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L.V. AKIMOV – Doctor of Engineering, professor, National Metallurgical Academy of Ukraine, akimov1939@i.ua, ORCID: http://orcid.org/0000-0002-2265-4785
A.V. NIKOLENKO – Candidate of Engineering Sciences, Docent, National Metallurgical Academy of Ukraine, nikolenkoETEP@i.ua, ORCID: http://orcid.org/0000-0003-3808-4249
V.V. KUZNETSOV – Candidate of Engineering Sciences, Docent, National Metallurgical Academy of Ukraine, wit1975@i.ua, ORCID: http://orcid.org/0000-0002-8169-4598
B. U. BILIY, student, National Metallurgical Academy of Ukraine, bogdan111@i.ua, ORCID: http://orcid.org/0000-0005-5543-2365
S. V. PROKOPENKO, student, National Metallurgical Academy of Ukraine, prokop@i.ua, ORCID: http://orcid.org/0000-0005-1256-4587
A. D. MOREV, student, National Metallurgical Academy of Ukraine, 45g55@i.ua, ORCID: http://orcid.org/0000-0003-6789-3292

ON PECULIARITIES OF REGULATION OF ELECTRIC DRIVE WITH TWO-MASS MECHANICAL PART AND NON-LINEAR LOAD

Introduction

It’s a well-known fact [1-3] that for the purposes of automation of certain industrial mechanisms more and more attention is focused on astatic systems for speed and position regulation development. These are electric drives (ED) of reversive and continuous wire mills, control systems, programmable control and many others ED of various mechanisms

The basic method of attaching astatic properties to automated system lies in application of integrating corrective regulating facilities [4].

The papers [5-7] considering two-mass electric drive with modal control system discovered the phenomenon of self-reactance astatism and defined conditions of its emerging.

This involves existing of certain value of average compound root ω_0 which provides zero value of n_0 coefficient of polynom $N(p) = n_j p^j + n_{j-1} p^{j-1} + \ldots n_1 p + n_0$ of transfer-function denominator resulting in increasing of its astatism by unit

This article develops the idea which was first described in [8], where the phenomenon of self-reactance astatism was grounded for vector control system of two-mass asynchronous drive with uniform load and synthesized polynomial method of speed regulation (SR). Prior familiarization with the mentioned sources is preferable

Let’s analyze possible variants of increase of the order of astatism ν for control $\nu_{U_З}$ and disturbance ν_{M_c} as exemplified by vector control system of two-mass asynchronous drive with non-linear load.

Definition of research objectives

The research objective is argumentation of self-reactance and structural astatism within the system of two-mass vector frequency-controlled asynchronous drive with non-linear load.

For the purposes of the objectives set forth herein the following tasks are settled:

– Defining of unknown coefficients m_{i-1} and n_{j-1}, polynoms $M(p)$ and $N(p)$ synthesized by way of polynomial method of astatic decreased order speed regulator as follows:

$$W_{pc}(p) = \frac{M(p)(2T_\mu p + 1)}{K_0 N(p) p},$$

where $K_0 = \frac{1,5 Z_p K_r \psi_{r0} K_{ДС}}{J_\Sigma K_T}$ − coefficient of amplification of an object; $К_Т$ − coefficient of current-sensing device; Z_p − number of couples of positives; $К_r$ − coefficient of rotor connection; ψ_{r0} – rotor flux linkage; К$_{ДС}$ – coefficient of speed sensor; T_μ – short time constant of circuit; $J_\Sigma = J_1 + J_2$ – joint interia moment of electric drive on spindle;

– argumentation of self-reactance astatism within the system according to the results of dependence diagram $n_0 = f(\omega_0)$ for different standard distributions;

– argumentation of structural astatism within the system in course of load variation.

Research materials

Let's notationally [8] approach to the system of asynchronous electric drive vector control (fig. 1) with two-mass mechanical part and non-linear load.

Upon the condition of constancy of rotor flux linkage ψr0 and compensation of mutual impact of induction motor (IM) and also availability of structural scheme in direct circuit, fig. 1 division-multiplication unit, single-channel linear structure could be laid as a ground for synthesis of regulators of vector control system similar to the structure of direct-current drive thyristor converter – motor, as shown on fig. 2.

Given this, all further researches will to the same extent relate to two-mass direct current drives and alternating-current drives with non-linear load.

For the structure illustrated on fig. 2 while operation of electric drive on the falling section of stress-related characteristics with stiffness β_c, in [9] there was synthesized an astatic regulator of reduced order speed by means of polynomial method. We apply the aforementioned research of direct current drive within the system of asynchronous drive vector control.

In accordance with [9] let's compose transfer function of astatic SR of reduced order for structure on fig. 1:

$$W_{pc}(p) = \frac{(2T_\mu p + 1)(\mathrm{m_2 p^2 + m_1 p + m_0})}{K_0(n_2 p^2 + n_1 p + n_0)p}. \quad (1)$$

This transfer function upon the introduction of response time T$_1$, T$_2^2$, T$_4^2$ и T$_3$ transforms into:

$$W_{pc}(p) = \frac{\mathrm{K_{pc}}(2T_\mu p + 1)(T_2^2\,\mathrm{p}^2 + T_1\,\mathrm{p} + 1)}{(T_4^2 p^2 + T_3 p + 1)p}, \quad (2)$$

where response time $T_1 = \frac{m_1}{m_0}$; $T_2{}^2 = \frac{m_2}{m_0}$; $T_4{}^2 = \frac{n_2}{n_0}$; $T_3 = \frac{n_1}{n_0}$; $K_{pc} = \frac{m_0}{K_0 n_0}$; β_c – stiffness of load mechanical characteristic. At the same time for compensation of cleaner polynom (2) in input to the system an installation of filter with transfer function is requisite:

$$W_\phi(p) = \frac{1}{(T_2{}^2\,\mathrm{p}^2 + T_1\,\mathrm{p} + 1)}. \quad (3)$$

The expression for calculation of unknown coefficients m_{i-1} and n_{j-1} of polinims $M(p)$ and $N(p)$ of astatic speed regulator, synthesides by way of polynomial method in [9] is as follows:

$$m_0 = \alpha_0;\ \mathrm{n}_2 = \frac{\omega^2{}_{12}\alpha_6}{T_c^*\omega_0^6};$$

$$\mathrm{n}_1 = \frac{\omega^2{}_{12}}{T_c^*}\left[\frac{n_2\gamma}{(\gamma-1)\omega^2{}_{12}} + \frac{\alpha_5}{\omega_0^5}\right]; \quad (4)$$

$$m_1 = \frac{\alpha_1}{\omega_0} + \frac{|\beta_c|}{C_{12}}\alpha_0 + \mathrm{n}_0;\ m_2 = \frac{\alpha_2}{\omega_0^2};$$

$$\mathrm{n}_0 = \frac{1}{(\gamma-1)T_c^* - \frac{|\beta_c|\gamma}{C_{12}}} \times$$

$$\times\left[\frac{\alpha_2\gamma}{\omega^2{}_0} - \frac{\omega^2{}_{12}\alpha_4}{\omega_0^4} + \frac{|\beta_c|\gamma\alpha_1}{\omega_0 C_{12}} + \gamma\left(\frac{|\beta_c|}{C_{12}}\right)^2 - \right.$$

$$\left. - \frac{\gamma^2}{\omega^2{}_{12}} - \left(\frac{\gamma}{(\gamma-1)} - \gamma\right)n_1 + T_c^*\omega^2{}_{12}n_2\right];$$

$$m_{21} = \frac{1}{\gamma}\left[\frac{\omega^2{}_{12}\alpha_4}{\omega_0^4} - \right.$$

$$\left. - T_c^* n_0 + \frac{\gamma}{(\gamma-1)}n_1 - \frac{T_c^*\omega^2{}_{12}n_2}{1}\right]$$

$$m_{22} = \frac{C_{12}}{|\beta_c|}\left[\frac{\gamma}{\omega_{12}^2} m_1 + \right.$$
$$\left. + T_c^* n_1 + \frac{\gamma}{(\gamma - 1)\omega_{12}^2} n_0 - n_2 - \frac{\alpha_3}{\omega_0^3}\right],$$

where C_{12} – stiffness of elastic mechanical part; $\omega_{12} = \sqrt{C_{12}\gamma / J_2}$ – resonance frequency of elastic vibrations; $\gamma = (J_1 + J_2) / J_1$ – variable denoting masses correlation.

We should point out that requisite condition of regulator efficiency is a positive value of all coefficients m_{i-1} and n_{j-1}.

Besides, for the purposes of quality of transient characteristic corresponding to chosen standard distribution an equation $m_{21} = m_{22}$ must be followed.

As the duration of the first five coefficients (4) is obvious, let's plot dependence diagrams $m_{22} = f(\omega_0)$ and $m_{12} = f(\omega_0)$ for different distributions and make their comparative analysis based on table 1.

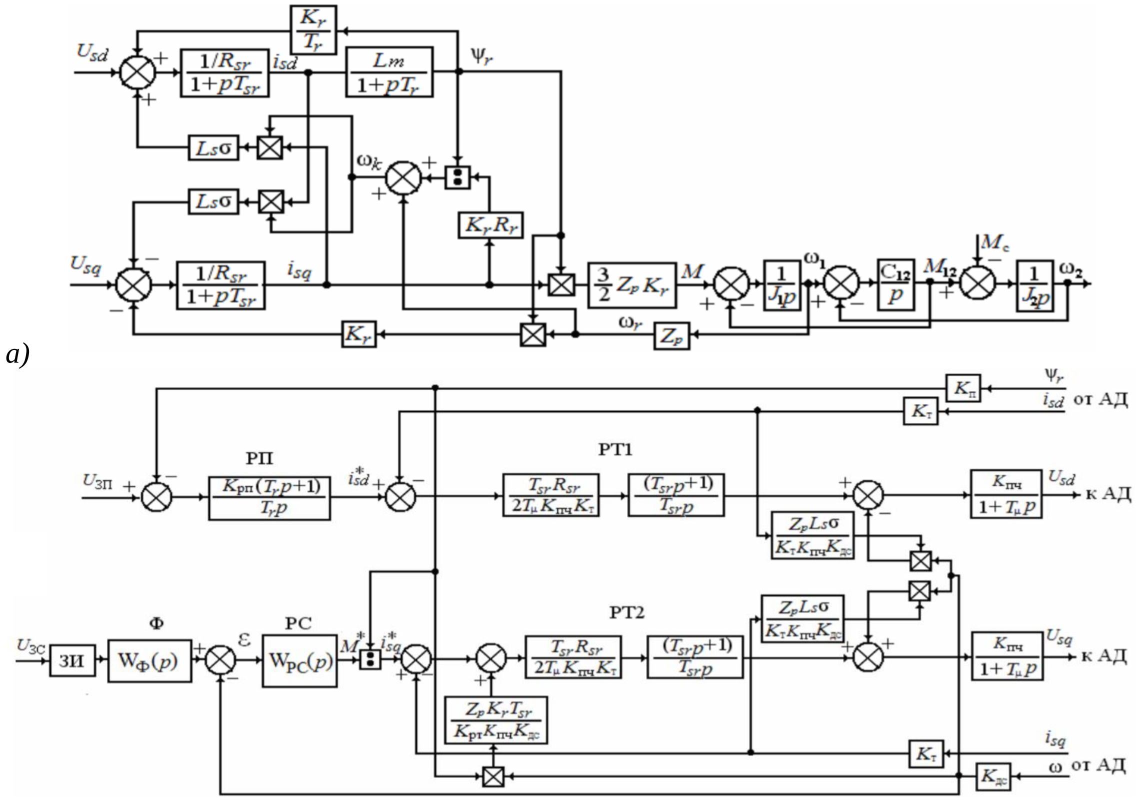


Fig. 1 Structural scheme of AD with КЗ rotor in rotating coordinates, oriented on rotor flux linkage (*a*) and its vector control system with its cross feedbacks compensation (*b*)

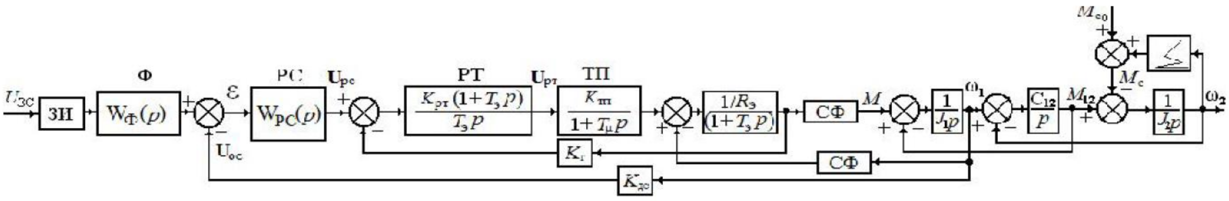


Fig. 2 Structural scheme of the system of subordinated speed regulation, under influence of negative viscous friction, two-mass electrical item

For computer modeling of AD with SR vector control (2) the following values have been taken $J_1=J_2=0{,}3875$ kg·mm^2; $K_r=0{,}9808$; $Z_p=4$; $T_{sr}=0{,}0028$ s; $R_{sr}=1{,}0657$ Ohm; $T_r=0{,}1088$ s; $L_s=0{,}07$ henry; $L_m=0{,}0683$ henry; $\sigma=0{,}0428$. at $U_{3C}=U_{3\text{П}}=10$ V let's consider that: $K_{\text{т}}=0{,}1258$ V/A; $K_{\text{дс}}=0{,}1384$ VS; $K_{\text{п}}=14{,}6326$ В/Вб; $K_{\text{пч}}=38$; $T_\mu=0{,}0002$ s; $\psi_{r0}=0{,}6834$ weber, $\gamma=2$, $C_{12}=7260$ Nm/rad; $\omega_{12}=193{,}6$ s^{-1}. Given При stiffness modulus of AD mechanical characteristics $\beta=28{,}58$ N·m·s the value of stiffness of falling section of mechanical load characteristic has been taken as $\beta_c= -30$ N·m·s, where $\beta_c / \beta = -1{,}05$.

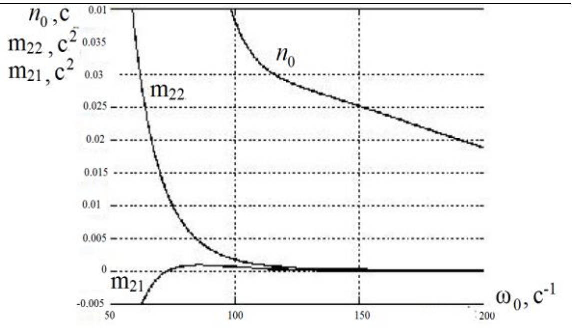
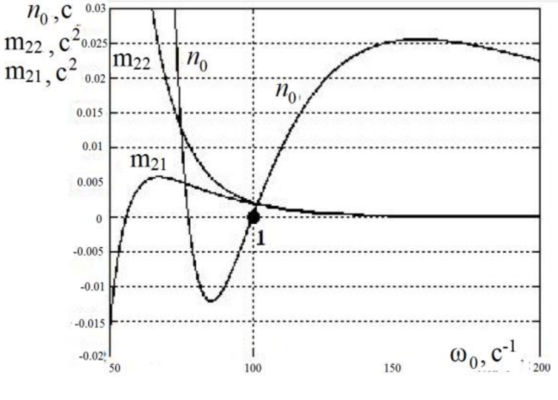
It should be pointed out that for the first three distributions as per table 1, synthesis of astatic SR (2) is impossible as far as the diagrams $m_{22} = f(\omega_0)$ and $m_{12} = f(\omega_0)$ come close to each other but do not cross ($m_{12} \neq m_{12}.$). Common image for the first three items table 1 with diagrams $m_{22} = f(\omega_0)$, $m_{12} = f(\omega_0)$ and $n_0 = f(\omega_0)$ has been given for ITAE distribution. Besides, key feature of these distributions is infeasibility of self-reactance astatism which is applicable as shown in [5] if diagram $n_0 = f(\omega_0)$ crosses abscissa axis. The next four distributions allow to synthesize SC (2) with first order astatism.

Besides there exist a possibility to increase astatism of regulator and entire system from $\nu_{U_з} = \nu_{M_c} = 1$ до $\nu_{U_з} = \nu_{M_c} = 2$ in point 1, where $n_0=0$ at $\omega_0=100$ s^{-1}. It is significant that in case of self-reactacnce astatism polynom of denominator N(p) of transfer function (2) becomes as follows:

$$N(p) = n_2 p^2 + n_1 p^1 = p(\mathrm{n}_2 + n_1).$$

Table 1

Table of standard distributions

	Distributions	Diagrams
1	Butterworth $p^6 + 3{,}86\omega_0 p^5 + 7{,}46\omega_0^2 p^4 + 9{,}13\omega_0^3 p^3 +$ $+7{,}46\omega_0^4 p^2 + 3{,}86\omega_0^5 p + \omega_0^6$	
2	Aliquant distribution of complex roots $p^6 + 3{,}73\omega_0 p^5 + 8\omega_0^2 p^4 + 10{,}3\omega_0^3 p^3 +$ $+8{,}56\omega_0^4 p^2 + 4{,}18\omega_0^5 p + \omega_0^6$	
3	ITAE $p^6 + 3{,}25\omega_0 p^5 + 6{,}6\omega_0^2 p^4 + 8{,}6{,}3\omega_0^3 p^3 +$ $+7{,}45\omega_0^4 p^2 + 3{,}95\omega_0^5 p + \omega_0^6$	
4	Maximum degree of stability (Binomial) $p^6 + 6\omega_0 p^5 + 15\omega_0^2 p^4 + 20\omega_0^3 p^3 +$ $+15\omega_0^4 p^2 + 6\omega_0^5 p + \omega_0^6$	
5	Critical attenuation of transition process $p^6 + 4{,}5\omega_0 p^5 + 9{,}75\omega_0^2 p^4 + 12{,}375\omega_0^3 p^3 +$ $+9{,}75\omega_0^4 p^2 + 4{,}5\omega_0^5 p + \omega_0^6$	
6	Bessel $p^6 + 4{,}495\omega_0 p^5 + 9{,}622\omega_0^2 p^4 + 12{,}358\omega_0^3 p^3 +$ $+9{,}92\omega_0^4 p^2 + 4{,}672\omega_0^5 p + \omega_0^6$	
7	Bessel's psedo-polynomial $p^6 + 4{,}81\omega_0 p^5 + 10{,}511\omega_0^2 p^4 + 13{,}395\omega_0^3 p^3 +$ $+10{,}51\omega_0^4 p^2 + 4{,}81\omega_0^5 p + \omega_0^6$	

Upon introduction of new time response $T_5=n_2/n_1$ and change of coefficient of speed regulator amplification towards value $K_{pc}=\dfrac{m_0}{K_0 n_1}$ SR transfer function which serves self-reactance astatism within the system is represented as follows:

$$W_{pc}(p)=\frac{\mathrm{K}^{*}_{\mathrm{pc}}(2T_{\mu}p+1)(T_2{}^2\,\mathrm{p}^2+T_1\,\mathrm{p}+1)}{(Tp^2+1)p^2}. \quad (5)$$

Common image with diagrams $m_{22}=f(\omega_0)$, $m_{12}=f(\omega_0)$ и $n_0=f(\omega_0)$ in table 1 for items 4-7 has been shown for distribution 5 – critical attenuation of transition process.

Calculation of SR parameters with second order astatism (5) has been delivered with the help of polynomial method with application of distribution corresponding to critical attenuation of sixth order transition process.

$$\alpha_6 p^6+\alpha_5\omega_0 p^5+\alpha_4\omega_0{}^2 p^4+\alpha_3\omega_0{}^3 p^3+$$
$$+\alpha_2\omega_0{}^4 p^2+\alpha_1\omega_0{}^5 p+\alpha_0\omega_0{}^6.$$

With the meaning of coefficients as follows:

$$\alpha_0=1;\alpha_1=4,5;\alpha_2=9,75;\alpha_3=12,375;$$
$$\alpha_4=9,75;\alpha_5=4,5;\alpha_6=1.$$

Regulator (5) has the following parameters $\mathrm{K}^*_{\mathrm{PC}}=8862,3$; $T_5=0,0019$ s; $T_1=0,0491$ s; $T^2{}_2=0,0021$ s^2.

It should be added that initially synthesized system had the first-order astatism according to control and disturbance impact. However upon the condition that $n_0=0$ it becomes second-order astatic ($\nu_{U з}=\nu_{Mc}=$ 2). Increase of astatism is strictly related to average compound root $\omega_0=100\text{s}^{-1}$, where $n_0=0$.

Speed transition process ω_2 within the system with synthesized SR (5), set to the point of self-reactance astatism 1 at $\omega_0=100\text{s}^{-1}$ with output filter, is shown on fig. 3 and defined with fig. 1.

Analysis of the nature of variation of dynamic deviation from nominal load excursion within 0.6 sec, its zero space in particular proves that the system under analysis upon grounded system setup is an astatic second-order disturbance system.

It should be noted that in the xourse of operation of the system with constant load under study, control astatism increases to the third order and disturbance astatism remains that of the second order. In this case self-reactance astatism is applicable as far as unstable nominimal all-pass network with transfer function as follows:

$$W(p)=\frac{1/\beta_c}{(T_c p-1)},\quad T_c=\frac{J_2}{\beta_c}.$$

On system output (img. 2), as a result of absence of positive feedback regarding speed ω_2 with coefficient β_c, becomes integrating element of traditional appearance is:

$$W(p)=\frac{1}{J_2 p}.$$

Transition characteristic shown on img.3 corresponding to this case has been denoted by figure 2. It should be added that the increase of readjustment of control transition characteristic 2 is typical of three-stage-integrating systems.

Estimation of parametrical sensibility of the system with astatic regulator (5) at C_{12} and J_2 parameters variation has been shown on fig. 4 where transition characteristics serving: 1 – input values of parameters, 2 – decrease of parameter by 20 %, 3 – increase of parameter by 60 %.

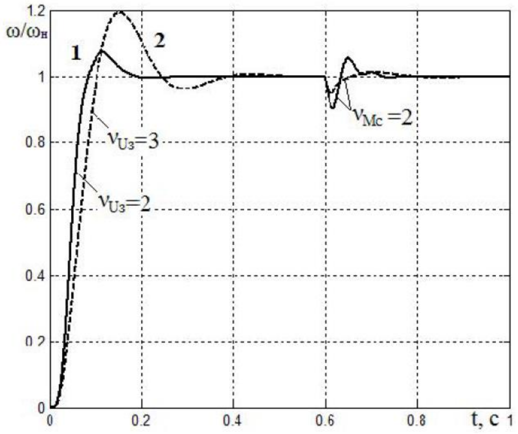


Fig. 3 Transition characteristics and speed ravine at constant load within 0,6 sec

Conclusions

It has been established that in two-mass direct current drive and alternating current drive with constant and variable load in speed function self-reactance astatism is applicable upon the condition of synthesis of system controlling part with root methods system applied. In particular, it relates to modal control systems and to the systems where the synthesis of speed regulators of decreased order is performed on the grounds of polynomial method. It has been defined that the majority of approached standard distributions allow acquiring self-reactance astatism within the system. Application of self-reactance astatism significantly simplifies regulator structure and provides the possibility of significant deviation of such ED parameters as stiffness of elastic linkage C_{12} and и second mass moment of inertia J_2.

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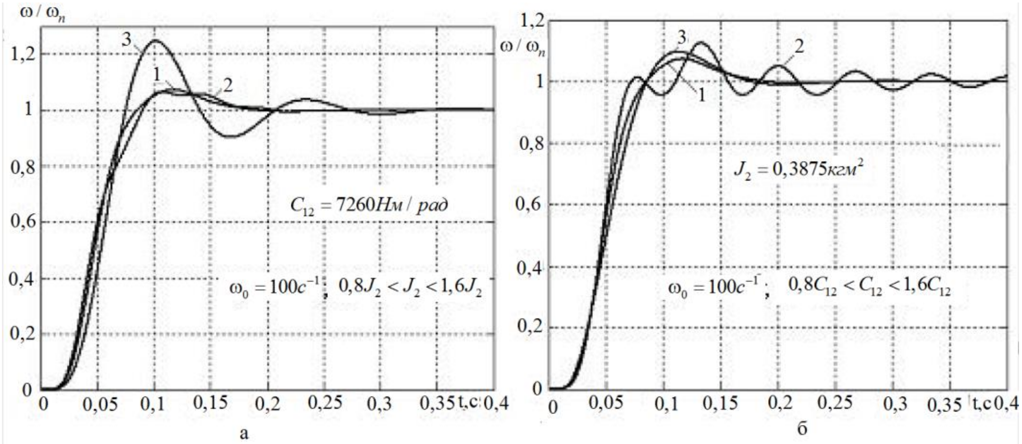

Fig. 4 Transition characteristics at J_2 – (*a*) and C_{12} – (*b*) changes within the system with astatic SR (5)

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