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ENERGY CHARACTERISTICS OF THE ELECTROMAGNETIC VIBRATION DRIVE WITH PULSE POWER SUPPLY OF VIBRATOR COILS

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Vibrating equipment provides various technological processes, such as transportation, separation, compaction of mixtures. The electromagnetic drive is usually used in vibrating conveyors, feeders and other devices where vibration parameters are automatically controlled. Increasing the energy efficiency of such devices is an important task. The paper examines the influence of the power supply voltage on the energy characteristics of the electromagnetic vibration drive and determines the most effective voltage form. To do this, an analysis of factors affecting the efficiency of the drive was carried out. It was found that one of the factors is the time interval between the maximum current and the minimum value of the air gap, and increasing the efficiency is possible by reducing this interval by forming bipolar rectangular voltage pulses with maximum amplitude, which create narrow sharp pulses of the vibrator coil current. As a result of the numerical modeling of the processes in the drive, it was found that with increasing power, current pulses cause short-term deep saturation of steel, which leads to increased losses and reduced efficiency. Therefore, a zero voltage interval was added between the positive and negative voltage pulses, which limits the peak current values. The simulation of the processes in the vibration drive with the voltage supply of the proposed form was carried out, its energy characteristics were calculated: the dependence of the efficiency on the frequency at different load values, the dependence of the maximum values of the efficiency on the power. It was established that the use of pulsed power supply makes it possible to increase the efficiency of the drive up to 80% in the power range from 0.25 of the nominal value to the nominal one, which is on average 10% more compared to sinusoidal voltage. The dependences of frequency and zero voltage interval optimal values (according to the criterion of maximum efficiency) on power, which can be used in automatic control of the drive, have been obtained. References 10, figures 9, tables 2.
Key words: electromagnetic vibration drive, power characteristics, impulse power supply.

Introduction. Vibrating equipment is used in various industries to ensure such technological processes as transportation, separation, compaction of mixtures [1, 2]. The problem of improvement and modernization of such equipment includes many scientific directions. One of them is increasing the energy efficiency of vibration drives, optimizing their parameters and operating modes. Many scientific works are devoted to the improvement of magnetoelectric [3] and electromagnetic [2, 4] vibration drives, which have high controllability, reliability and durability. Modern automatic control systems make it possible to automatically support the operation of such drives in resonant and near-resonant modes, ensuring high energy efficiency. But, to date, the energy characteristics of electromagnetic vibration drives have not been sufficiently studied, which makes it impossible to achieve their maximum efficiency. In particular, the influence of the electromagnet power supply voltage shape on the energy efficiency has not been determined. Therefore, the research in this direction is an important task.

Analysis of previous studies. The electromagnetic drive is very often used in systems where vibration parameters are automatically controlled. At the same time, the electromagnet coil voltage is formed by a semiconductor converter, and the form of the voltage is determined by its scheme, the work algorithm and the control signal. In [4], the processes in the electromagnetic drive of the vibrating conveyor with phase control and with the sinusoidal current half-waves formed by the pulse-width modulation (PWM) were investigated. The authors [4] later note that a thyristor converter with phase control can be used only in cases of a constant load on the working body, since the phase control system does not allow to control the frequency for resonance tuning [5]. Regarding the PWM converter, which forms a sinusoidal current (or semi-wave sinusoid), the work [5] states that the use of a high-frequency PWM signal leads to high energy losses in the converter when switching transistors, as well as in electromagnetic steel. Therefore, [5] proposes a system that forms multi-polar rectangular voltage pulses that provide a current close to triangular. A positive voltage pulse causes the current increase in electromagnet windings as soon as possible. It is

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followed by a negative pulse, which reduces the current to zero. After that there is a zero pause until the next positive voltage pulse comes. The current amplitude is regulated by the width of the voltage pulses, and the frequency − by the duration of the zero pause.

In [4, 5] both simulation and physical modeling of the processes in the drive with the specified forms of voltage and current of electromagnetic vibrators were carried out. However, the energy characteristics of the drive have not been investigated, which does not make it possible to give a justified preference to one or another form of voltage and current from the energy efficiency point of view.

In [6] the energy characteristics of the electromagnetic vibration drive were obtained, taking into account the losses in the copper and steel of the electromagnets, in the frequency converter, and in the elastic elements using the circle-field modeling method. The influence of the load and frequency tuning from the resonant frequency on the value of the efficiency of the drive was studied, the optimal frequency was determined according to the criterion of the maximum efficiency, which is 0.96 of the resonant frequency for the device considered in the work at the nominal load. However, in work [6] only the sinusoidal form of the power supply voltage of electromagnets, formed by high-frequency PWM, has been considered.

The goal of the work. The purpose of this work is to determine the shape of the power supply voltage of the electromagnets, which ensures the maximum efficiency of the electromagnetic vibration drive, and to study its energy characteristics.

Analysis of factors affecting the efficiency of the electromagnetic vibration drive. In work [6] it is shown that the largest share of energy losses in an electromagnetic drive is copper losses, therefore the highest value of efficiency is achieved under conditions when the required amplitude of oscillations is provided by the minimum value of the coil RMS current I_{RMS}. If the oscillation amplitude is automatically maintained by the control system at a given level, the coil RMS current value depends on the required amplitude of the electromagnetic force F_a and the size of the air gap δ_{Imax}, which corresponds to the moments of maximum current. Smaller values of F_a and δ_{Imax} correspond to smaller values of I_{RMS}. Taking into account the amplitude-frequency and phase-frequency characteristics of the mechanical oscillating system, the minimum F_a takes place at the resonance frequency, and δ_{Imax} monotonically increases with increasing frequency, since the phase lag of the oscillations from the electromagnetic force increases. Therefore, as shown in [6], the maximum efficiency does not coincide with the resonant frequency, but it takes place at a frequency that is several percent lower than the resonant one.

In [6] this is explained on the oscillograms of the electromagnetic force, air gap and current (Fig. 2 [6]): at the resonant frequency ($\omega=\omega_r$) for the considered vibrator the maximum force corresponds to the air gap of 1.5 mm, and at a frequency 5% lower ($\omega=0.95\omega_r$) − 1 mm. Therefore, at this frequency, the same amplitude of oscillations is provided by a smaller current, despite the larger amplitude of the electromagnetic force. Let's consider the moments of current maxima. At the resonant frequency they correspond to a gap value of 2.5 mm, and at the frequency of 0.95 of the resonant one − 2 mm. Taking into account that the air gap change range is 0.6..2.6 mm, there is a potential opportunity to increase the efficiency not only due to the selection of the optimal frequency, but also by applying a special form of supply voltage at which the maximum current value will correspond to smaller value of the gap than at the sinusoidal power supply.

To do this, let's analyze in more detail oscillograms of the electromagnetic force, the air gap size and the vibrator coil current calculated in [6] at $\omega=0.95\omega_r$ (Fig. 1). The phase difference between the electromagnetic force and the armature movement at this frequency is about 60°, which corresponds to the time interval Δt_1 between the maximum of the force and the minimum of the air gap. The current reaches a maximum by Δt_2 earlier than the force, because the force continues to increase due to the decrease of the air gap. Therefore, the maximum current leads the minimum value of the air gap by $\Delta t_1 + \Delta t_2$. If this interval is shortened, the maximum current will correspond to a smaller air gap. At constant force amplitude this will lead to the RMS current decrease and, as a result, to the vibrator efficiency increase.

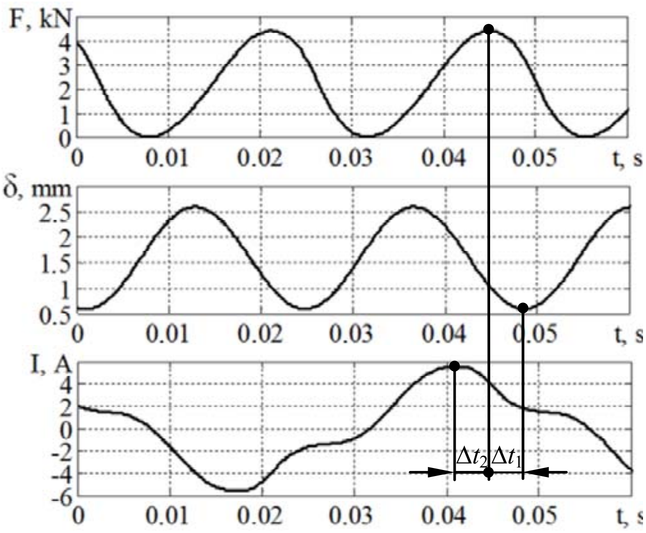

Fig. 1

The interval Δt_1 is determined by the phase difference between the electromagnetic force and the displacement at a given frequency and is practically independent of other factors. Thus, it is possible to bring the maximum current closer to the minimum value of the air gap due to the reduction of the interval Δt_2 between the maximum current and electromagnetic force. To minimize this interval, it is necessary that the current, after reaching the maximum, falls to zero as quickly as possible. This is provided by bipolar rectangular voltage pulses, the amplitude of which is determined by the inverter supply voltage, and the width − by the required current amplitude. This form of supply voltage is proposed in [5] to reduce energy losses in the inverter, but taking into account the above considerations, it will also ensure high efficiency of the vibrator.

Modeling of processes in a vibration drive with pulsed power supply of electromagnets. To calculate the energy characteristics, we will take as a basis the mathematical and simulation models described in [7, 8]. They are created using the circle-field method, which is described in detail in [9], as well as in [10] when applied to a vibration system. In the model proposed in [7], one of the modifications of this method is used. Its essence is that for a number of combinations of fixed positions of the electromagnet armature and fixed values of the direct current in the coil, numerical calculations of the flux linkage ψ and the electromagnetic force F are carried out, after which the functions $IW(\psi,\delta)$ and $F(IW, \delta)$, where IW is the magnetomotive force, δ is the size of the air gap. Then, on the basis of the electromagnet equivalent circuit and the obtained function $IW(\psi,\delta)$, the differential equations of the electric circuit are compiled, taking into account hysteresis and eddy currents. The input values for these equations are the coil voltage and the air gap size δ, so they are solved compatible with the equations of the control system signal transformation and with the equations of the vibrating system mechanics. In work [8] this model is implemented in the form of a circuit in the Simulink environment, built according to the modular principle: the equations of the control system, electromagnetic processes and mechanics are implemented as three interconnected subsystems. This provides convenience for improving and scaling the model.

To take into account the pulse supply voltage it is necessary to give a mathematical description of the voltage form and adjust the expression for losses in the inverter.

Equations of bipolar rectangular pulses described in [5] with frequency ω and relative width h can be obtained as a result of performing the following mathematical operations:

$$s_1(t) = \text{sign}\left(\sin\frac{1}{2}\omega t\right); \qquad s_2(t) = \frac{\omega}{\pi}\int s_1(t)dt - 1; \qquad s_3(t) = |s_2(t)|; \qquad (1)-(3)$$

$$s_4(t) = \begin{cases} 1 \text{ if } s_3(t) \le h; \\ 0 \text{ if } s_3(t) > h; \end{cases} \qquad s_5(t) = -\text{sign}\left(\frac{ds_3}{dt}\right)\cdot s_4(t); \qquad u(t) = U_{\max}\, s_4(t), \qquad (4)-(6)$$

where $U_{\max}$ is the maximum voltage at the output of the inverter.

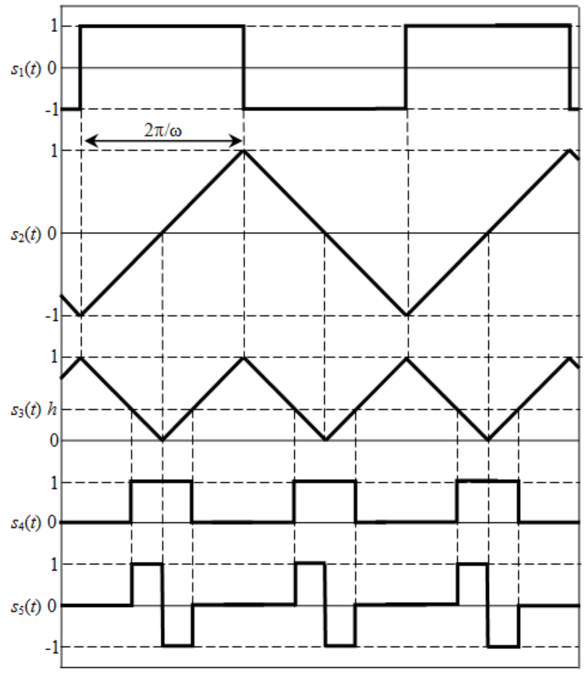

Fig. 2

Time diagrams of signals during the generation of voltage pulses $s_1(t)...s_5(t)$ are shown in Fig. 2.

In [6], the formula for power losses in a transistor inverter with a sinusoidal output voltage generated using PWM is given. This formula can also be used for the rectangular shape of the voltage, replacing the PWM frequency with the current frequency:

$$P_{inv} = 2I_{av}\cdot\left(\frac{U_d\omega}{I_{st}U_{st}\cdot 2\pi}(E_{on}+E_{off}+E_{rec}) + \frac{1}{2}(U_{CE}+U_{IF})\right), \qquad (7)$$

where I_{av} is the average value of the inverter output current module; U_d is the average value of the inverter input voltage; f_{PWM} is the frequency of the pulse width modulation (PWM) signal; E_{on}, E_{off} and E_{rec} are, respectively, turn-on, turn-off and diode reverse recovery energy losses at the standard voltage and current values U_{st} and I_{st}, which are given in the datasheet; U_{CE} is the collector-to-emitter saturation voltage; U_{IF} is the inverter diode forward voltage drop.

In the simulation model used in [8], the supply voltage of the vibrators is generated in the "Control System" subsystem. It includes, in particular, amplitude and frequency regulators, which determine, respectively, the amplitude and frequency of the supply voltage, and its form is determined by the "sin" block. In order for a pulsed voltage to be generated instead of a sinusoidal voltage, we replace the "sin" block with a block for generating rectangular pulses with a width h set by the amplitude regulator and a frequency ω set as a constant (Fig. 3). The structure of this block for forming voltage pulses (Fig. 4) is formed on the basis of equations (1) - (6).

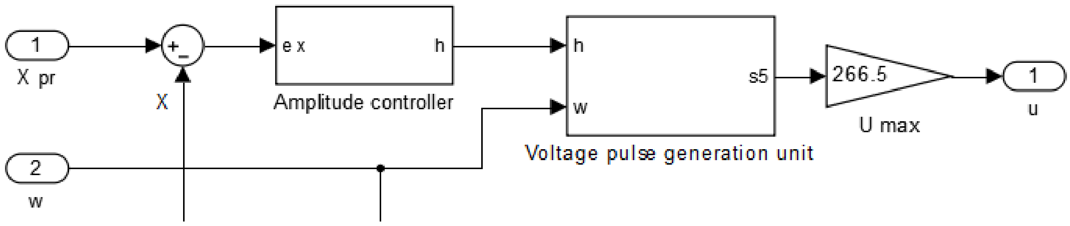

Fig. 3

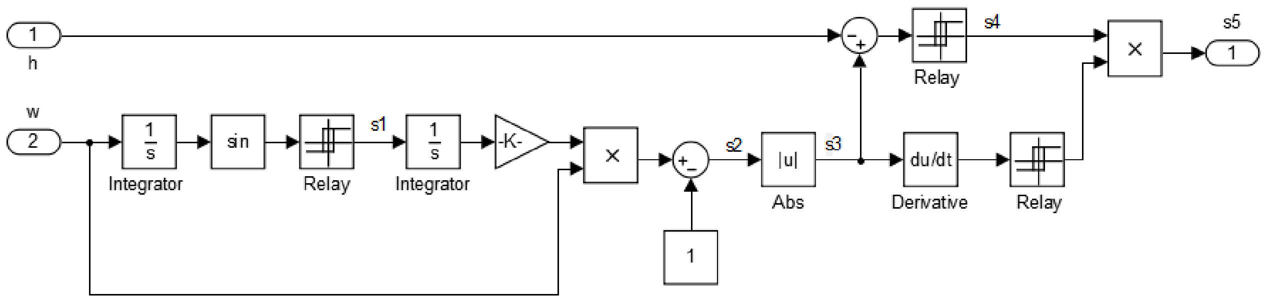

Fig. 4

To the "Electromagnetic System of Vibrator" subsystem, we add a unit for calculating of the drive loss components and its efficiency, which includes the expressions given in [6], as well as formula (7) for calculating losses in the inverter.

By means of the updated simulation model, the time diagrams of voltage, current, air gap and other values, as well as the values of loss the components and the drive efficiency, for different output power values, were calculated. In order for the results to be compared with the case of sinusoidal voltage, the parameters of the drive considered in [6] were taken, the main ones are given in Table 1.

Table 1

Mechanical parameters of the vibration device		**Electromagnetic vibrator parameters**		
Nominal output power of the drive P_{out}, W	250	Number of the electromagnets n_{elmagn}		2
Nominal vibration amplitude X, mm	0.5	Number of the electromagnet coil turns W		800
Resonance frequency f_r, Hz	44.312	Connection of the coils		parallel
Mass of the moving part m, kg	129	The initial value of the air gap size δ, mm		1.8
Total stiffness of the vibrator springs c, N/m	10^7	Active resistance of the electromagnet coil R, Ohm		2.8
Coefficient of viscous friction in vibrator springs b, N·s/m	100	Parameters of the electromagnet equivalent circuit [7], characterizing losses in steel, kΩ	$R^*_{e.c}$	65.5
			$R^*_{h.st}$	151.5
Frequency converter parameters		Electrical steel		3413
The average value of the inverter input voltage U_d, V	270	The shape of the core and of the armature		U
Total energy losses when opening and closing the transistor and restoring the inverter diode (at a current of 10 A and a voltage of 400 V) $E_{on}+E_{off}+E_{rec}$, μJ	575	Length of the core and of the armature, mm		50
PWM frequency f_{PWM}, kHz	8	Core height, mm		71
Collector-to-emitter saturation voltage U_{CE}, V	1.75	Armature height, mm		58
Inverter diode forward voltage drop U_{IF}, V	1.9	Pole width, mm		24
Rectifier diode forward voltage drop U_R, V	0.8	Distance between poles, mm		41
Active reactor resistance R_r, Ohm	0.2			

At the same time, the current frequency was set, which, according to [6], is optimal according to the maximum efficiency criterion for the corresponding power value. The obtained oscillograms and the corresponding efficiency values for different powers are shown in Fig. 5. Here we can see that for the power of 0.5 and 0.75 of the nominal one, drive efficiency is 13% and 7% higher, respectively, than with a sinusoidal power supply. But, when the power increases to the nominal one, the efficiency is reduced significantly. This is due to the increase in peak current values due to saturation of the vibrator steel (Fig. 5).

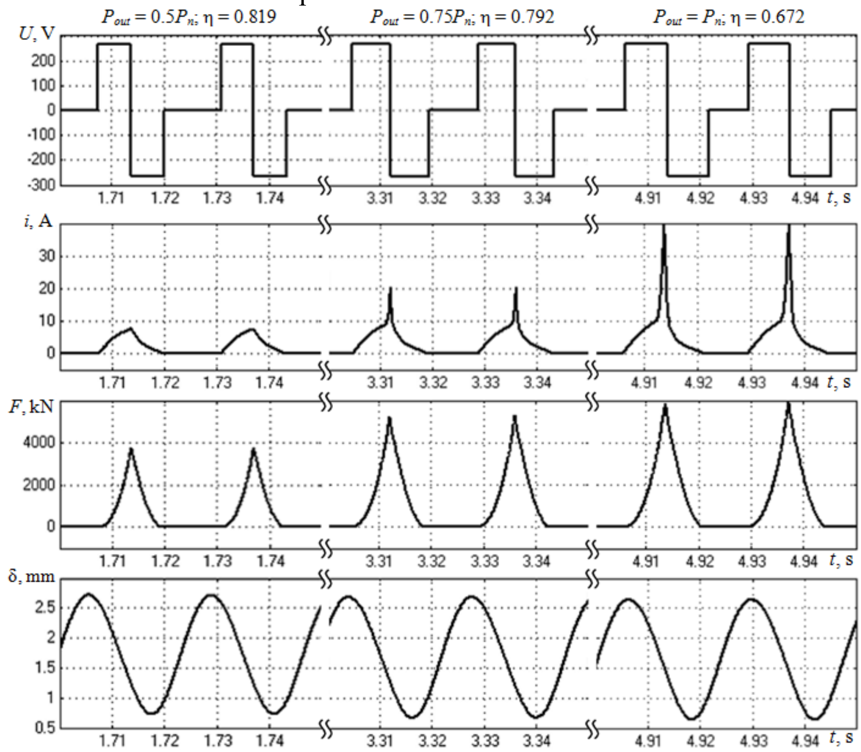

Fig. 5

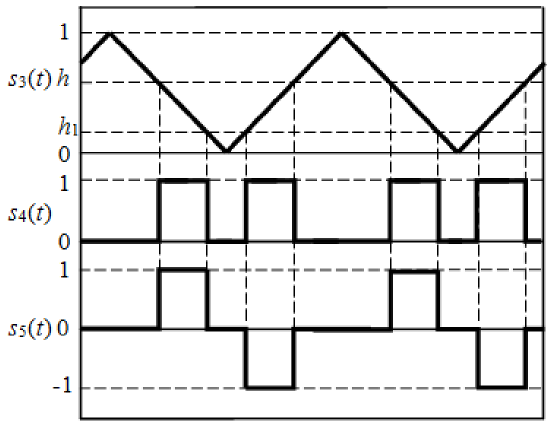

Fig. 6

Modeling of processes in the vibration drive when there is a zero voltage interval between positive and negative pulses of the supply voltage. To avoid a drop in efficiency due to steel saturation, it is necessary to limit the maximum current value by increasing the width of its pulses. To do this, it is necessary to use a zero voltage interval with a relative width h_1 between positive and negative voltage pulses (Fig. 6). Mathematically, this can be described by adjusting expression (4):

$$s_4(t) = \begin{cases} 1 \text{ if } h_1 \le s_3(t) \le h; \\ 0 \text{ if } (s_3(t) > h) \vee (s_3(t) < h_1). \end{cases} \tag{8}$$

Thus, the new voltage form is described by equations (1) – (3), (8), (5), (6).

When using a bridge transistor inverter, the zero voltage interval h_1 is implemented by forming a high-frequency PWM signal with a fill factor of 0.5. Therefore, power losses in the inverter should be calculated according to the formula:

$$P_{inv} = 2I_{av} \cdot \left(\frac{U_d}{I_{st}U_{st}} \left(h_1 f_{PWM} + (1-h_1)\frac{\omega}{2\pi} \right)(E_{on} + E_{off} + E_{rec}) + \frac{1}{2}(U_{CE} + U_{IF}) \right), \tag{9}$$

where f_{PWM} is the PWM frequency.

After making appropriate adjustments to the simulation model, we obtain the calculation results shown in Fig. 7 – oscillograms of processes when using supply voltage with a zero interval between positive and negative pulses. The h_1 value for each power value was selected in such a way as to ensure the maximum efficiency value.

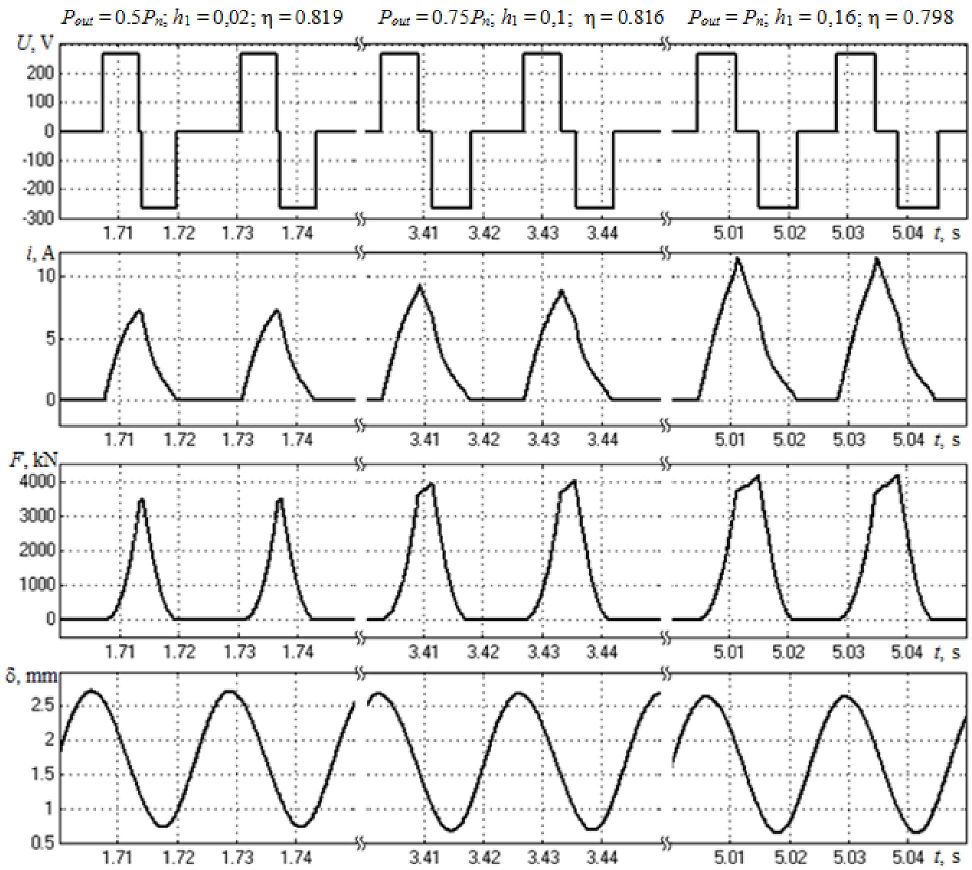

Fig. 7

The obtained results show that using of a zero voltage interval made it possible to reduce the peak values of the current and to avoid a significant decrease in efficiency when the drive power increases.

There are the dependences of the drive efficiency on the frequency for different values of the output power in fig. 8. Comparing them with similar dependencies obtained in [6] for a sinusoidal supply voltage, the following conclusions can be drawn:

− the value of efficiency when supplied with voltage in the form of rectangular pulses with optimal parameters is significantly higher: the increase in efficiency is from 8% to 16%, depending on the load;

− efficiency maxima are observed at almost the same frequencies as with sinusoidal power supply.

In fig. 9 the dependence of the maximum efficiency on power are shown. For comparison, the dotted line shows the corresponding dependence for a sinusoidal supply voltage. Graphs of dependences of optimal frequency values (according to the criterion of maximum efficiency) and zero interval h_1 on power, also obtained for this drive, are shown below. Similar characteristics can be obtained for any electromagnetic vibration drive and used in control to ensure maximum energy efficiency under changing load conditions.

Table 2 shows the values of the loss components and the efficiency of the electromagnetic drive for different values of the output power at the optimal values of the frequency and zero voltage interval h_1.

The obtained data indicate that the increase in efficiency is achieved mainly due to the reduction of losses in the vibrator coil, which for the power range of $0.5P_n…P_n$ make up more than half of the total energy losses in the drive. Their decrease is caused by the decrease in the RMS current at the same output power. Moreover, for a lower load, we observe a much greater decrease in losses in copper, since the zero voltage interval is almost absent, and the maximums of current and electromagnetic force practically coincide (Fig. 7). Thus, for the nominal load, the losses in the winding are reduced by one and a half times, and at half of the nominal load − more than twice.

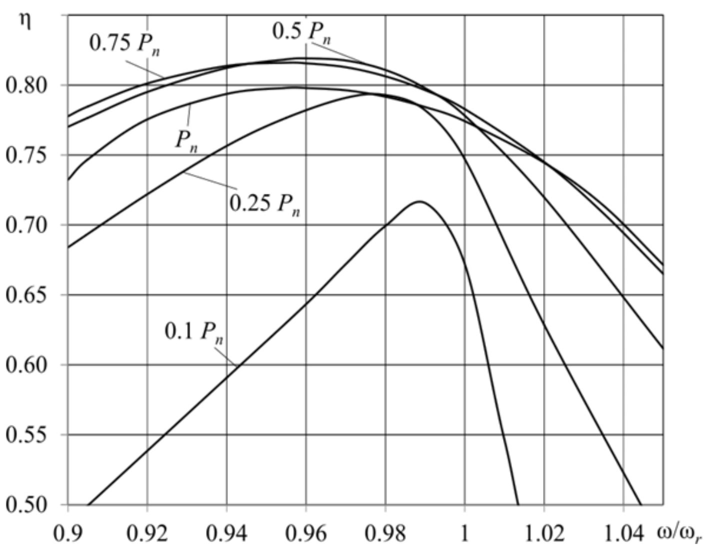

Fig. 8

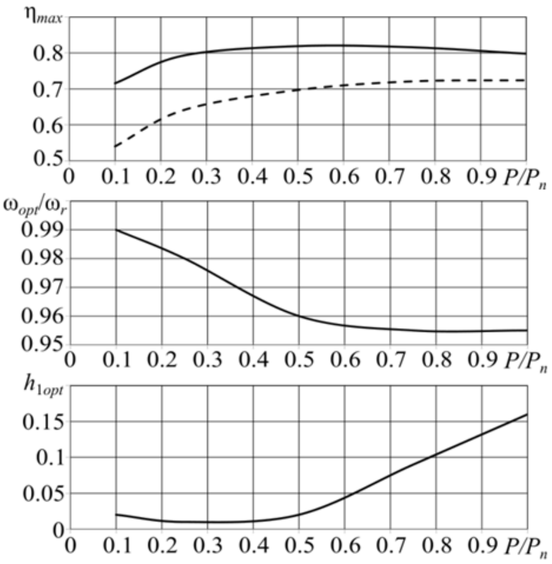

Fig. 9

Table 2

Relative drive output power P_{out}/P_n		0.1	0.25	0.5	0.75	1
The resulting efficiency of the drive η		0.716	0.793	0.819	0.816	0.798
Frequency converter efficiency η_{conv}		0.924	0.937	0.944	0.946	0.944
The efficiency of the vibrator η_{mot}		0.775	0.846	0.868	0.863	0.845
Drive output power P_{out}, W		24.97	62.45	125	187.5	250
Losses in the inverter P_{inv}, W		2.378	4.315	7.161	10.28	14.18
Losses in the rectifier P_{rect}, W		0.281	0.634	1.228	1.848	2.518
Losses in the reactor P_r, W		0.009	0.047	0.177	0.4	0.743
Losses in the vibrator coil P_{Cu}, W		2.418	6.213	13.75	25.35	40.26
Hysteresis losses P_h, W		0.33	0.452	0.573	0.591	0.614
Eddy current losses, W	Low-frequency component $P_{e.c.LF}$	0.67	0.909	1.127	1.158	1.203
	High-frequency component $P_{e.c.HF}$	0.028	0.014	0.028	0.126	0.224
Losses in the vibrator springs P_{spr}, W		3.799	3.722	3.572	3.535	3.535

A significant impact on the drive efficiency is also exerted by the reduction of losses. The reduction of losses in the inverter also has a significant impact on the drive efficiency. They decrease mainly due to the reduction of the high-frequency PWM signal duration: it takes place only during the zero interval h_1. Since its value increases with increasing load (to avoid deep saturation of steel), we have a greater reduction of losses in the inverter at small power values: for the nominal output power, they decrease by 1.6 times, and for half of the nominal − by 2.3 times.

A decrease in the duration of the voltage with the PWM frequency also causes a decrease by an order of magnitude in the high-frequency component of the eddy currents. Therefore, despite some increase in hysteresis losses at low loads, the total losses in the vibrator steel decreased by approximately 1.5 times.

Rectifier and reactor losses also decreased, but only slightly. Losses in the vibrator springs remained practically unchanged.

Conclusions. The highest efficiency of the electromagnetic vibration drive is achieved when feeding the vibrator coils with voltage in the form of bipolar rectangular pulses, the amplitude of which is determined by the inverter supply voltage, and their width is determined by the required current amplitude. To prevent deep saturation of the vibrator steel, it is necessary to limit the peak value of the current by using a zero voltage interval between the positive and negative pulses. The results of numerical simulation of the processes in the drive using the circuit-field method showed that the use of pulsed power supply makes it possible to increase the drive efficiency up to 80% in the power range from 0.25 of nominal power to the nominal one. This is on average 10% more compared to a sinusoidal voltage. The obtained dependences of the frequency and zero voltage interval values optimal according to the maximum efficiency criterion on the drive power can be used for control to provide maximum energy efficiency under conditions of load changes.

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ЕНЕРГЕТИЧНІ ХАРАКТЕРИСТИКИ ЕЛЕКТРОМАГНІТНОГО ВІБРАЦІЙНОГО ПРИВОДА ЗА ІМПУЛЬСНОГО ЖИВЛЕННЯ ОБМОТОК ВІБРАТОРА

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Вібраційне обладнання забезпечує різні технологічні процеси, такі як транспортування, сепарація, ущільнення сумішей. Електромагнітний привод зазвичай використовується у вібраційних конвеєрах, живильниках та інших пристроях, де здійснюється автоматичне керування параметрами вібрації. Підвищення енергетичної ефективності таких пристроїв є актуальною задачею. В роботі досліджено вплив форми напруги живлення на енергетичні характеристики електромагнітного вібраційного привода та визначено найефективнішу форму напруги. Для цього було проведено аналіз факторів, що впливають на ККД привода. Виявлено, що одним з факторів є часовий інтервал між максимумом струму та мінімумом величини повітряного проміжку, а підвищення ККД можливе за рахунок зменшення цього інтервалу шляхом формування двополярних прямокутних імпульсів напруги з максимальною амплітудою, які створюють вузькі гострі імпульси струму обмотки вібратора. В результаті чисельного моделювання процесів у приводі виявлено, що у разі збільшення потужності імпульси струму викликають короткочасне глибоке насичення сталі, яке призводить до збільшення втрат і зменшення ККД. Тому, між позитивним та від'ємним імпульсами напруги було додано нульовий проміжок, що обмежує пікові значення струму. Проведено моделювання процесів у вібраційному приводі у разі живлення напругою запропонованої форми, розраховано його енергетичні характеристики: залежності ККД від частоти за різних величинах навантаження, залежність максимальних значень ККД від потужності. Встановлено, що застосування імпульсного живлення дає можливість підвищити ККД привода до 80% у діапазоні потужностей від 0.25 від номінальної до номінальної, що в середньому на 10% більше у порівнянні з синусоїдальною напругою. Отримано залежності оптимальних за критерієм максимуму ККД значень частоти та нульового проміжку від потужності, які можуть бути використані у разі автоматичного керування приводом. Бібл. 10, рис. 9, табл. 2.

Ключові слова: електромагнітний вібраційний привод, енергетичні характеристики, імпульсне живлення.

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