Scholarly Publisher
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ISNI: 0000 0004 8495 2390

Dolna 17, Warsaw, Poland 00-773
Tel: +48 226 0 227 03
Email: editorial_office@rsglobal.pl

JOURNAL	World Science
p-ISSN	2413-1032
e-ISSN	2414-6404
PUBLISHER	RS Global Sp. z O.O., Poland

ARTICLE TITLE	THE SYSTEM OF FORMING THE CONTROL MODE OF THE ELECTRIC DRIVE DURING THE START-UP OF THE VIBRATION MACHINE
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ARTICLE INFO	Nozhenko Viktoriia, Bialobrzheskyi Olexii, Rodkin Dmytro, Druzhynina Viktoriia, Yakymets Serhii. (2021) The System of Forming the Control Mode of the Electric Drive During the Start-Up of the Vibration Machine. World Science. 7(68). doi: 10.31435/rsglobal_ws/30072021/7639
DOI	https://doi.org/10.31435/rsglobal_ws/30072021/7639
RECEIVED	23 May 2021
ACCEPTED	21 July 2021
PUBLISHED	27 July 2021
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THE SYSTEM OF FORMING THE CONTROL MODE OF THE ELECTRIC DRIVE DURING THE START-UP OF THE VIBRATION MACHINE

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DOI: https://doi.org/10.31435/rsglobal_ws/30072021/7639

ARTICLE INFO

Received: 23 May 2021
Accepted: 21 July 2021
Published: 27 July 2021

KEYWORDS

control system, induction motor, above resonance vibration machine, starting mode, resonance zone.

ABSTRACT

The above resonance vibration machines are widely used in various industries, but have a number of shortcomings associated with increasing of the oscillations amplitude when passing the resonance zone during start-up. It is noted that to reduce the oscillations amplitude and quickly pass the resonance zone, it is advisable to use a frequency-controlled electric drive with the formation of additional control effects. Features of frequency start of the electric drive of the vibration machines are noted. The structure of the electric drive control system during passing the resonance zone in the process of starting the above resonance vibration machine in the form of a block-scheme is proposed. The algorithm of operation of the control system is given.

Citation: Nozhenko Viktoriia, Bialobrzheskyi Olexii, Rodkin Dmytro, Druzhynina Viktoriia, Yakymets Serhii. (2021) The System of Forming the Control Mode of the Electric Drive During the Start-Up of the Vibration Machine. *World Science.* 7(68). doi: 10.31435/rsglobal_ws/30072021/7639

Introduction. The above resonance vibration machines (VM) are widely used in construction, mining, engineering, metallurgy and other industries, where the stability of the equipment functioning is required when changing the load during operations such as transportation of bulk cargo, compression of concrete mixtures, crushing of rocks, abrasives, etc. [1, 2]. Such VM are usually equipped with unbalance vibration exciters, are large and powerful. As you know, the main problem of this type VM is to pass the resonance zone during the start-up, because most of VM shortcomings are related to this [2–6]. To partially solve this problem, in practice, it is used the unregulated induction motor drive with 2–5 times high capacity of drive motors. This solution allows you quickly overcome the resonance zone, but leads to low energy performance compared to the electromagnetic drive of vibration device [7]. In this regard, a number of ways have been developed to reduce the amplitude of oscillations of VM actuating device during passing the resonance zone both by upgrading the mechanical part of VM and with the help of electric drive systems. However, the analysis of existing methods, which is given in [8], allowed to identify shortcomings that prevent their widespread use, namely insufficient reliability, high cost, sensitivity to errors in determining the parameters of the oscillating system, the possibility of using only to VM start with self-synchronizing, unconnected among themselves unbalance vibrating exciters, lack of control exit to the resonance mode. In the writings [8, 9], to reduce the amplitude of oscillations of VM actuating device during passing the resonance zone, it is offered the use of a frequency-controlled electric drive. This solution allows turning off the possible "jamming" of the drive motors rotors and reduces the dynamic loads on VM structural elements when using motors with the power required operating in the technological operating mode. Therefore, for wide application of this method to the above resonance VM of various purposes, a timely and urgent task is to build a control system for starting the electric drive of VM, taking into account the peculiarities of passing the resonance zone.

The objective of the work is to develop the structure of the electric drive control system of the above resonance vibration machine during passing of the resonance zone during start-up.

Research and results. In designing the structure of the control system of the electric drive of the above resonance VM, it is important to take into account the peculiarities of the behavior of oscillating systems during passing the resonance zone during start-up, which include [2–4, 10]:

– the maximum value of the oscillations amplitude is observed a little later than the moment of compliance of the frequency of forcing oscillations with the natural frequency of the oscillating system;

– the greater the acceleration of the drive affects the oscillating system, the smaller will be its oscillations amplitude, which corresponds to the resonance value;

– a vibration moment occurs when the actuating device of VM oscillates, which creates the additional load on the rotors of the drive motors and has a resonance character.

In [8, 9], the studies of VM start-up using frequency-controlled electric drive were carried out taking into account the above-mentioned features of VM behavior during passing the resonance zone. The analysis of these researches allowed defining the following requirements to frequency start of VM electric drive for maintenance of guaranteed passing of the resonance zone without "jamming" of drive motors rotors:

– starting of drive motors must be carried out with the law of frequency control $U/f = const$;

– the frequency sweep time should be chosen to ensure that the resonance zone is pass with maximum acceleration;

– when approaching the resonance zone, the supply voltage of the drive motors must be increased abruptly to exceed the dynamic torque of the motor over the vibration moment.

To implement the frequency start-up of VM electric drive, taking into account the above requirements, the structure of the above resonance VM electric drive control system in the form of a block-scheme is proposed (Fig. 1). In Fig. 1 is defined: VM – vibration machine; IM – induction motor with short-circuited rotor; QF – circuit breaker; FBR – full bridge rectifier; C – capacitor; I – inverter; SU – sensor unit, which includes current sensor and voltage sensor; L – choke; IPCU – instantaneous power calculation unit; APCU – active power calculation unit; PAU – power approximation unit; EDU – extremum detection unit; EDCU – electric drive control unit; SDU – slip detection unit; UFTM – unit of formation of a technological mode; VCU – voltage calculation unit; ICU – inverter control unit; U_{ABC} – amplitude value of supply voltage of IM; ω_{op} – angular idle rotation rate of IM; ω_{ref} – set value of angular rotation rate of IM in the technological mode; u_{ABC} – instantaneous values of the stator phase voltage A, B, C of IM; i_{ABC} – instantaneous values of the stator phase current A, B, C of IM; p – instantaneous power; s – slip; P – active power; ΔP – approximate active power; ΔP_e – greater extremum of the approximated active power; ΔU – magnitude of the supply voltage, which is an abrupt increasing; U_{ABC}^{ref} – set amplitude value of the supply voltage of IM; U_i – inverter control pulse voltage. A vibration platform with unbalance vibrating exciters was chosen as VM, which is used for compression of concrete mixtures in the form of.

The algorithm for controlling the start-up of the electric drive of the above resonance VM is shown in Fig. 2. The operation of the control system begins with the entry of IM rated values and the calculation of its replacement scheme. With the help of UFTM unit (Fig. 1) the amplitude value of IM supply voltage of (U_{ABC}), the angular idle rotation rate of IM (ω_{op}) and angular rotation rate of IM in the technological mode (ω_{ref}) are entered. And after that, the start-up of VM IM starts with the frequency control law $U/f = c_1$ and the set value of the frequency sweep time.

Next, the important step in the process of VM start-up is timely determination of the moment when it is necessary to abruptly increase the supply voltage.

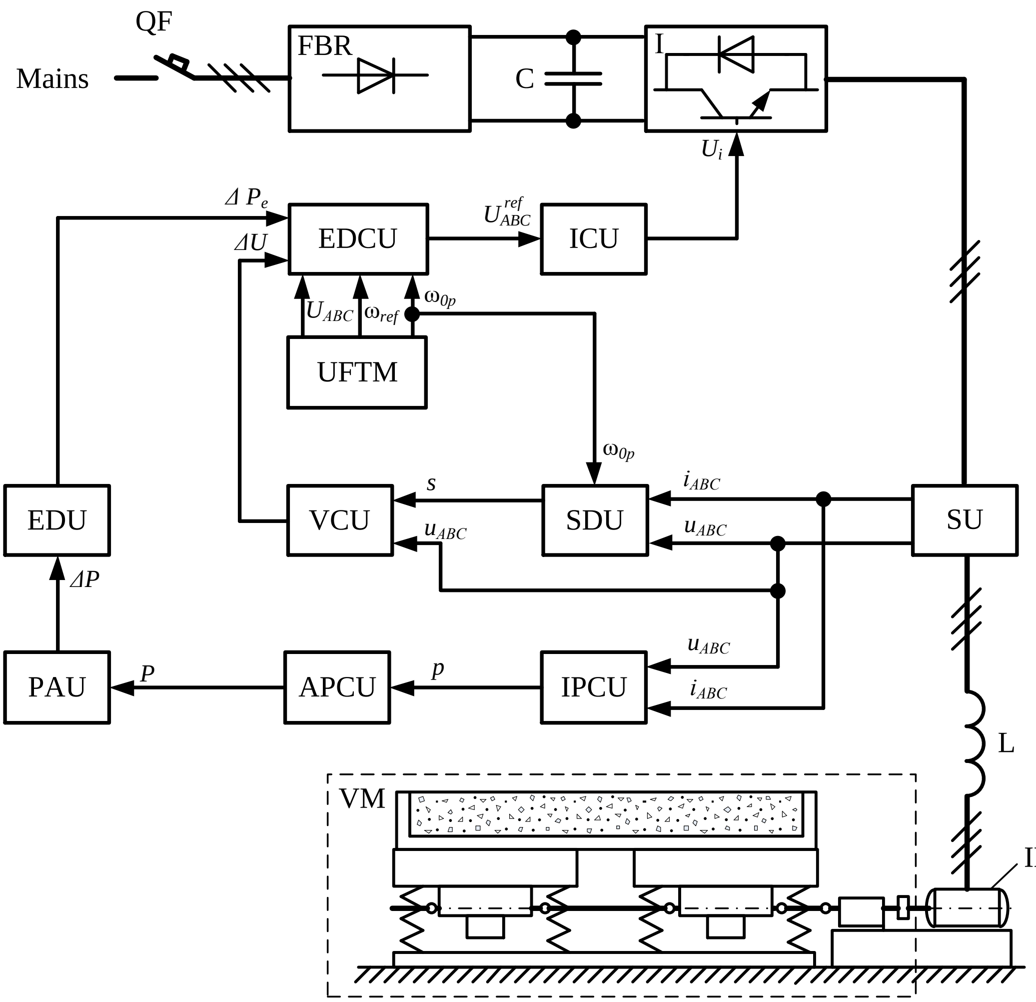


Fig. 1. Block-scheme of the control system for starting the electric drive of the above resonance vibration machine

In the writings [8, 9], it is proposed to perform the abrupt increase in the supply voltage when IM supply frequency is equal to the resonance frequency of VM. However, it is advisable to apply this solution to VM with a predetermined resonance frequency. Since in practice, usually the mass of the treated medium on VM can vary, which will affect the value of the resonance frequency of the entire oscillating system, so to effectively pass the resonance zone, the moment of abrupt increase in supply voltage must be determined regardless of VM parameters.

In the proposed control system (Fig. 1), the moment when it is necessary to abruptly increase the supply voltage is determined by the greater extremum of the active power of IM, which indicates the entrance to the resonance zone [4]. To do this, simultaneously with the start-up of IM begins the measurement of the instantaneous values of voltage (u_{ABC}) and current (i_{ABC}) of the stator phases A, B, C of IM in SU (Fig. 1). Next, in IPCU, the instantaneous power (p) is calculated according to the equation:

$$p = u_A i_A + u_B i_B + u_C i_C \,. \qquad (1)$$

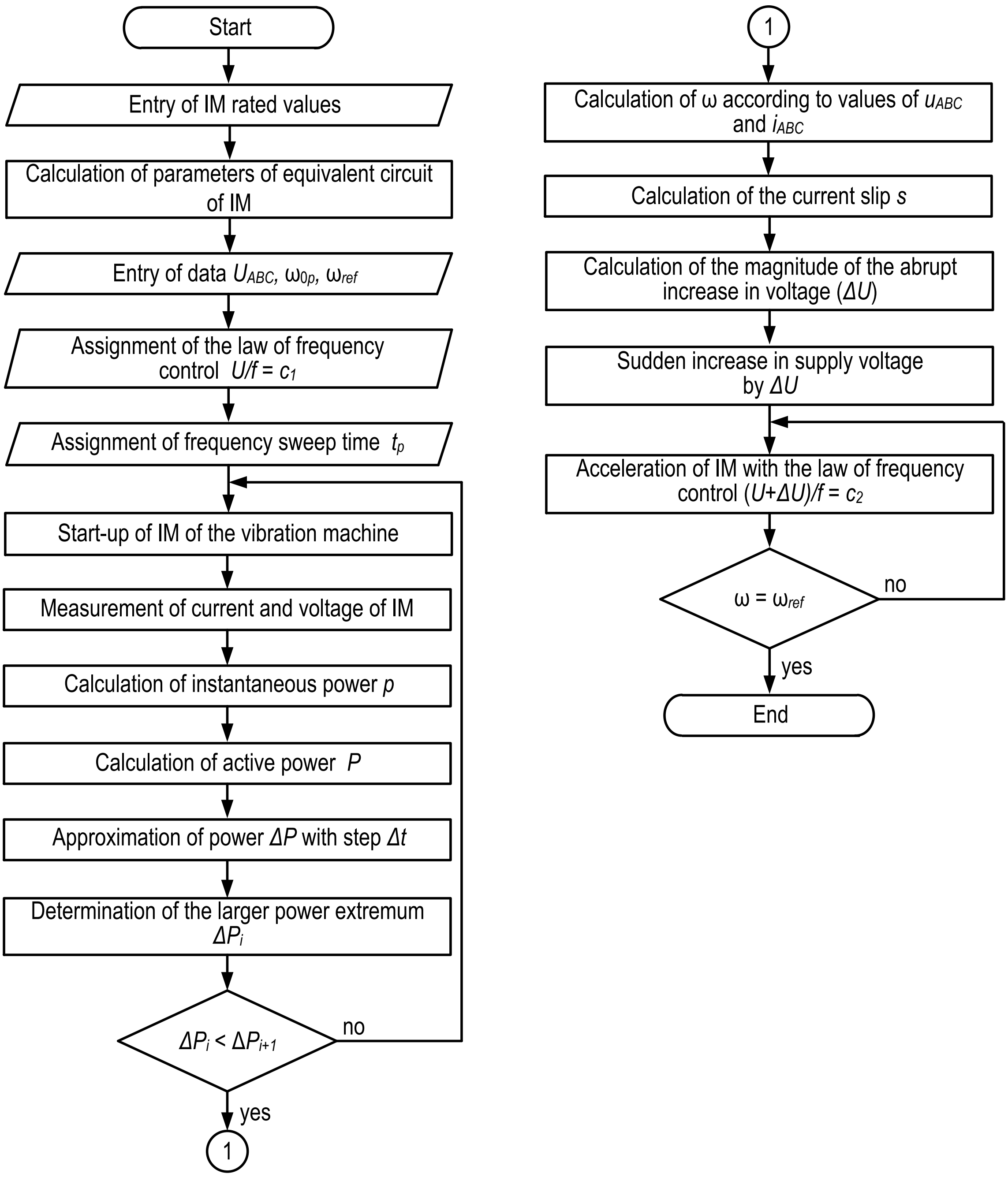


Fig. 2. Algorithm for controlling the start-up of the electric drive of the above resonance vibration machine

The active power is determined in APCU.

$$P = \frac{1}{T}\int_0^T p(t)dt\,, \tag{2}$$

where T – period; t – time.

After calculating the active power, it is approximation (ΔP) in PAU (Fig. 1) with a step Δt and the larger extremum of the approximated active power in EDU is measured by comparing the value of the approximated active power at the point i (ΔP_i) with the value of the approximated active power in the point i+1 (ΔP_{i+1}) (Fig. 2). If the condition $\Delta P_i < \Delta P_{i+1}$ is met, the next step is to determine the magnitude of the amplitude of the supply voltage (ΔU), which is necessary to make the abrupt increase. To do this, the value of the current slip according to the formula is calculated in SDU

$$s = \frac{\omega_{0p} - \omega}{\omega_{0p}}, \tag{3}$$

where ω – the current value of angular idle rotation rate of IM is determined by the instantaneous values of voltage (u_{ABC}) and current (i_{ABC}) of the stator phases A, B, C of IM according to known methods [11].

After calculating the current slip, the value of the amplitude of the supply voltage ΔU is determined, by which it is necessary to make the abrupt increase according to the equation:

$$\Delta U = U' - U_m, \tag{4}$$

where U' – the value of the amplitude of the supply voltage of the IM at start-up current; U_m – the current value of the amplitude of the supply voltage.

The value of the supply voltage of the induction motor at start-up current is determined by the equation:

$$U' = I_n \sqrt{\left(r_1 + \frac{r_2'}{s}\right)^2 + \left(x_1 + x_2'\right)^2}\,. \tag{5}$$

where I_n – start-up current of IM; r_1 – stator active resistance of IM; r'_2 – reduced to the stator winding rotor resistance of IM; x_1 – inductive stator resistance of IM; x'_2 – inductive resistance of the rotor of IM reduced to the stator winding.

The current value of the supply voltage amplitude assuming it is symmetrical is determined by the equation:

$$U_m = \frac{\pi}{2T}\int_0^T |u_A| dt\,, \tag{6}$$

where u_A – instantaneous value of the voltage of phase A of the stator of IM.

After determining ΔU there is the abrupt increase in the supply voltage of IM by the value of ΔU and further acceleration of the motor is carried out with the law of frequency control $(U + \Delta U) / f = c_2$. The next step is to compare the current value of angular rotation rate of IM (ω) with its specified value (ω_{ref}). If the condition $\omega = \omega_{ref}$ (Fig. 2) is met, then IM goes into operation technological mode.

The frequency start checking of the electric drive of the above resonance VM according to the proposed algorithm (Fig. 2) was carried out using mathematical modeling. As the VM considered the above resonance vibration platform with a load capacity of 9.8 tons of block structure with two-shaft unbalanced vibration exciters. The mathematical model of the vibration platform consists of two parts: electrical and mechanical. The electrical part includes a frequency converter and two IM with a short-circuited rotor. Mathematical description of the frequency converter was carried out according to equations [12]. The mathematical model of IM was built in a three-phase coordinate system according to [13].

The system of equilibrium equations for the stator and rotor circuits is described as

$$\begin{cases} u_A = i_A R_A + \dfrac{d\psi_A}{dt}; \\ u_B = i_B R_B + \dfrac{d\psi_B}{dt}; \\ u_C = i_C R_C + \dfrac{d\psi_C}{dt}, \end{cases} \qquad \begin{cases} 0 = i_a R_a + \dfrac{d\psi_a}{dt}; \\ 0 = i_b R_b + \dfrac{d\psi_b}{dt}; \\ 0 = i_c R_c + \dfrac{d\psi_c}{dt}, \end{cases} \tag{7}$$

where u_A, u_B, u_C – instantaneous voltage values of the stator phases A, B, C, respectively; i_A, i_B, i_C – currents of three phases of the stator A, B, C, respectively; i_a, i_b, i_c – currents of three phases of the rotor a, b, c, respectively; R_A, R_B, R_C – active supports of the three phases of the rotor a, b, c, respectively; R_a, R_b, R_c – active supports of the three phases of the rotor a, b, c, respectively; ψ_A, ψ_B, ψ_C – complete flux couplings of the three phases of the stator A, B, C, respectively; ψ_a, ψ_b, ψ_c – complete flux couplings of the three phases of the rotor a, b, c, respectively.

The complete flux coupling of the stator and rotor phases is determined by the expressions:

$$\psi_A = \left(l_1 + \frac{2}{3} L_1 \right) i_A + \frac{2}{3} L_1 \cos(\rho)\, i_B + \frac{2}{3} L_1 \cos(2\rho)\, i_C +$$
$$+ \frac{2}{3} L_\mu \cos(\rho \gamma_R) i_a + \frac{2}{3} L_\mu \cos(\rho \gamma_R + \rho) i_b + \frac{2}{3} L_\mu \cos(\rho \gamma_R - \rho) i_c;$$
$$\psi_B = \frac{2}{3} L_1 \cos(\rho)\, i_A + \left(l_1 + \frac{2}{3} L_1 \right) i_B + \frac{2}{3} L_1 \cos(\rho)\, i_C +$$
$$+ \frac{2}{3} L_\mu \cos(\rho \gamma_R - \rho) i_a + \frac{2}{3} L_\mu \cos(\rho \gamma_R) i_b + \frac{2}{3} L_\mu \cos(\rho \gamma_R + \rho) i_c;$$
$$\psi_C = \frac{2}{3} L_1 \cos(\rho)\, i_A + \frac{2}{3} L_1 \cos(\rho)\, i_B + \left(l_1 + \frac{2}{3} L_1 \right) i_C +$$
$$+ \frac{2}{3} L_\mu \cos(\rho \gamma_R + \rho) i_a + \frac{2}{3} L_\mu \cos(\rho \gamma_R - \rho) i_b + \frac{2}{3} L_\mu \cos(\rho \gamma_R) i_c;$$
$$\psi_a = \left(l_2 + \frac{2}{3} L_2 \right) i_a + \frac{2}{3} L_2 \cos(\rho)\, i_b + \frac{2}{3} L_2 \cos(2\rho)\, i_c +$$
$$+ \frac{2}{3} L_\mu \cos(\rho \gamma_R) i_A + \frac{2}{3} L_\mu \cos(\rho \gamma_R - \rho) i_B + \frac{2}{3} L_\mu \cos(\rho \gamma_R + \rho) i_C; \tag{8}$$
$$\psi_b = \frac{2}{3} L_2 \cos(\rho)\, i_a + \left(l_2 + \frac{2}{3} L_2 \right) i_b + \frac{2}{3} L_2 \cos(2\rho)\, i_c +$$
$$+ \frac{2}{3} L_\mu \cos(\rho \gamma_R + \rho) i_A + \frac{2}{3} L_\mu \cos(\rho \gamma_R) i_B + \frac{2}{3} L_\mu \cos(\rho \gamma_R - \rho) i_C;$$
$$\psi_c = \frac{2}{3} L_2 \cos(2\rho)\, i_a + \frac{2}{3} L_2 \cos(\rho)\, i_b + \left(l_2 + \frac{2}{3} L_2 \right) i_c +$$
$$+ \frac{2}{3} L_\mu \cos(\rho \gamma_R - \rho) i_A + \frac{2}{3} L_\mu \cos(\rho \gamma_R + \rho) i_B + \frac{2}{3} L_\mu \cos(\rho \gamma_R) i_C,$$

where L_1, L_2 – inductance of self-induction of the stator and rotor phases, respectively; l_1, l_2 – scattering inductance of the stator and rotor phases, respectively; $\rho = \frac{2\pi}{3}$ – phase shift between the stator (rotor) windings; L_μ – the maximum value of the inductance of mutual induction between the phase of the stator and rotor; $\gamma_R(t) = \int \omega(t) dt$ – rotor rotation angle.

The expression for calculating the electromagnetic moment has the form:

$$M_{em} = \frac{1}{\sqrt{3}} p L_\mu \left(i_A \left(i_{\mu B} - i_{\mu C} \right) + i_B \left(i_{\mu C} - i_{\mu A} \right) + i_C \left(i_{\mu A} - i_{\mu B} \right) \right), \tag{9}$$

where p – the number of pole pairs; $i_{\mu A}$, $i_{\mu B}$, $i_{\mu C}$ – magnetizing currents of the stator phases.

The mechanical part of the VM mathematical model is described by a system of differential equations, which is given in [14]:

$$m_{pl} x'' + b_x x' + c_x x = m_1 r_1 \left(\phi_1'' \sin \phi_1 + \phi_1'^2 \cos \phi_1 \right) - m_2 r_2 \left(\phi_2'' \sin \phi_2 + \phi_2'^2 \cos \phi_2 \right);$$
$$m_{pl} y'' + b_y y' + c_y y = m_1 r_1 \left(\phi_1'' \cos \phi_1 - \phi_1'^2 \sin \phi_1 \right) + m_2 r_2 \left(\phi_2'' \cos \phi_2 - \phi_2'^2 \sin \phi_2 \right); \tag{10}$$
$$J_{\Sigma i} \frac{d\omega_i}{dt} = M_{em_i} - M_{meh_i} + M_{v_i}, \; i = 1, 2,$$

where x, y – relocation of an operating device of the vibration machine along an axis X and Y (vibration relocation) respectively; x', y' – speed of the vibration machine along an axis X and Y (vibration speed) respectively; x'', y'' – acceleration of the vibration machine along an axis X and Y (vibrational acceleration) respectively; m_{pl} – the full reduced mass of the fluctuating parts of the vibration machine with the form and a concrete compound; $c_x = c_y = c_0$ – coefficients of horizontal and vertical rigidness of support of the vibration machine respectively; $b_x = b_y = b_0$ – coefficients of horizontal and vertical damping respectively; $m_1 = m_2 = m_0$ – mass of the first and second unbalances, respectively; $r_1 = r_2 = r_0$ – distance of the first and second unbalances from a spin axis respectively; φ_1, φ_2 – turning angles unbalances mass; $J_{\Sigma i}$ – brought to a motor shaft of moment of inertia of i motor respectively; M_{em_i} – electromagnetic torque of i motor respectively; M_{meh_i} – section modulus of i motor; M_{v_i} – vibration moment of i motor respectively.

The section modulus of the motors is determined mainly by the resistance in the bearings of the exciters and is determined according to the expression:

$$M_{meh_i} = 0.5\, f_{tr} m_i r_i \omega^2 d\,, \tag{11}$$

where f_{tr} – reduced coefficient of friction in bearings; ω – rotational speed of the unbalance; d – diameter of bearing inner race.

The vibration moment of one motor:

$$M_{v_i} = m_i r_i \left(x'' \sin\phi + y'' \cos\phi + g\cos\phi \right), \tag{12}$$

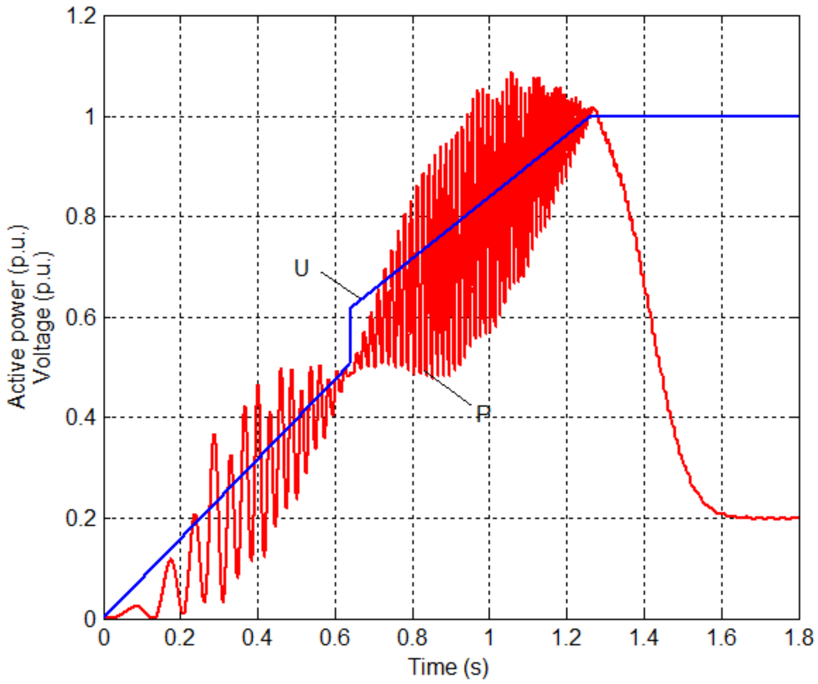
where $g = 9.8$ m/c^2 – acceleration of gravity.

To study the proposed system using mathematical modeling adopted the following parameters of above resonance vibration machine and induction motor, which are shown in table 1.

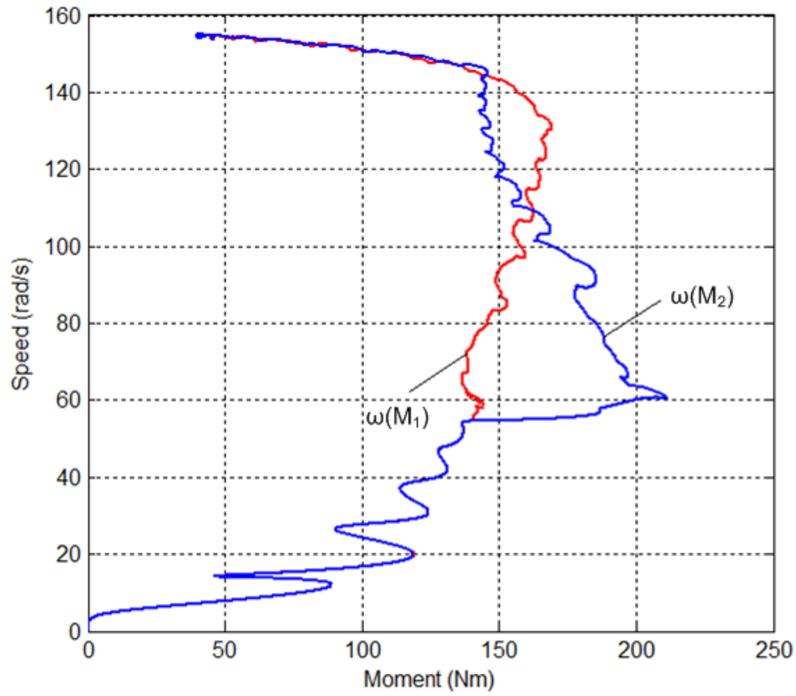
Table 1. Technical characteristics of the vibrating platform

Parameter name	Parameter value
Constructional parameter of the vibration platform	
The full reduced mass of the VM	11000 kg
The mass of the unbalance	22 kg
The distance of the unbalance from a spin axis	0.1 m
Rigidness coefficient of the actuating unit supports	$1.268 \cdot 10^8$ N/m
Damping coefficient	30600 Ns/m
Passport data of an induction motor with a capacity of 11 kW	
Rated power	11 kW
Rated voltage	220 V
Synchronous speed	1500 rpm
Rated current	21.53 A
Stator resistance	0.462 Ohm
Rotor resistance	0.312 Ohm
Stator inductive resistance	0.831 Ohm
Inductive resistance of the rotor	1.262 Ohm
Inductive resistance of the magnetization circle	27.5 Ohm

On the basis of the given mathematical model of the above resonance vibration machine electric drive time dependences of active power of induction motor (P) during start-up and the principle of formation of supply voltage of induction motor (U) at overcoming of a resonant zone (fig. 3a), and also dynamic characteristics (fig. 3b) of induction motor without abrupt increase of supply voltage abrupt increase ($\omega(M_1)$) and with abrupt increase of supply voltage abrupt increase ($\omega(M_2)$) during overcoming of a resonant zone.



a)



b)

Fig. 3. Time dependences of active power and supply voltage and dynamic characteristics of induction motor

As shown in Fig. 3, the abrupt increase in supply voltage is performed when the oscillations of the active power are significantly reduced, which indicates the approach to the resonance zone.

The efficiency of the abrupt increase of the supply voltage during passing of the resonance zone in the process of starting the VM is confirmed by the results of mathematical modelling and experimental studies, which are given in [9].

Conclusions. The application of frequency-controlled electric drive to the above resonance VM allows to pass the resonance zone without "jamming" the rotors of the drive motors due to the abrupt increase in supply voltage when approaching the resonance.

The proposed structure of the control system for starting the electric drive of the above resonance VM and the algorithm of its operation allows to determine the moment of abrupt increase of the supply voltage without previously known parameters of the oscillating system. The proposed control system should be applied to VM with variable load.

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