ГЕОТЕХНОЛОГИЯ. ГОРНЫЕ МАШИНЫ

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Non-linear dynamics of vibration transport machine as an electromechanical system

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Abstract

Introduction. *Vibration transport machines are widely used in mining industry as well as in other production spheres. In order to design vibration transport machine with new characteristics, a closer analysis is required of the working element oscillation parameters and vibration exciters self-synchronization. This paper presents some new results on the numerical simulation of dynamics of vibration transport machines with independently rotating vibration exciters.*

Research objective. *Most of researchers describe only synchronous motions of vibration transport machines. The authors set the task of studying the transient dynamic processes. These processes accompany the start of the machine from its standstill until its reaching (or not-reaching) stabled synchronous motion.*

Methods of research *include carrying out numerical experiments with a mathematical model. The model is based on the solution of a rigidly bound system of differential equations of mechanics and electromechanics. In previous papers the above-mentioned system was non-linear only in mechanical part of differential equations. Electric motors dynamics equations were linear. This model gives inadequate results when describing the transient processes that occur during the startup of the vibration transport machine. In this paper the authors present a new model, which describes an influence of the current displacement effect on the asynchronous driver rotor resistance. The system of differential equations for movement of “vibration transport machine – electric motors” in this case are non-linear in all parts.*

Results. *The paper considers in detail the influence of the current displacement effect on the asynchronous driver rotor resistance and provides a mathematical description of this phenomenon. It made it possible to derive a new, more general system of differential equations that takes into account not only the influence of motors on the machine, but also the influence of the machine on the motors. Formulae for inverse transforms of a real three-phase machine currents calculation are given.*

Conclusions. *A new system of differential equations was obtained that provides a more accurate description of the unsteady dynamics of the “vibration transport machine – electric motors” electromechanical system. In particular, the system takes into account the influence of the current displacement effect on the asynchronous drive rotor resistance. The system is nonlinear in both the mechanical and electrical parts and allows a more accurate description of transient processes when starting the machine.*

Keywords: *vibration transport machine; asynchronous electric motors; vibration exciter; non-linear dynamics; self-synchronization; mathematical model; non-linear differential equations; vibration.*

Introduction. Vibration transport machines (VTM) are intended for transporting and/or separating bulk materials of different density. Most of these machines are constructed as solid bodies (working elements, WE) fixed on springs or by means of other elastic elements that enable their plane-parallel motion (Figure 1).

The motion of working elements is excited by special devices called vibration exciters (VE). Unbalanced rotors driven by electric motors act as VE.

Lately VTM with independent rotating VE have the increasing application. The concept of their action is based on active usage of physical phenomenon called self-

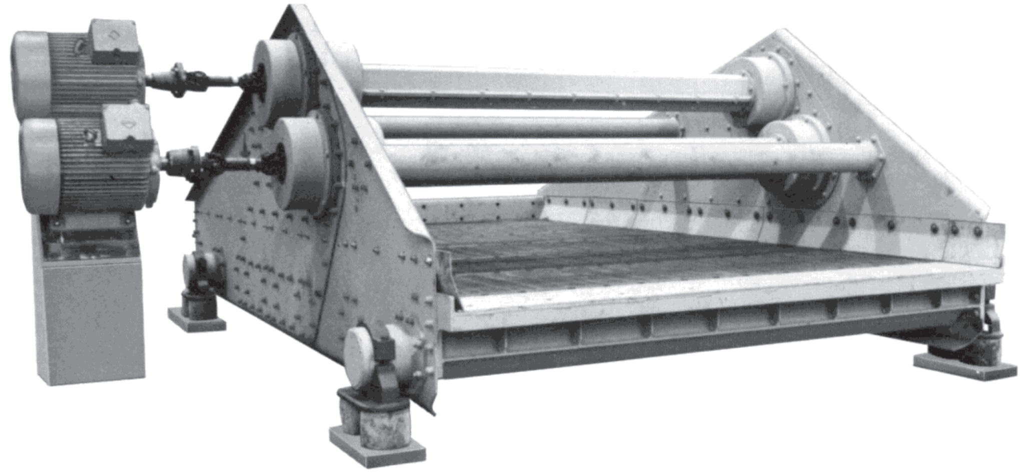

Figure 1. Vibration transport machine with two vibration exciters
Рисунок 1. Вибротранспортная машина с двумя вибровозбудителями

synchronization (SS) of vibrators. In these machines synchronism and relation of VE' phases are achieved automatically due to characteristic properties of the vibration system [1].

The dynamics of VTM with independently rotating VE was observed in works of I. I. Blekhman, N. P. Iaroshevich, L. A. Vaisberg, A. L. Fradkov, J. Baltazar and other researchers [2–8].

Methods of research. Most of above-mentioned authors' works were denoted to synchronous motions. We had stated the problem of transient dynamic processes researching. These processes are accompanying the start of the machine from its standstill until its reaching (or not-reaching) stabled synchronous motion [9–11]. This approach allows evaluating the time until synchronization and the type of connections between this time and various factors.

The VTM dynamics with n independently rotating VE is given by the following system of differential equations:

$$\begin{cases} \ddot{x} = \dfrac{1}{M}\left[-k_x\dot{x} - k_{x\varphi}\dot{\varphi} - c_x x - c_{x\varphi}\varphi + \sum\limits_{i=1}^{4} m_i\varepsilon_i\left(\ddot{\varphi}_i\sin\varphi_i + \dot{\varphi}_i^2\cos\varphi_i\right)\right], \\ \ddot{y} = \dfrac{1}{M}\left[-k_y\dot{y} - k_{y\varphi}\dot{\varphi} - c_y y - c_{y\varphi}\varphi + \sum\limits_{i=1}^{4} m_i\varepsilon_i\left(\dot{\varphi}_i^2\sin\varphi_i - \ddot{\varphi}_i\cos\varphi_i\right)\right], \\ \ddot{\varphi} = \dfrac{1}{J}\Bigg[-k_{x\varphi}\dot{x} - k_{y\varphi}\dot{y} - k_{\varphi}\dot{\varphi} - c_{x\varphi}x - c_{y\varphi}y - c_{\varphi}\varphi + \\ +\sum\limits_{i=1}^{4} m_i\varepsilon_i r_i\left(\dot{\varphi}_i^2\sin\left(\varphi_i - \delta_i - \varphi\right) - \ddot{\varphi}_i\cos\left(\varphi_i - \delta_i - \varphi\right)\right)\Bigg], \\ \ddot{\varphi}_i = \dfrac{1}{J_i}I_i\left[L_i\left(\dot{\varphi}_i\right) - R_i\left(\dot{\varphi}_i\right)\right] + \dfrac{m_i\varepsilon_i}{J_i}\Big[\ddot{x}\sin\varphi_i - \ddot{y}\cos\varphi_i - g\cos\varphi_i - \\ - r_i\ddot{\varphi}\cos\left(\varphi_i - \delta_i - \varphi\right) - r_i\dot{\varphi}^2\sin\left(\varphi_i - \delta_i - \varphi\right)\Big], \\ (i = 1,\ldots,n). \end{cases} \quad (1)$$

where x, y, φ, φ_i are generalized coordinates of the system, where x, y are the coordinates of the mass centre of VTM's WE in some Cartesian coordinate system strictly connected to earth; φ is the angle of WE rotation about the axis passing through the mass centre perpendicular to the motion plane of the machine; φ_i is an angle of i-th eccentric weight rotation about the motor axis; $L_i(\varphi_i)$ is the rotation moment of i-th eccentric weight; $R_i(\varphi_i)$ is the moment of the rotating resistance for i-th eccentric weight; I_i are indices of the rotation direction of i-th eccentric weight, where the value is taken equal to 1 for eccentric weights rotating counterclockwise (positive direction) and –1 for eccentric weights rotating clockwise; M is the total VTM mass (of WE and eccentric weights); m_i is the mass of the i-th eccentric weight; J is the second moment of VTM relative to the mass centre; J_i is the second moment of i-th eccentric weight relative to the rotative axis; ε_i is the radius of gyration of the i-th eccentric weight relative to the rotative axis (Figure 2); δ_i is the angle assigning the i-th eccentric weight position; r_i is the distance from the mass centre to the axis of the i-th eccentric weight; c_x, c_y, c_φ, $c_{x\varphi}$, $c_{y\varphi}$ are the generalized coefficients of elastic supporting elements' hardness; k_x, k_y, k_φ, $k_{x\varphi}$, $k_{y\varphi}$ are the viscous drag coefficients; g is the free fall acceleration. The model describes only non-stationary dynamics of VTM itself without taking into account transient dynamic processes in motors. However, by the start-up and impact loads affecting the machine, there may arise transient dynamic processes in electric motors, resulting in strong deviation of torque/angular speed dependence from the static characteristic. Accounting for these effects will allow describing more precisely not only the influence of motors on non-stationary VTM dynamics, but also influence of VTM dynamics on electromagnetic processes in the motor.

The dynamics of "VTM – electric motors" system in case of an asynchronous motor drive with random quantity of poles' pairs is given by the following system of differential equations [12]:

$$
\begin{aligned}
&\ddot{x} = \frac{1}{M}\left[-k_x\dot{x} - k_{x\varphi}\dot{\varphi} - c_x x - c_{x\varphi}\varphi + \sum_{i=1}^{n} m_i\varepsilon_i\left(\ddot{\varphi}_i \sin\varphi_i + \dot{\varphi}_i^2\cos\varphi_i\right)\right],\\
&\ddot{y} = \frac{1}{M}\left[-k_y\dot{y} - k_{y\varphi}\dot{\varphi} - c_y y - c_{y\varphi}\varphi + \sum_{i=1}^{n} m_i\varepsilon_i\left(\dot{\varphi}_i^2 \sin\varphi_i - \ddot{\varphi}_i\cos\varphi_i\right) - F_{\text{impact}}\right],\\
&\ddot{\varphi} = \frac{1}{J}\Bigg[-k_{x\varphi}\dot{x} - k_{y\varphi}\dot{y} - k_\varphi\dot{\varphi} - c_{x\varphi}x - c_{y\varphi}y - c_\varphi\varphi +\\
&+\sum_{i=1}^{n} m_i\varepsilon_i r_i\left[\dot{\varphi}_i^2\sin\left(\varphi_i - \delta_i - \varphi\right) - \ddot{\varphi}_i\cos\left(\varphi_i - \delta_i - \varphi\right)\right] + M_{\text{impact}}\Bigg],\\
&\ddot{\varphi}_i = \frac{1}{J_i} I_i\left[A_i\left(\psi_{i2}\psi_{i3} - \psi_{i1}\psi_{i4}\right) - R_i\left(\dot{\varphi}_i\right)\right] + \qquad\qquad (2)\\
&+\frac{m_i\varepsilon_i}{J_i}\Big[\ddot{x}\sin\varphi_i - \ddot{y}\cos\varphi_i - g\cos\varphi_i - r_i\ddot{\varphi}\cos\left(\varphi_i - \delta_i - \varphi\right) -\\
&- r_i\dot{\varphi}^2\sin\left(\varphi_i - \delta_i - \varphi\right)\Big],\\
&\dot{\psi}_{i1} = U_m\cos\left(\omega_{\text{c}}t + \alpha\right) - K_{i1}\psi_{i1} + K_{i2}\psi_{i3};\\
&\dot{\psi}_{i2} = U_m\sin\left(\omega_{\text{c}}t + \alpha\right) - K_{i1}\psi_{i2} + K_{i2}\psi_{i4};\\
&\dot{\psi}_{i3} = -K_{i3}\psi_{i3} + K_{i4}\psi_{i1} - p_i\dot{\varphi}_i\psi_{i4};\\
&\dot{\psi}_{i4} = -K_{i3}\psi_{i4} + K_{i4}\psi_{i2} + p_i\dot{\varphi}_i\psi_{i3};\\
&(i = 1,\ \ldots,\ n),
\end{aligned}
$$

where F_{impact} – the impact force of a monolith falling on the machine's working element; M_{impact} – the moment about the center of mass resulting from this force [9–11]; U_m – the amplitude of a sinusoidal voltage.

This system contains 3 + 5n differential equations describing movement of "VTM – asynchronous driven motors" electromechanical system. The phase variables of this system are generalized coordinates x, y, φ, rotational angle φ_i of i-th motor, and magnetic-flux linkages of motors ψ_{i1}, ψ_{i2}, ψ_{i3}, ψ_{i4}; p is the number of pairs of poles. Coefficients A_i, K_{ij} (j = 1, …, 4) are calculated by formulas:

$$K_{i1} = \frac{r_{is} L_{ir}}{L_{is} L_{ir} - M_i^2}; \quad K_{i2} = \frac{r_{is} M_i}{L_{is} L_{ir} - M_i^2};$$

$$K_{i3} = \frac{r_{ir} L_{is}}{L_{is} L_{ir} - M_i^2}; \quad K_{i4} = \frac{r_{ir} M_i}{L_{is} L_{ir} - M_i^2};$$

$$A_i = \frac{3 p_i M_i}{2\left(L_{is} L_{ir} - M_i^2\right)},$$

where M_i, L_{is}, L_{ir} are mutual inductance and complete inductances of stator and rotor windings.

The research was carried out using the VTM dynamics mathematical model based on numerical solution of system (1) or (2).

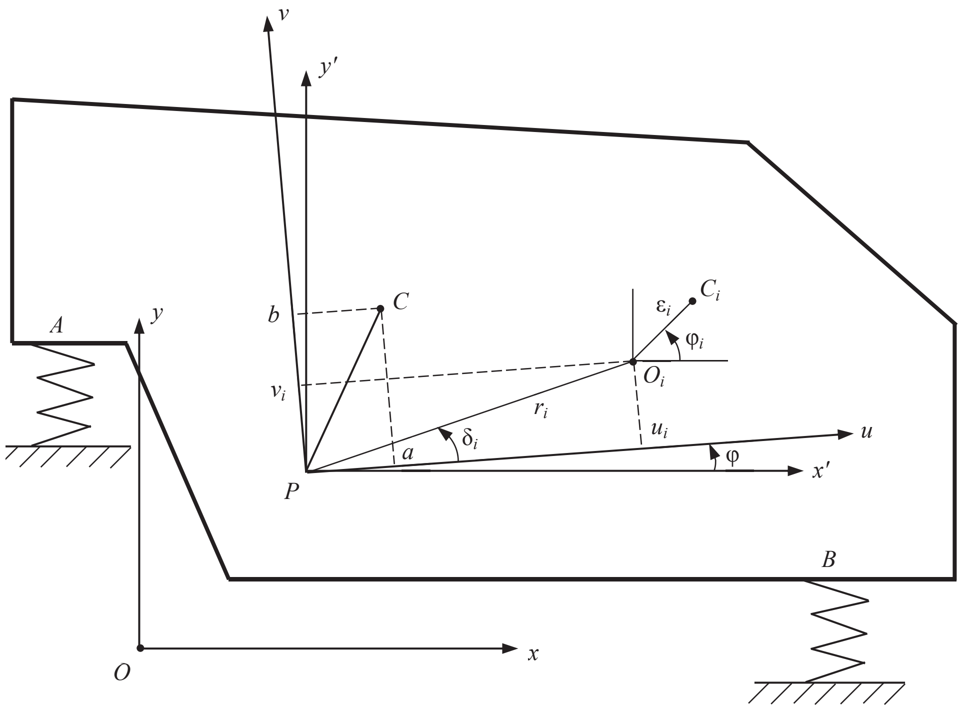

Figure 2. Calculation scheme of the vibration transport machines
Рисунок 2. Расчетная схема вибротранспортных машин

Problem formulation. The system (2) includes coefficients A_i and K_{i1}–K_{i4} that depend on the active and inductive resistances of stators and rotors of the motors. These values used to be considered constant and equal to the values of relevant nominal rating resistances.

The research, which was conducted using numerical experiment with the mathematical model [13–16], has stated that differential equations of asynchronous motors with constant coefficients, included in the system (2), can be applied well to the VTM working process during the operating mode, as well as to the transient processes that appear in the VTM when its vibration exciters are accelerated. However, this model gives inadequate results when describing the transient processes that occur during the startup of the VTM.

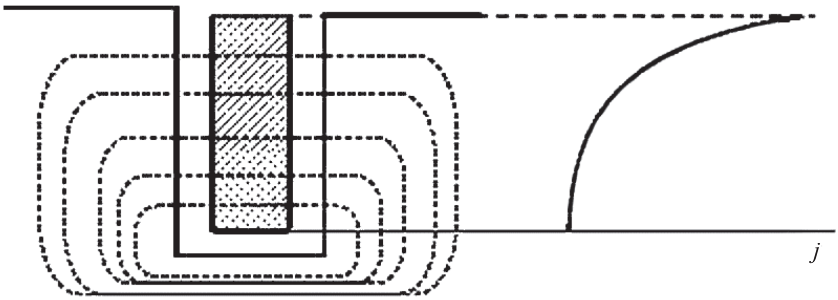

Figure 3. Current density allocation in the short-circuit motor winding bar with deep-bar slots on the rotor
Рисунок 3. Распределение плотности тока в стержне обмотки короткозамкнутого двигателя с глубокими пазами на роторе

It is obvious that startup transient processes modeling must take into account variability of the range of physical parameters of motors, and, consequently, variability (i.e. dependence on the current angular speed of the rotors) of the coefficients A_i and K_{i1}–K_{i4}. Thus, the decision was taken to consider a non-linear model that would take into account the current displacement effect in rotor winding bars of asynchronous drivers as the factor that has the greatest influence on the starting torque value.

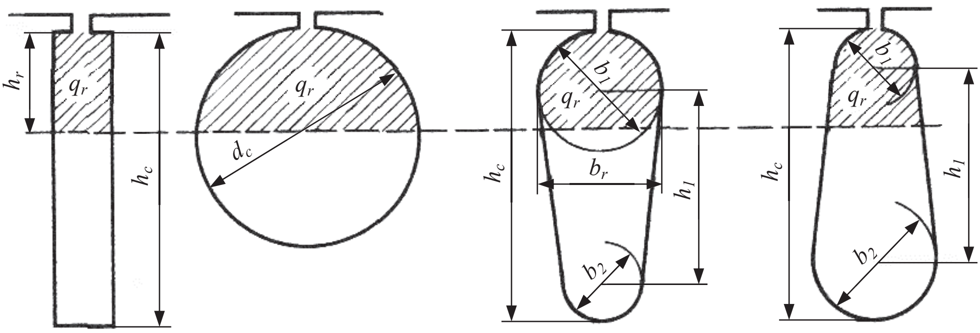

Figure 4. Depth of current penetration into the bar for slots of various configurations
Рисунок 4. Глубина проникновения тока в стержень для пазов различной конфигурации

Influence of the current displacement effect on the asynchronous driver rotor resistance. It is known [17] that in case when there is alternate current in the winding, conductors produce whirling currents that combine with the principal current and increase (or decrease) the current density in different areas of the conductor sections. The current density evenness is disturbed, which increases the active resistance of the conductor.

The greatest current density will occur in upper parts of the conductor sections, i.e. in the areas that are located closer to the slot opening into the air gap (Figure 3).

Because it looks as if the current has been displaced into the upper part of the conductor section, this phenomenon is called the current displacement, whereas the coefficient k_r, which registers the active resistance change caused by this affect, is called the current displacement coefficient.

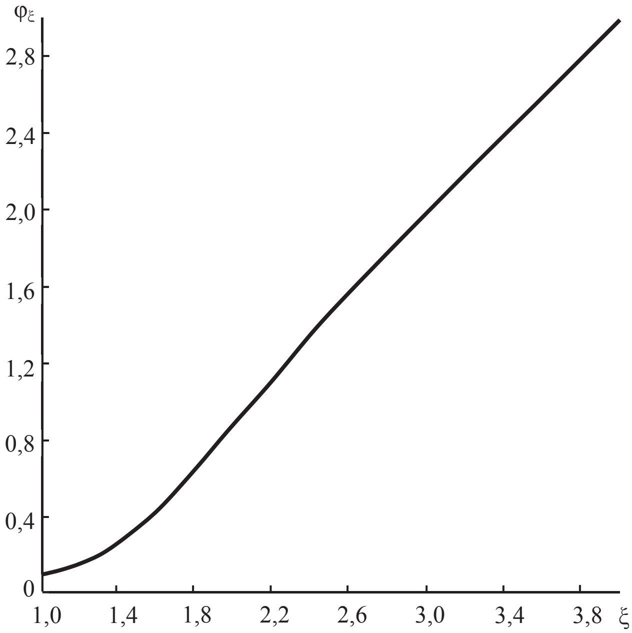

Figure 5. Dependence of φ_ξ on ξ
Рисунок 5. Зависимость φ_ξ от ξ

Calculations showed that it is less practical to define directly the active and inductive bar resistance by the uneven current allocation, than to define their relative change caused by the influence of the current displacement effect. These changes are measured with the use of coefficients k_r and k_d [18, 19]. Coefficient k_r shows by how many folds the active resistance r_{cp} of the slotted bar area by the uneven current density in the bar has increased in comparison with its resistance r_c by equal density throughout all the bar section $k_r = r_{cp}/r_c$.

The damping coefficient k_d shows how the magnetic conductance $\lambda'_{p\xi}$ of the slot area with the conductor under current has decreased in comparison with the resistance of the same area by the even current density λ'_p in the bar $k_D = \lambda'_{p\xi} / \lambda'_p$.

Rotor winding active resistance with account for the current displacement

$$r_{2\xi} = r_2 K_R.$$

Overall rotor resistance increase coefficient caused by the current displacement effect

$$K_R = 1 + \left(k_r - 1\right) r_c \big/ r_2 .$$

The current displacement coefficient k_r is defined by the equation $k_r = q_c / q_r$, where q_c is the bar section area; q_r is the section area constrained by the height h_r (Figure 4).

Current penetration depth $h_r = h_c / (1 + \varphi_\xi)$, where φ_ξ is the coefficient that depends on ξ [18], (Figure 5).

The ξ value for the cast aluminum rotor winding is defined by the equation

$$\xi(\dot{\varphi}) = 65{,}15 h_c \sqrt{(\omega_c - p\dot{\varphi})/\omega_c},$$

where ω_c is the power-line frequency; $\dot{\varphi}$ is the rotor angular speed.

Rotor winding inductive resistance with allowance for the current displacement effect:

$$X_{2\xi} = X_2 K_X, \qquad K_X = 1 - (1 - k_d)\lambda'_{p2}/\lambda_{2\Sigma}.$$

The damping coefficient k_d is considered to be equal to φ'_ξ, where φ'_ξ is the coefficient that depends on the ξ value [18], (Figure 6).

The differential VTM equation system with allowance for the current displacement effect in the rotors of driven motors can be written in this case as

$$\begin{aligned}
&\ddot{x} = \frac{1}{M}\left[-k_x\dot{x} - k_{x\varphi}\dot{\varphi} - c_x x - c_{x\varphi}\varphi + \sum_{i=1}^{n} m_i\varepsilon_i\left(\ddot{\varphi}_i \sin\varphi_i + \dot{\varphi}_i^2\cos\varphi_i\right)\right],\\
&\ddot{y} = \frac{1}{M}\left[-k_y\dot{y} - k_{y\varphi}\dot{\varphi} - c_y y - c_{y\varphi}\varphi + \sum_{i=1}^{n} m_i\varepsilon_i\left(\dot{\varphi}_i^2 \sin\varphi_i - \ddot{\varphi}_i\cos\varphi_i\right)\right],\\
&\ddot{\varphi} = \frac{1}{J}\Bigg[-k_{x\varphi}\dot{x} - k_{y\varphi}\dot{y} - k_\varphi\dot{\varphi} - c_{x\varphi}x - c_{y\varphi}y - c_\varphi\varphi +\\
&+\sum_{i=1}^{n} m_i\varepsilon_i r_i\left[\dot{\varphi}_i^2\sin(\varphi_i - \delta_i - \varphi) - \ddot{\varphi}_i\cos(\varphi_i - \delta_i - \varphi)\right]\Bigg],\\
&\ddot{\varphi}_i = \frac{1}{J_i} I_i\left[A_i(\dot{\varphi}_i)(\psi_{i2}\psi_{i3} - \psi_{i1}\psi_{i4}) - R_i(\dot{\varphi}_i)\right] +\\
&+\frac{m_i\varepsilon_i}{J_i}\left[\ddot{x}\sin\varphi_i - \ddot{y}\cos\varphi_i - g\cos\varphi_i - r_i\ddot{\varphi}\cos(\varphi_i - \delta_i - \varphi) - r_i\dot{\varphi}^2\sin(\varphi_i - \delta_i - \varphi)\right],\\
&\dot{\psi}_{i1}(\dot{\varphi}_i) = U_m\cos(\omega_c t + \alpha) - K_{i1}(\dot{\varphi}_i)\psi_{i1} + K_{i2}(\dot{\varphi}_i)\psi_{i3};\\
&\dot{\psi}_{i2}(\dot{\varphi}_i) = U_m\sin(\omega_c t + \alpha) - K_{i1}(\dot{\varphi}_i)\psi_{i2} + K_{i2}(\dot{\varphi}_i)\psi_{i4};\\
&\dot{\psi}_{i3}(\dot{\varphi}_i) = -K_{i3}(\dot{\varphi}_i)\psi_{i3} + K_{i4}(\dot{\varphi}_i)\psi_{i1} - p_i\dot{\varphi}_i\psi_{i4};\\
&\dot{\psi}_{i4}(\dot{\varphi}_i) = -K_{i3}(\dot{\varphi}_i)\psi_{i4} + K_{i4}(\dot{\varphi}_i)\psi_{i2} + p_i\dot{\varphi}_i\psi_{i3};\\
&(i = 1,\ \ldots,\ n),
\end{aligned} \tag{3}$$

where

$$K_{i1}(\dot{\varphi}_i) = \frac{r_{is}L_{ir}(\dot{\varphi}_i)}{L_{is}L_{ir}(\dot{\varphi}_i) - M_i^2}; \quad K_{i2}(\dot{\varphi}_i) = \frac{r_{is}M_i}{L_{is}L_{ir}(\dot{\varphi}_i) - M_i^2};$$

$$K_{i3}(\dot{\varphi}_i) = \frac{r_{ir}K_{Ri}(\dot{\varphi}_i)L_{is}}{L_{is}L_{ir}(\dot{\varphi}_i) - M_i^2}; \quad K_{i4}(\dot{\varphi}_i) = \frac{r_{ir}K_{Ri}(\dot{\varphi}_i)M_i}{L_{is}L_{ir}(\dot{\varphi}_i) - M_i^2};$$

$$A_i(\dot{\varphi}_i) = \frac{3p_iM_i}{2\left(L_{is}L_{ir}(\dot{\varphi}_i) - M_i^2\right)};$$

$$L_{ir}(\dot{\varphi}_i) = \left(X_{12i} + X_{2i}K_{Xi}(\dot{\varphi}_i)\right) / \omega_c;$$
$$K_R(\dot{\varphi}_i) = 1 + \left(k_r(\xi_i) - 1\right) r_c / r_2;$$
$$K_X = 1 - (1 - k_d)\lambda'_{p2} / \lambda_{2\Sigma}.$$
$$\xi(\dot{\varphi}) = 65{,}15 h_c \sqrt{(\omega_c - p\dot{\varphi}) / \omega_c}.$$

In this differential equation system coefficients A_i and K_{i1}–K_{i4} are no longer constant and are nonlinearly dependant on the angular speed of the rotors in the driven electric motors. Angular rotation rates of the i-th VE (the rotor of the motor) φ_i, or else their derivatives, are included into all these equations. On the other hand, the flux linkage rates of the i-th electric motor ψ_{i1}, ψ_{i2}, ψ_{i3}, ψ_{i4}, are included into the VE angular acceleration. Thus, the system poses a rigidly bound differential equation system. It is impossible to solve some of its equations separately from the others, all the system must be integrated in unison.

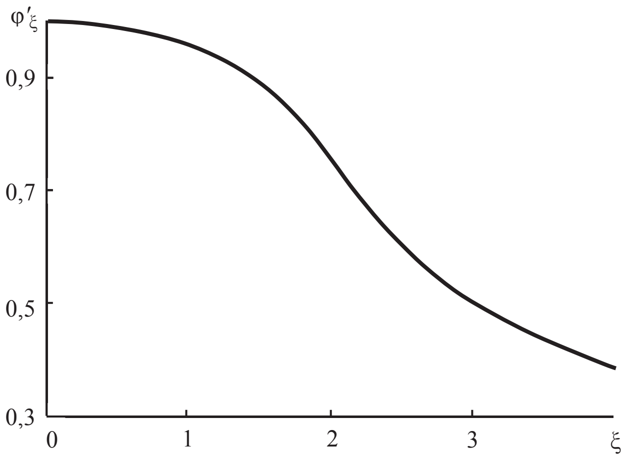

Figure 6. Dependence of φ'_ξ on the ξ value

Рисунок 6. Зависимость φ'_ξ от значения ξ

To calculate the currents of the real three-phase machine it is possible to take advantage of formulas of return transformations which are as follows for stator and rotor magnitudes:

$$i_A = i_{s\alpha}\cos 0 - i_{s\beta}\sin 0;$$
$$i_B = i_{s\alpha}\cos(-120°) - i_{s\beta}\sin(-120°);$$
$$i_C = i_{s\alpha}\cos 120° - i_{s\beta}\sin 120°;$$
$$i_a = i_{r\alpha}\cos(0 - \varphi) - i_{r\beta}\sin(0 - \varphi);$$
$$i_b = i_{r\alpha}\cos(-\varphi - 120°) - i_{r\beta}\sin(-\varphi - 120°);$$
$$i_c = i_{r\alpha}\cos(-\varphi + 120°) - i_{r\beta}\sin(-\varphi + 120°).$$

The current $i_{s\alpha}$ will be correspondent to real phase current of the one of stator phases of three-phase machine.

Conclusion. Therefore, a new differential equation system (3) has been deduced that describes non-stationary dynamics of "VTM – electric motors" electromechanical system, which is highly-nonlinear in the electrical as well as in the mechanical parts and allows a more precise measuring of the startup transient processes.

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Нелинейная динамика вибротранспортной машины как электромеханической системы

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Реферат

Введение. *Вибротранспортные машины широко применяются как в горной промышленности, так и в других производственных сферах. Проектирование вибротранспортных машин с новыми качествами требует более подробного анализа параметров колебаний рабочего органа машины и самосинхронизации вибровозбудителей. В статье представлены некоторые новые результаты численного моделирования динамики вибротранспортных машин (ВТМ) с независимо вращающимися вибровозбудителями.*

Цель работы. *Большинство исследователей описывают только синхронные движения ВТМ. Авторы поставили задачу исследования переходных динамических процессов. Эти процессы сопровождают пуск машины из состояния покоя до ее выхода (или невыхода) на установившееся синхронное движение.*

Методика исследования *заключается в проведении численных экспериментов с математической моделью, в основе которой лежит решение связанной системы дифференциальных уравнений механики и электромеханики. В предыдущих работах упомянутая система была нелинейной только в механической части дифференциальных уравнений. Уравнения динамики электродвигателей были линейными. Такая модель дает неадекватные результаты при описании переходных процессов, возникающих при запуске ВТМ. В данной статье авторы представляют новую модель, которая описывает влияние эффекта вытеснения тока на сопротивление ротора асинхронного привода. Система дифференциальных уравнений движения «ВТМ–электродвигатели» в этом случае нелинейна во всех частях.*

Результаты. *В статье подробно рассмотрено влияние эффекта вытеснения тока на сопротивление ротора асинхронного привода и приведено математическое описание этого явления. Это позволило вывести новую, более общую систему дифференциальных уравнений, учитывающую не только влияние двигателей на машину, но и влияние машины на двигатели. Приведены формулы обратных преобразований расчета токов реальной трехфазной машины.*

Выводы. *В статье получена новая система дифференциальных уравнений, которая более точно описывает нестационарную динамику электромеханической системы «ВТМ–электродвигатели», в частности, учитывает влияние эффекта вытеснения тока на сопротивление ротора асинхронного привода. Эта система нелинейна как в механической, так и в электрической части и позволяет более точно описывать переходные процессы при пуске машины.*

Ключевые слова: *вибротранспортные машины; асинхронные электродвигатели; вибровозбудитель; нелинейная динамика; самосинхронизация; математическая модель; нелинейные дифференциальные уравнения; вибрация.*

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