that were theoretically obtained and confirmed by experimentation.

5. The obvious and non-obvious limitations are identified, the optimization criterion for choosing the ideal parameters that provide the nominal thrust force of the UEMQV is assigned, and by increasing the load of the vibration device, the device thrust force practically remains stable in the low frequency range throughout the work process.

6. On the basis of empirical studies, the validity of the performed theoretical studies was comparatively validated in practice, and a three-phase EVF was created and it was used to empty the final product from the reservoir and select grain in the separator device at the "Ineks LTD" LLC flour mill.

7. The three-phase vibration device that was created using the parameters that were chosen was used in production and enabled the achievement of fairly respectable outcomes. It should be noted that the outcomes of the scientific-theoretical research carried out in the dissertation work currently under discussion, methodological recommendations, can be successfully applied in the future in the creation of various types, more modern type, TPEMVF, and in the process of using comparable facilities.

THE MAIN PROVISIONS OF THE DISSERTATION ARE REFLECTED IN THE FOLLOWING WORKS

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Author's personal participation

The books [8, 13, 14, 15] listed in the bibliography for the PhD dissertation were written by the author. The author owns the context of the scientific problem, as well as the approach taken to solve it in publications [1-7, 9-12, 13, 16, 17] that were co-authored.

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