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SYNTHESIS OF THE METHODS OF RESEARCH OF STABILITY OF THE ELECTRIC DRIVE "THYRISTOR VOLTAGE CONVERTER – INDUCTION MOTOR"

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На підставі отриманої передаточної функції електромагнітної частини асинхронного двигуна виконано синтез розрахунково-аналітичного методу дослідження стійкості розімкнутих систем електропривода ТПН-АД. Виконано дослідження стійкості з асинхронними двигунами різної потужності та типовиконання. Показано, що дослідження певних співвідношень електромагнітних та електромеханічних постійних часу електроприводу ТПН-АД дозволяє прогнозувати можливість виникнення його нестійких режимів роботи

Ключові слова: асинхронний двигун, тиристорний перетворювач, розімкнута система, стійкість, передаточна функція

На основании полученной передаточной функции электромагнитной части асинхронного двигателя выполнен синтез расчетно-аналитического метода исследования устойчивости разомкнутых систем электропривода ТПН-АД. Выполнено исследование устойчивости с асинхронными двигателями различной мощности и типоисполнения. Показано, что исследование определенных соотношений электромагнитных и электромеханических постоянных времени электропривода ТПН-АД позволяет прогнозировать возможность возникновения его неустойчивых режимов роботы

Ключевые слова: асинхронный двигатель, тиристорный преобразователь, разомкнутая система, устойчивость, передаточная функция

1. Introduction

One of the topical issues of research of dynamic modes of the performance of the electric drive (ED) «Thyristor voltage converter – induction motor" (TVC-IM) is the study of its stability. As is known, in the open-loop systems of electric drive of TVC-IM with the synchronization with the line voltage on the working section of the mechanical characteristics, in some cases one may observe the oscillations in the output values. The nature and quantitative indicators of the oscillatory processes are very different. They depend on many parameters and factors, which can include: the value of the angle of valves switching, the parameters of IM, the IM load torques, the total torque of inertia of an electric drive, initial electromagnetic conditions (IEMC), the initial velocity of IM, schematic configuration of the TVC and the systems of pulse-phase control (SPPC), the way to synchronize the TVC valves. Forced oscillations are seen as an extremely negative phenomenon that disrupts the normal performance of the open-loop systems of the ED TVC IM. To ensure safe operation of the EP it is essential to search for and identify the areas of its safe performance. Of the same principal interest is the possibility of partial or complete removal of oscillatory modes. This allows simplification of the calculation and tuning of the closed electromechanical systems, and it provides the required quality of the control of coordinates and high energy performance.

2. Analysis of scientific literature and the problem statement

The emergence of self-oscillations in the open-loop systems of ED TVC-IM is explained by the majority of researchers by the presence of positive feedback between the angle shear of the current of the load and the amplitude of the first harmonic of the output voltage of the converter [1–3]. But also by the nonlinearity of the electric driver's parameters. The oscillation process can be conditionally divided into two categories – "small" and "large" fluctuation modes. "Small" oscillations are undamped harmonic oscillations of the output parameters of an induction motor under the condition that the rotor speed varies within the first quadrant (not exceeding synchronous, i. e. $0<\omega<\omega_0$) [4]. It is specified in [5, 6] that physically this kind of self-oscillations is associated with the exchange of energy between electromagnetic contours and inertial flywheel masses of ED. Characteristic charts of the change in velocity, torque and current of the IM's stator in a "small" oscillations mode are presented in Fig. 1.

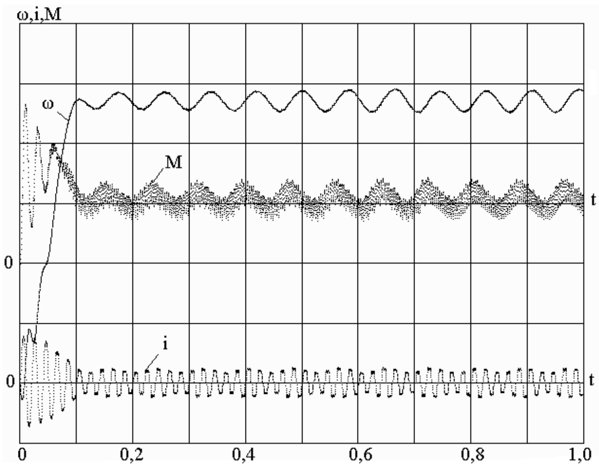

Fig. 1. Charts of the change of velocity ω, torque M and the stator current i of IM 4A80B4 in a "small" oscillations mode; α=50 el. degrees, M_s=1.1 M_m, J_Σ=J_{IM}. Scale: m_i=4I_n/div.; m_m=1M_n/div.; m_ω=0.2ω_0/div

The second category is a large oscillations mode (Fig. 2) [7]. In this case the motor's velocity can exceed the synchronous and the area of oscillations covers the first and the second quadrants. Significant is the performance of the open-loop system of ED TVC-IM in the starting mode when approaching the synchronous speed and in the area of overshoot [7]. If the settings of the IM and switching conditions create preconditions to the overshooting of the velocity, then when approaching the subsynchronous velocity, the current phase increases and the output voltage of the converter increases due to the action of internal feedback [8]. At the speed exceeding the synchronous, when the phase of current grows over 90 el. degrees, the process is accompanied by almost full opening of the TVC valves, regardless of the specified angle of switching [9]. Thanks to the electromagnetic inertia, the motor remains in the motor mode at the speed exceeding the synchronous, which contributes to the process of strengthening of overshooting [10]. As a result, the overshooting develops in the ED, even if an artificial mechanical characteristic with the voltage lower than nominal is set. The ED can enter a large oscillations mode with overshooting of the IM on the velocity of up to 40 % and drops to $0.5\omega_0$ [4]. The period of oscillations switches on the process of sharp breaking by one or more pulses of the torque until a certain minimum speed with a subsequent acceleration of the motor [5, 11].

The features of the processes in a large oscillations mode suggest that their occurrence is associated not so much with a change in the velocity of the rotor but with the vibrational movement and the interaction between generalized vectors of the circuit voltage and the EMF of stator windings, as well as with the stator and rotor linkage [2, 4].

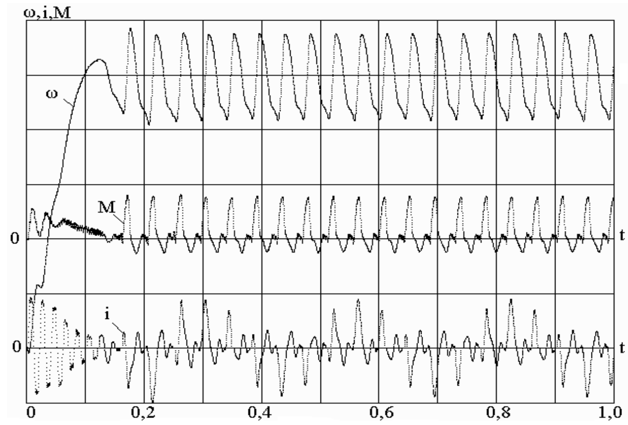

Fig. 2. Charts of the change of velocity ω, torque M and the stator current i of IM 4A80B4 in a "large" oscillations mode; α=70 el. degrees, M_s=0.5 M_n, J_Σ=1.5J_{IM}. Scale: m_i=2.5I_n/div.; m_m=4M_n/div.; m_ω=0.2ω_0/div

The need to evaluate the influence of various factors and parameters of ED on the character of oscillatory processes of an open-loop system of ED TVC-IM, in its turn, determines the need to design new methods of research of its stability [1–6].

3. The purpose and objectives of the study

The objective of these studies is to design a numerical-analytical method of research and to study the stability of an open-loop system of electric drive «Thyristor voltage converter – induction motor".

To achieve the set goal, the following tasks were solved:

– synthesis and application of computational and analytical calculation method for the the study of stability;

– evaluation of the impact of the IM parameters on stability;

– evaluation of the impact of schematic configuration features of the systems of pulse-phase control of the TVC on the nature of unstable modes;

– the formation of a new way to control TVC, enabling the absence of unstable modes.

4. Materials and methods of research of the study of stability of an open-loop system of ED TVC-IM

4. 1. Experimental research base

The study of the stability of ED TVC-IM was conducted by both the simulation and the usage of existing industrial electrical drives. During the simulation, a complete model of IM was applied, taking into account the nonlinearity of its parameters with a subsequent TVC modeling based on logical commutational functions [10]. During the experiment, the electric drives, control and measuring devices and other laboratory facilities of the Institute of Electromechanics and Energy Management of the Odessa National Polytechnic University (Ukraine) were used, as well as of organizations and enterprises of Odessa Region.

4. 2. Computational and analytical calculation method of the study of stability of an open-loop system of electric drive of TVC-IM

Real transient processes of asynchronous electric drive are accompanied by changing in the speed of the motor. However, in some cases, it is useful to use the results of the solutions of a system of differential equations of asynchronous motor at a constant speed of its rotation [11]. Estimated structural scheme of an open-loop system of ED TVC-IM is depicted in Fig. 3 [12].

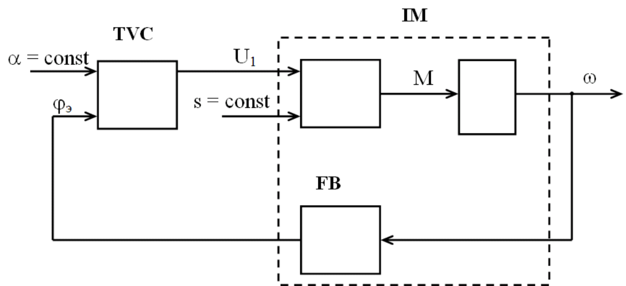

Fig. 3. Estimated structural scheme of an open-loop system of ED TVC-IM

A characteristic feature of the above scheme is the use of dependency of the phase of the current not on the slip but on the current value of velocity. In this view, the output signals of all links are directly dependent on the input signals, and the inner contour of the system yields positive feedback. With a mathematical description of the elements of a structural scheme, their nonlinear properties are taken into account [13].

Induction motor is presented by three links with transfer functions which are denoted by [14]: $H_{EM}(p)$ is the transfer function of the IM electric magnetic part;

$$H_{м}(p)=\frac{1}{J_{\Sigma}p}$$

is the transfer function of the ED electrical-mechanical part;

$$H_{FB}(p)=K_{\varphi}=\frac{\Delta\varphi_e}{\Delta\omega}$$

is the transfer function of the link of the internal feedback, by the angle of load.

Thyristor converter is presented by an amplifying link with an amplifying coefficient K_{TVC}, which, during the transition to the increments, will be determined by [14]:

$$K_{TVC}=\frac{\Delta U_1}{\Delta\phi_e}, \quad (1)$$

in the point defined by the angle of control α and the slip s.

Substantial non-linearity, introduced by valves, is taken into account due to the approximation of the output voltage of the TVC. The equations of the amplitude of the voltage of the first harmonic U_1, derived in the process of identification, have the form [13]:

$$\left.\begin{aligned}
&A_0=-0{,}1291+0{,}06165\cdot\phi_e-7{,}2407\cdot10^{-4}\cdot\phi_e^2,\\
&A_1=-0{,}02723-0{,}0015212\cdot\phi_e+2{,}038\cdot10^{-5}\cdot\phi_e^2,\\
&A_2=-2{,}1534\cdot10^{-4}+8{,}2836\cdot10^{-6}\cdot\phi_e-1{,}1941\cdot10^{-7}\cdot\phi_e^2,\\
&U_1=A_0+A_1\cdot\alpha+A_2\cdot\alpha^2,
\end{aligned}\right\} \quad (2)$$

taking into account the recommended restrictions:

$$\left.\begin{aligned}
&U_1=1 \quad \forall\alpha\le\phi_e,\\
&U_1=1 \quad \forall U_1>1,\\
&U_1=0 \quad \forall U_1<1.
\end{aligned}\right\} \quad (3)$$

The current phase is determined by the equivalent values of active and reactive components of the impedances of equivalent circuit of IM:

$$\varphi_e=\operatorname{arctg}\frac{x_e}{r_e}, \quad (4)$$

where x_e, r_e are the equivalent impedances of an asynchronous motor for T-equivalent circuit, which are defined by expressions:

$$r_e=r_1+\frac{x_0^2 r_2'/s}{\left(x_2'+x_0\right)^2+\left(r_2'/s\right)^2};$$

$$x_e=x_1+x_0-\frac{x_0^2\left(x_2'+x_0\right)}{\left(x_2'+x_0\right)^2+\left(r_2'/s\right)^2}, \quad (5)$$

The link characterizing the IM's electromagnetic part is described on the basis of analytical expression that defines a transitional component of an electromagnetic torque as a reaction to the jump in the input voltage [12]:

$$M_{EM}=\sum_{i=1}^{9}M_i. \quad (6)$$

This expression contains nine components, of which the first one is the achieved value of the torque, two are exponential, three are cosine and three are sine components [15]:

$$\left.\begin{aligned}
&M_1(t)=M_c;\,M_2(t)=A_2e^{-\frac{t}{T_2}};\,M_3(t)=\\
&=A_3e^{-\frac{t}{T_3}};\,M_4(t)=A_4e^{-\frac{t}{T_4}}\cos\Omega_4 t;\\
&M_5(t)=A_5e^{-\frac{t}{T_5}}\cos\Omega_5 t;\,M_6(t)=\\
&=A_6e^{-\frac{t}{T_6}}\cos\Omega_6 t;\,M_7(t)=A_7e^{-\frac{t}{T_7}}\sin\Omega_7 t;\\
&M_8(t)=A_8e^{-\frac{t}{T_8}}\sin\Omega_8 t;\,M_9(t)=\\
&=A_9e^{-\frac{t}{T_9}}\sin\Omega_9 t.
\end{aligned}\right\} \quad (7)$$

The amplitudes A_i, frequencies of free oscillations Ω_i and constants of attenuation time T_i of exponential and periodic components depend on the motor's parameters, values of the rotor slips and are characterized by two attenuation coefficients (α_1, α_2) and two basic frequencies of oscillations (ω_1, ω_2), which in their turn depend on the IM settings [13].

Transient components of the torque depend on the velocity at which the motor switches on. During the slips close to 1, the amount of the transient components are relatively slowly damping oscillations, while during the slips, less than critical, and especially close to synchronous speed, fast damping occurs and the periodic components are expressed weakly. Fig. 4 presents, on a time interval of 0.03 s, all nine components, and Table 1 presents the parameters characterizing them for motors of four dimensions.

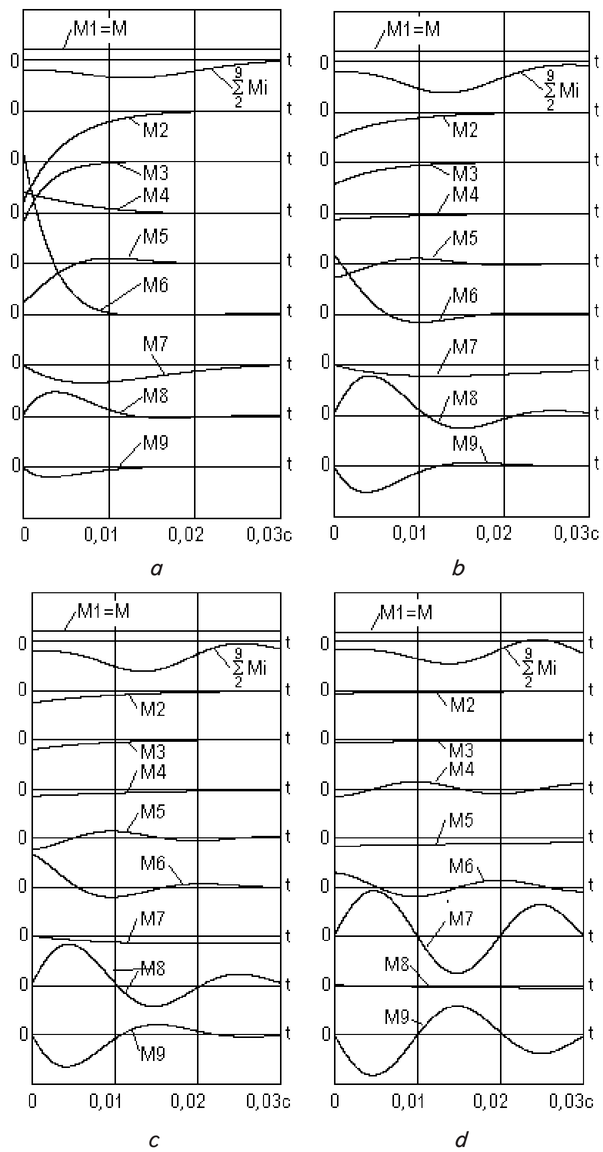

Fig. 4. Charts of the components of electric magnetic torque of IM when switching with zero IEMC during constant slip s=s$_n$. The scale of the torques 5M$_n$/div: *a* – 4A80A6; 0.75 kW; *b* – 4A100L 4; 4 kW; *c* – 4A132M4; 11 kW; *d* – 4A355S4, 250 kW

In the analysis it is accepted that the motor's parameters remain constant. The parameters of T-shaped equivalent circuit are marked at the end of Table 1 [16]. For the exponential components, initial amplitudes and damping time constants are shown. For harmonic components, initial A(0) and amplitude A(max) are shown, without taking into account attenuation values, as well as the constants of time of damping and frequency of free oscillations. The amplitudes and frequencies are in relative units, where nominal torque and synchronous speed of rotation are taken as the base. By Fig. 4 it is possible to trace the "evolution" of the individual components of the transient torque depending on the settings of the motor. When referring to the motors of low or high capacity we mean that with the increase in power, the rigidity of mechanical characteristics increases, the active resistance of the stator and rotor windings reduces, the electromagnetic inertia increases and the magnetization current reduces. In the considered examples, all permanent constants of time increase with the power growth.

Table 1

Parameters of the components of the transient torque when switching of induction motors with zero IEMC during constant slip s=s$_n$

Component of torque		Characterizing parameters	Motor type			
#	Type		4A80A6 0,75 kW	4A100L4 4 kW	4A132M4 11 kW	4A355S4 250 kW
M1	Constant	M$_{state}$	0,992	1,019	1,007	0,836
M2	Exponent	A2 T2	–9,194 4,75	–2,64 6,60	–1,287 10,6	–0,323 26,8
M3	Exponent	A3 T3	–6,257 2,76	–2,25 5,02	–1,055 7,82	–0,297 26,5
M4	Cosinusoid	A4(0) A4(max) T4 Ω4	1,946 1,946 9,51 0,311	–0,63 –0,63 13,2 0,126	–0,775 –0,775 21,2 0,058	–0,81 –0,81 53,6 0,996
M5	Cosinusoid	A5(0) A5(max) T5 Ω5	–3,928 –3,928 5,52 0,773	–1,409 –1,409 10,03 0,92	–1,239 –1,239 15,65 0,969	–0,861 –0,861 53,04 0,0134
M6	Cosinusoid	A6(0) A6(max) T6 Ω6	16,44 16,44 3,49 –0,461	5,915 5,915 5,7 –0,794	3,349 3,349 9,00 –0,911	1,456 1,456 26,66 0,983
M7	Sinusoid	A7(0) A7(max) T7 Ω7	0 –5,792 9,51 0,311	0 –6,29 13,2 0,126	0 –5,68 21,2 0,058	0 5,05 53,59 0,996
M8	Sinusoid	A8(0) A8(max) T8 Ω8	0 5,792 5,52 0,773	0 6,29 10,03 0,92	0 5,68 15,65 0,969	0 –5,05 53,04 0,0134
M9	Sinusoid	A9(0) A9(max T9 Ω9	0 5,792 3,49 –0,461	0 6,29 5,70 –0,79	0 5,68 9,00 –0,911	0 –5,05 26,66 0,983
Parameters of T-shaped equivalent circuit of IM in rel.units		X$_0$ R'$_1$ X'$_1$ R''$_2$ X''$_2$	1,50 0,16 0,12 0,12 0,20	2,400 0,067 0,079 0,053 0,140	3,200 0,043 0,085 0,032 0,130	4,600 0,013 0,090 0,013 0,130

The amplitudes of exponential and cosine components are displayed more vividly in the motors with lower power. With the rise in power they are significantly reduced. The sine components, on the contrary, are displayed more vividly with the increasing motor power. At high amplitudes of selected sine and cosine components, their total effect may not be so significant, because most often the same components with high amplitudes are in pairs in opposite phases. It is to be noted that for the low power motors at considerably larger values of separate free components, the total transient torque, defined as the sum of the components from the 2nd to the 9th, looks much more modest. For the motors of higher power, the total transient torque is comparable by amount to practically all the components. The physical meaning of negative frequencies for the 6th and the 9th components is in the change of the direction of rotation of these components of the electromagnetic torque [17]. On the charts this is displayed by that the direct- and back-spinning components are in antiphase. The damping time constant for all motors happens to be less than the period of the oscillations of low-frequency components and, therefore, such components degenerate and carry little resemblance to harmonic oscillations. A low motor displays this effect even for the high frequency components of the torque when the the cosine components M4, M5, M6, Fig. 4, *a*, resemble the exponents more than the cosinusoids. The specific combination of different time constants of individual components leads to that the powerful motors' oscillations, practically during all slips, last longer and are accompanied by a preliminary growth of the torque during several periods, followed by a subsequent drop. The low-power motors' transient torque begins to subside immediately.

4. 3. Results of the study of stability of an open-loop system of ED TVC-IM

Analytical solution of the issue of stability involves the approximation of a real link $H_{IM}(p)$ by a combination of certain elementary links, which provide the maximal approximation of dynamic properties to the properties of the real object. On the one hand, the approximating functions should not be of a high order, to preserve the possibility of an analytical solution. On the other hand, given the large number of components, it is difficult to expect a simple approximation, and with a high accuracy at that.

It follows from the big difference in the form of components and their different share in a transient torque of different power motors that the approximating functions can also be different and an "individual" approach is needed to individual groups of motors. Fig. 5 presents the same torques as Fig. 4 but they are united in groups according to functional type.

Charts M2, 3 present the total of exponential torques, charts M4, 5 ,6 – the sum of cosinusoidal components and the M7, 8, 9 – of sinusoidal components. Charts M4–9 represent the sum of all harmonic components. By analyzing the form of the charts of the torques shown in Figure 5 one can conclude that for the low-power and other motors with rapid damping and indistinctly displayed harmonic components of the transition torque, the most suitable approximating functions are the exponents, equivalent to groups M2, 3 and M4–9.

For the motors of considered conditionally medium power, 4 and 11 kW, more characteristic approximating function is a damping cosinusoid M4–9 in conjunction with the exponent M2, 3. For the motor of 250 kW, the accuracy of approximation with the help of 2–3 elementary links is not sufficient, as practically all components of the electromagnetic torque are significant. Each of the elementary links adopted at the approximation is described by certain equivalent settings, giving the closest approximation to the desired view of the transient response.

For example, for the motor 4A100L4 of 4 kW power, the best approximation to the transient response is given by the functions of damping cosinusoid and decreasing exponent. The transfer function of an electromagnetic part of a motor fits the view of these functions by Laplace:

$$H_{TVC}(p)=\frac{A_1p^2+\dfrac{A_1}{T_1}p}{p^2+\dfrac{2}{T_1}p+\left(\dfrac{1}{T_1^2}+\omega^2\right)}+\frac{A_2T_2p}{T_2p+1}. \quad (8)$$

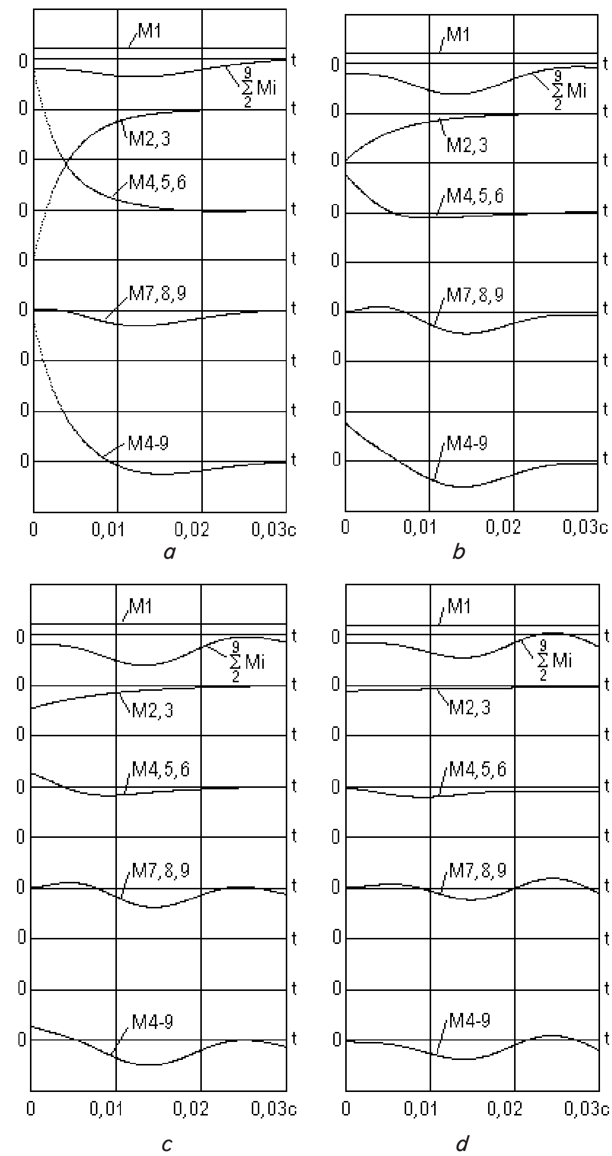

Fig. 5. Charts of equivalent components of electric magnetic torque of IM at switching with zero IEMC at continuous slip $s=s_n$. The scale of torques $5M_n$/div: *a* – 4A80A6; 0.75 kW; *b* – 4A100L 4; 4 kW; *c* – 4A132M4; 11kW; *d* – 4A355S4, 250 kW

The transfer function of an open-loop system of ED TVC-IM [17]:

$$H_p(p)=\frac{K_{TVC}\cdot H_{EM}(p)}{J_\Sigma p}. \quad (9)$$

The transfer function of a closed system of ED:

$$H_{cl}(p)=\frac{H_p(p)}{1-H_p(p)\cdot K_\varphi}. \quad (10)$$

Characteristic equation of a closed system of ED:

$$p^3+a_2p^2+a_1p+a_0=0, \quad (11)$$

where

$$a_2=\frac{2}{T_1}+\frac{1}{T_2}-\frac{k_{TVC}k_\varphi}{J_\Sigma}(A_1+A_2),$$

$$a_1 = \frac{1}{T_1^2} + \omega_1^2 + \frac{2}{T_1 T_2} - \frac{k_{TVC} k_\varphi}{J_\Sigma}\left(\frac{A_1}{T_2} + \frac{1}{T_1}(A_1 + 2A_2)\right),$$

$$a_0 = \frac{1}{T_1^2 T_2} + \frac{\omega_1^2}{T_2} - \frac{k_{TVC} k_\varphi}{J_\Sigma}\left(\frac{A_1}{T_1 T_2} + A_2\left(\frac{1}{T_1^2} + \omega_1^2\right)\right).$$

When selecting the equivalent settings, the data from Table 1 are used, and to determine the frequency of a cosine component, a specific feature of the form of a transient torque is taken into account. Namely, in all the range of considered torques and slips (in area $0<s<s_K$), regardless of the IM settings, the extremum of the transient torque always occurs around the same time $t_{max}\approx 0.0135$ s [18]. Considering that it is important for the amplitude of the approximating function to "hit" during this first and main peak of the torque, the equivalent frequency for the cosinusoid will amount to, for all cases, π / t_{max} or $\omega_{1e} \approx 232\ s^{-1}$. The equivalent amplitude of the cosine component is determined by the total of initial amplitudes 4, 5 and 6 and the components of the transient torque, i. e. A_{1e}=A4(0)+A5(0)+A6(0). The time constant is taken as the average of the three time constants of the cosinusoidal components, in particular, the largest $T_{1e}=T_4$. The parameters of the equivalent exponent are defined by the sum of amplitudes of exponents M2 and M3 (A_{2e} =A2+A3) and maximum constant T_{2e}=T2.

In the study of stability, with the known torque of the ED inertia, the conditions of stability in the specified area of the slips and torques are determined. Such an approach is more in line with the possibilities of numerical methods of integration [15]. In this case, the worst case is accepted, when the inertia coefficient is 1, because it is known in advance that with the increased torque of inertia, the area of unstable performance decreases [12]. The slips area is limited to three-, four times the value, relative to nominal, and within the given area, a family of mechanical characteristics forms. By scanning this area with the specified step along α and s, one determines the points of stable or unstable performance of ED TVC-IM. The stable one is a working point in which all coefficients of the characteristic equation (11) are positive and for which the Hurwitz stability criterion is realized [14].

Fig. 6 presents a family of mechanical characteristics with the results of stability analysis. The area of unstable performance, defined theoretically using the Hurwitz criterion, is marked by bold lines, stable – by thin ones. Here the boundary between stable and unstable modes is also marked, determined by the results of simulation of the switching mode with the set angle and the load torque [18]. This boundary was tested by the experiments and by using the mathematical model of ED-TVC IM [19].

The stability analysis revealed certain features, previously unknown. Thus, for small switching angles of 40...50 el. degrees, the area of unstable performance is limited as the manifestations of instability are only possible within that load range in which the angle of the valves' switching exceeds the phase of the stator current [19]. When reducing the switching angle down to 30 el. degrees, for example, for the analyzed induction motor, there is a single point of unstable performance at M_s=1,45M_n. At the switching angles of the valves of $50<\alpha\leq 100$ el. degrees, the area of unstable work starts at M=0 to some border value of the torque load, after exceeding which the motor starts to run steadily.

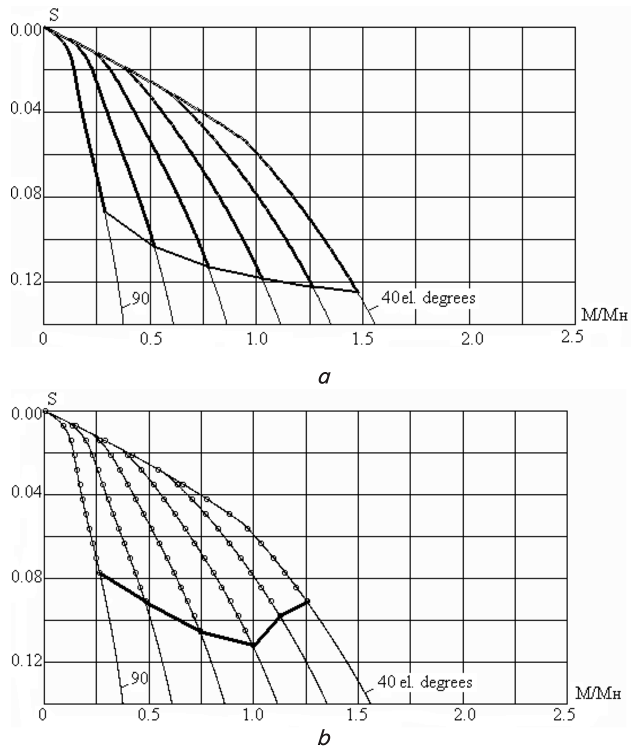

Fig. 6. Families of mechanical characteristics with certain areas of unstable performance by the computational analytical method (*a*) and by using mathematical and physical IM models of ED TVC-IM (*b*) for the motor 4A100L4

4. 4. Assessment of the impact of the IM parameters on stability

As already stated, with the increase of the total inertia torque of the system, the area of stable performance increases and vice versa [13, 20]. Considering a family of four-pole electric motors of series 4A of basic design with a power of 0.25...250 kW [16], it should be noted that for the TVC-IM with a 4A355S4 engine, 250 kW, we were unable to identify any point where the self-oscillations exist. With the decrease in power of induction motors, and, as a consequence, of their inertia torques, there appears and increases the area of unstable work (Fig. 7, 8). This is fixed for the IM with power of 1.5 kW and higher. In the study of TVC IM with electric motors less than 1.5 kW of power, the reverse picture displays – the area of unstable performance decreases with the decreasing powers of IM, and for the electric motor 4AA63A4, 0,25 kW (similar to 4A355S4) it is non-existent at all (Fig. 8, *b*).

This phenomenon can be explained by the fact that in reality the system's stability is defined not by the absolute value of the total inertia torque of the ED but by the influence of its relative value on the nature of the transient process of the IM [21]. This influence can be expressed by the ratio of electromechanical time constant $T_м$ to the electromagnetic time constant of the fourth transient component of electromagnetic torque – T_4.

During the linearization of mechanical characteristic in the area $0<s<s_n$, the electromechanical time constant can be found [17]:

$$T_м = J_\Sigma \frac{1}{|\beta|} \approx J_\Sigma \frac{\Delta\omega_n}{\Delta M_n} \approx J_\Sigma \frac{\omega_0(1-s_n)}{M_n}, \quad (12)$$

where J_Σ is the aggregated reduced inertia torque of ED, kg×m^2.

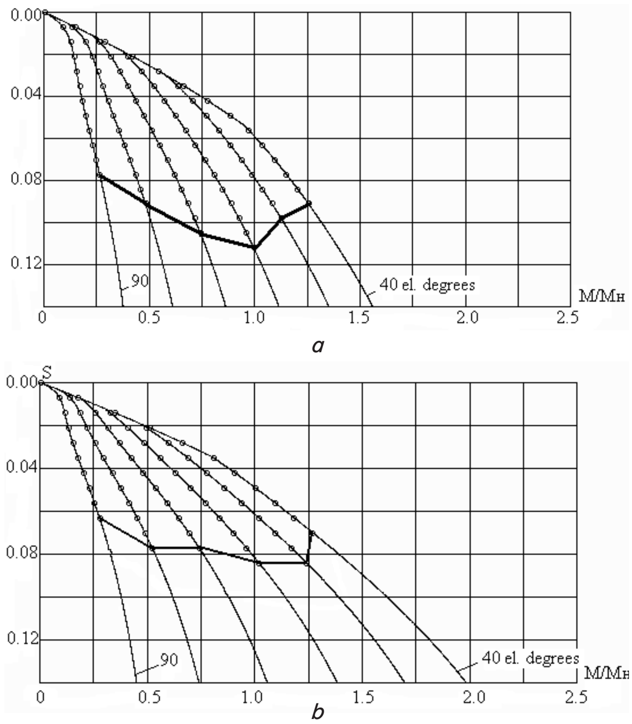

Fig. 7. Families of mechanical characteristics with certain areas of unstable performance for motors: *a* – 4A100L4; *b* – 4A132M4

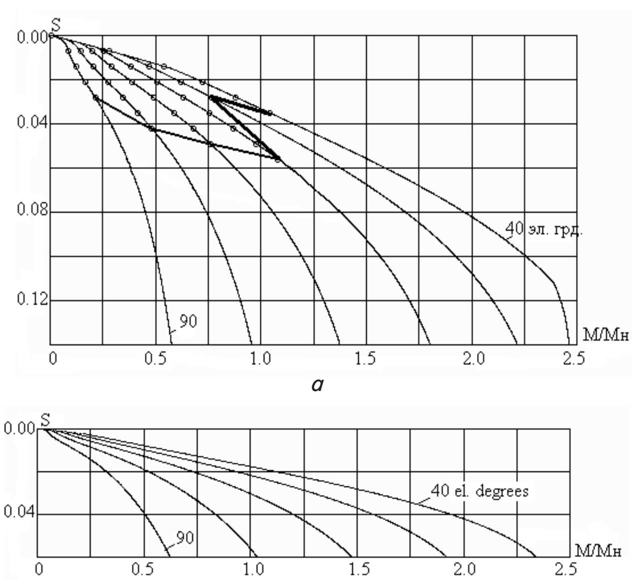

Fig. 8. Families of mechanical characteristics with certain areas of unstable performance for motors: *a* – 4A200L4; *b* – 4A355S4

Table 2 shows the values $T_м$, T_4 and their ratios $T_м/T_4$ for the family of induction motors of the studied series. The results of the analysis show that there is a relationship between the values of the ratio $T_м/T_4$ and the size of the areas of unstable performance. The higher the ratio $T_м/T_4$, the less is the likelihood of self-oscillations occurrence in an open-loop system of ED TVC-IM when using these types of motors. At the same time, this conclusion does not give the right to assert that at closely related or equal ratio values for certain types of motors (for example, 4A180M4 and 4A71A4), the areas of unstable performance will be identical.

Table 2

Parameters of time constants and their ratios for the ED row of 4A series

#	ED standard size	Nominal power, kW	T_m, s	T_4, s	$T_м/T_4$
1	4A355S4	250	0,58	0,0535	10,8
2	4A280M4	132	0,446	0,0464	9,61
3	4A250S4	75	0,32	0,0452	7,08
4	4A200L4	45	0,24	0,0418	5,74
5	4A180M4	30	0,182	0,0336	5,42
6	4A132M4	11	0,085	0,0214	3,97
7	4A132M4	7,5	0,087	0,0217	4,01
8	4A100L4	4	0,062	0,0174	3,56
9	4A80B4	1,5	0,048	0,0133	3,61
10	4A80A4	1,1	0,064	0,0132	4,85
11	4A71B4	0,75	0,039	0,0083	4,70
12	4A71A4	0,55	0,051	0,0093	5,48
13	4AA63B4	0,37	0,077	0,0119	6,47
14	4AA63A4	0,25	0,1	0,0110	9,09

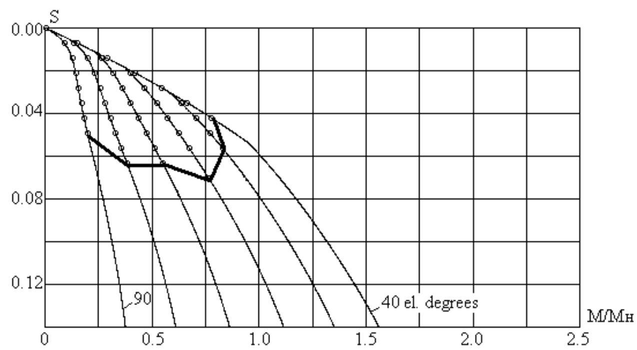

Fig. 9. Mechanical parameters with the indication of the area of unstable performance of TVC-IM with the engine 4A100L4, aggregated inertia torque J_Σ=2 J_{IM}

The example of back analysis is possible when the ratio $T_м/T_4$ changes not due to the changes in the motor's dimensions but by changing the aggregated inertia torque of the electric drive when applying the same IM. For example, when using the motor 4A100L4 with an aggregated inertia torque of the electric drive $J_\Sigma=2J_{IM}$, the ratio $T_м/T_4$ increases to 7.12 and in this case the area of unstable performance significantly reduces. This is illustrated by the mechanical characteristics of the IM described in Fig. 7, *a* and Fig. 8, respectively. The given analysis was conducted and the findings have been confirmed for a number of families of induction motors of series 4A and 5A (IP44, IP23) with the number of pairs of poles p=2, 3 and 4.

4. 5. Assessment of the impact of the SPPC schematic configurations on the nature of unstable modes

The nature of the processes occurring in the unstable modes of TVC-IM may depend on the schematic configurations adopted when designing the SPPC and the output stages of TVC. Most often, the SPPC of TVC with synchronization with the network voltage are performed by "vertical" principle and have 6 separate channels of synchronization, 6 SPPC and 6 individual, according to the number of thyristors, pulse shapers or output stages [22]. Conditionally this system can be described as SPPC-6. There is a strict priority of switching valves not only by the state of power anode circuits of valves, but also by the algorithm of the SPPC performance itself. In some cases, for the sake of simplicity and cost-saving, three-way SPPC are used and, what is important in this case, dual pulse shapers. Each of these shapers has two output channels, for example, an output transformer with two secondary windings, and it delivers the control pulses simultaneously on the two thyristors included in antiparallel (this is SPPC-3) [22]. Under normal conditions, that thyristor turns on, the anode of which has positive voltage, the switching sequence is not violated, and the features of this scheme do not display. Under normal conditions, phase current in each half period finishes outside of the respective voltage half period. This phenomenon is due to the inductive nature of current and is described by the angle of the lag of the current termination. In an oscillation mode, there are abrupt changes in the current phase, so that in one of the phases it may finish or, what is the same, to change its sign before the end of the half period of voltage [24]. This does not happen in the SPPC-6 because the control signals are absent on this thyristor and thus the feature of the process stops. In the TVC with SPPC-3 a parallel thyristor has the ability to engage, because the controlling current is fed to the controlling transfer. Thus the breakdown of normal switching of valves and voltage regulation occurs, since the parallel valve switches not only with the angle $\alpha=0$, but much earlier, in the previous half period. The current pulse in this thyristor becomes abnormally wide and can reach 2π or higher. During the existence of the pulse of such width, a generalized current vector lags behind the voltage vector by one rotation. The phenomenon can be called a current phase reversal. The charts of the current, obtained experimentally, are shown in Fig. 10 [20]. The cases of anomalous increase in the current phase are highlighted by the circles on the estimated waveform.

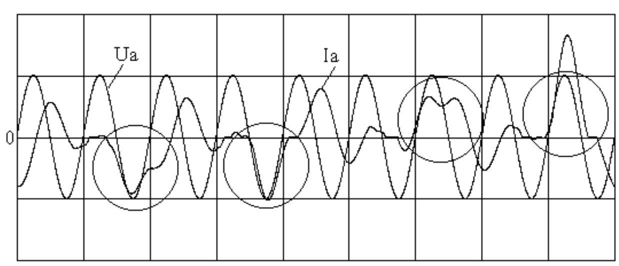

Fig. 10. Waveforms of the phase current of induction motor 4A100M4, 3 kW, in an oscillations mode for the case of SPPC-3 with switching angle α=83 el. degrees; M_c=0.01M_n; J=1.05J_{IM}

The consequence of a current phase reversal and the collapse of commutation is the formation of a positive torque pulse, which provides large acceleration and quick transition into the second quadrant. After the commutation recovery, equally intensive braking begins and the period of oscillations repeats. The frequency of such oscillations is several times higher than in the oscillations mode with the SPPC-6 described above. Experimental waveforms of an oscillations mode in electric drive TVC-IM with SPPC-3 are shown in Fig. 11.

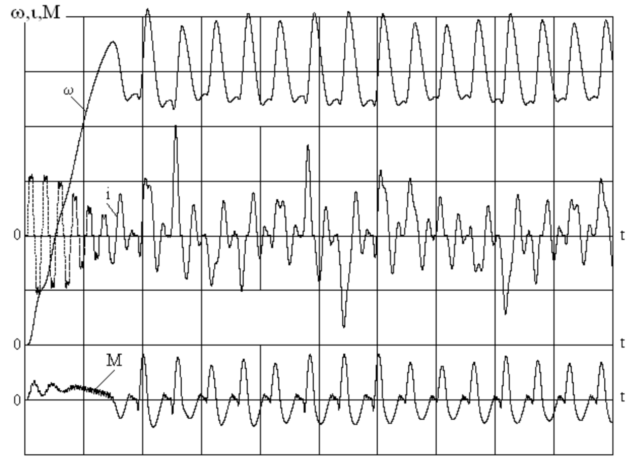

Fig. 11. Waveform of a transient process of switching and an oscillations mode of ED 4A100M4, 3 kW, with switching angle α=83 el. degrees; M_s=0.01M_n; J=1.05J_{IM} for the case of SPPC-3. Scale: m_i=25A/div.; m_m=4M_n/div.; m_ω=0.2ω_0/div, m_t=0,08s/div

The real systems of ED with SPPC 3 and SPPC-6, producing different pictures of an oscillations mode, have their analogs among mathematical models of electric drive TVC-IM. The experimental waveforms of an oscillations mode in the systems with SPPC-6 correspond to the waveforms obtained on the exact simulation, taking into account switching valves [8]. Experimental waveforms with SPPC-3 correspond to the waveforms obtained on simplified idealized simulations in which the IM supply comes from a polyharmonic source (providing the needed voltage, but not containing physical nonlinearities, inherent in thyristors). It is also possible to attribute the models of mathematical description of the linearized drive, applied during stability studies to the same idealized case [18]. Hence it follows that an oscillations mode without switching breakdowns, as is the case in the ED with SPPC-6, may not be described analytically in principle, because, even after overcoming the difficulties of the linearization of parameters and characteristics of the IM and the TVC, the variant of oscillations is formed in line with the TVC-IM with a SPPC-3 script.

4. 6. The method of forming TVC output voltage, invariant to the phase of load current

The output voltage of a three-phase TVC is a complex function of control action – valves switching angle α and the disturbance input – equivalent phase of the stator current φ_e of an induction motor [5]. The current phase of IM is unstable and depends on the parameters of the equivalent sheme and the current slip. Particularly significant phase changes occur on the working section of a mechanical characteristic, from $\varphi_e\approx90$ el. degrees when idling, until a minimum value φ_e near the point of nominal mode. For example, during a controlling action α=90 el. degrees, the first harmonic of the output voltage U_{1TVC} changes from U_n at φ_e=90 el. degrees to 0.22U_n at φ_e=30 el. degrees. That is why the feature of a family of the mechanical characteristics of IM constructed with different values of α=const is the similarity of the total form, but the inconsistence with the characteristics constructed at U=const [24]. The second feature that affects the stability of IM is a proportional dependence of the output voltage on the current phase. This dependence should be viewed as an internal positive feedback between U_{1TVC} and φ_e. If we examine the action of this feedback by the example of load acceptance and shedding on the IM shaft (at a constant value of the controlling action), then while idling, when $\varphi_e \to 90$ el. degrees, the full voltage is applied to the stator's winding. During the load acceptance $M_s=0.5M_n$, the decrease in the velocity starts and φ_e begins to decrease. At $\varphi_e=60$ el. degrees we have the TVC output voltage $U_{1TVC}=0.52-0.3U_n$, at $\varphi_e=30$ el. degrees $U_{1TVC}=0.34-0{,}22U_n$. Deep drop in the output voltage of the TVC leads to the decrease in electromagnetic torque. On the contrary, during the load shedding, the reverse process occurs and the voltage on the stator's winding restores back to nominal [7]. Thus, the internal positive feedback causes a reaction of the IM to the changes in the load on its shaft. This feature can lead to unstable, vibrational, modes of an open-loop system ED TVC-IM, as was previously analysed, at controlling angles α=50–90 el. degrees, incomplete motor load and at low, reduced inertia torques of the engine.

One can suggest a way to compensate the action of this internal positive feedback. The task can be formulated as follows: the controlling system should ensure proportional dependence between the controlling voltage U_Y and the output voltage of TVC, in this case the action of the internal positive feedback is automatically offset by corresponding changes in the current controlling angle α. This is possible if one uses a well-known close analytical dependence $U_{1TVC}=f(\alpha, \varphi_e)$ [24]. This dependence must be converted to mean $\alpha=f(U_{1TVC}, \varphi_e)$, where the controlling action is U_{1TVC}, the disturbing one is still φ_e, and the valves switching angle α is automatically calculated to maintain the specified voltage, regardless of the current phase of the IM's stator current:

$$\alpha = \frac{-A_1 - \sqrt{A_1^2 - 4A_2\left(A_0 - U_{1TC}\right)}}{2A_2}, \qquad (13)$$

where

$A_0=-0.1291+0.06165\varphi_e-7.2407E-04\varphi_e^2$,

$A_1=0.02723-0.0015212\varphi_e+2.038E-05\varphi_e^2$,

$A_2=-2.1534E-04+8.2836E-06\varphi_e-1.1941E-07\varphi_e^2$.

Fig. 12 presents for the illustration two experimental waveforms of switching, load acceptance and shedding during the control of ED TVC-IM exposed to the controlling action α=const (a) and U_{1TVC}=const (b).

In the first case, after the finish of the switching process, characteristic continuous oscillations occur, during load acceptance Ms=Mn, the oscillations damp, but the load acceptance process is accompanied by a drop in velocity by 35 %. During load shedding, the oscillations occur again. In the second case, a drop in velocity during load acceptance decreases down to 15 % while continuous oscillations do not occur.

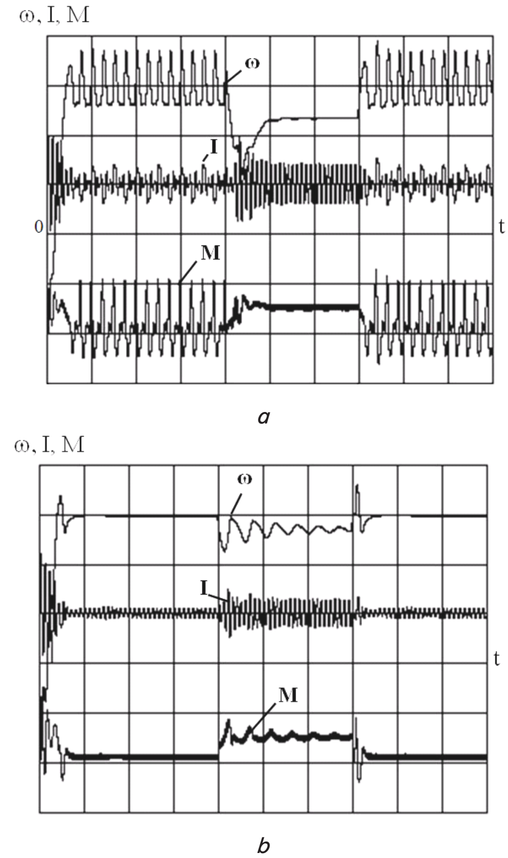

Fig. 12. Waveforms of the processes of switching and load acceptance and shedding of the motor 4A100L4, 4 kW, $J_{sum}=1.1J_{IM}$: *a* – controlling action α=70 el.degrees; *b* – controlling action $U_1=0.85U_n$. The constants scale: mt=0.2 c/div.; m_m=2 Mn/div.; mω=0.2ω_0/div

5. Discussion of the results of application of the simplified method of the study of stability of an open-loop system ED "TVC-IM"

The application of the proposed simplified numerical-analytical method of the study of stability of ED TVC-IM allows, with minimal errors, searching for the area of unstable performance, in this case within the time 20–30 less than the similar experimental studies or the research using a mathematical simulation of ED [25]. Differences in the results of the analysis of the stability by the simplified method and by using the experiment can be explained:

– the impossibility of full account of nonlinear properties in dynamic modes of ED performance;

– the presence of dependency of the forming of self-oscillations on the initial conditions;

– inevitable errors in the mathematical description and the simulation of processes (functional identification of the TVC output voltage, numerical solutions of the specifiers of high order, etc.);

– relative complexity of the search for the exact boundary of the area of unstable performance of TVC-IM with the help of the experiment and by using mathematical models.

It was illustrated that the nature of the mode of large oscillations and its parameters – frequency and the amplitude of oscillations of the torque and velocity, depend on the schematic configurations adopted when designing the SPPC and the TVC output stages. The discovered differences in the dynamics of an electric drive are methodically important, since they provide an opportunity to identify by properties the real systems of an electric drive with different variants of their models and to justify the frontiers of applicability of analytical methods and different variants of mathematical models in the study of TVC-IM in the mode of large oscillations. The differences in the dynamics of an oscillatory mode are possible only in the electric drive with the TVC, which has a synchronization of valves with the circuit voltage and in which "broad" controlling pulses form. When performing the synchronization of the valves with the stator current, oscillatory modes generally do not occur at all and, because the valves receive control from the individual "narrow" pulses, the erroneous switching is excluded.

These studies are a continuation of theoretical research of static, dynamic and energetic characteristics of electric drives of the TVC IM, carried out for more than 20 years at the Institute of Electromechanics and Energy Management of the Odessa National Polytechnical University of Ukraine.

A special feature of this work is the study of the open-loop and closed systems of ED TVC-IM, conducted not only by using the methods of mathematical simulation, but also on the operating experimental devices, primarily on the elevator lifting-transporting electromechanical systems. The possibility to analyze experimental data in specific modes of performance, which include unstable modes of performance of the open-loop systems of TVC-IM, made it possible, in some cases, to look differently at the physics of processes and the research methods of ED. Further research is to be applied to the design of technical recommendations for implementing the controlling algorithm, in line with the way of formation of the TVC output voltage, invariant to the phase of load current.

6. Conclusions

1. The transfer function of electromagnetic part of an induction motor was determined, which characterizes the transient function when taking into account characteristic components of electromagnetic torque of the motor. A simplified method of the study of stability of an open-loop system of electric drive TVC-IM was proposed, which combines analytical research methods with computational-numerical methods. The method is universal; it takes into account the nonlinearities of IM, TVC, and can be used to study the stability of ED with all known induction motors.

2. The research of the dynamic properties of induction motors in an open-loop system of ED TVC-IM has confirmed that the view, the nature and the very existence of unstable modes of performance of IM depend entirely on the electric drive's settings and initial electromagnetic conditions. It was determined that in the area of working slips, ED TVC-IM with asynchronous engines of average power are mostly prone to the unstable modes. Each family of induction motors of series 4A has a "border" IM with which an electric drive has a maximum area of unstable performance, whereas when using motors of more or less power, the area of unstable performance decreases. The analysis of the ratios of some time constants of an electric drive allows not only analyzing indirectly the occurrence of unstable performance of an open-loop system of electric drive of TVC-IM, but also designing recommendations for the use of various types of motors within the same series.

3. An oscillation mode, switching smoothly, as is observed in the ED TVC-IM with a 6-channel SPPC, cannot be described analytically in principle, because even after overcoming the difficulties of the linearization of parameters and characteristics of IM and the TVC, the variant of oscillations forms in line with the ED script with a three-channel SPPC.

A method of three-phase control over a thyristor voltage converter was proposed, with which the specified output voltage of the converter is provided, regardless of the phase of the load current. A characteristic feature of the control is ensuring the proportional dependency between the TVC output voltage and the controlling voltage by the controlling system. In this case, the action of the internal feedback is automatically offset by corresponding changes in the current control angle. Thanks to this feature, the use of this method provides a principal absence of instability in the open-loop systems of ED TVC-IM in all modes of their performance.

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