Development and Research of Motion Control Algorithms of Elastic Electromechanical Systems Taking into Account the Damping Properties of the Electric Drive

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Abstract. The paper presents the results of studies of the effect of the counter-electromotive force (CEMF) of the dc machine on the parameters of the elastic oscillation control system of a two-mass electromechanical system, synthesized based on solving the inverse problems of dynamic in accord with prescribed nature of controlled motion. It is shown by the method of numerical simulation that taking into account the CEMF leads to an increase of the damping properties of the electromechanical system and an increase of the gains of the feedbacks on the force in the cable. A method for the selection of these gains is proposed, based on their comparison with the gains obtained in an electromechanical system without taking into account the CEMF and an approximate assessment of its effect on the nature of the transient processes.

1. Introduction

Improving the performance and functional efficiency of the electromechanical systems of technological and transport machines requires an increase of the speed of their electric drives which leads to the appearance of oscillatory movements of the actuators due to the presence of elastic links with weak damping properties [1-3]. Oscillatory movements reduce the accuracy and functional efficiency of electromechanical systems, therefore limiting oscillations is an important task the solution of which is carried out either based on the introduction of various feedbacks [4, 5] or by choosing the design parameters of the mechanisms [6, 7], excluding the possibility of their occurrence.

The widespread use of digital control systems with the possibility of implementing various control algorithms on their basis determines the prospects for using a controlled electric drive as the main means of compensating the oscillatory movements in mechanisms. There are known works on the control of elastic oscillations in electromechanical systems of mining machines [8-10], industrial mechanisms [11,12], mine hoist [13], etc. In these works, the dynamics of a system equipped with a dc machine with a high-speed thyristor converter and a two-loop feedback automatic control system were investigated. The synthesis of control actions was carried out based on a mathematical model of the control object which did not take into account the internal feedback on the CEMF. In work [14] it was shown that taking into account the CEMF significantly complicates the calculations in the synthesis of feedback automatic control system. At the same time, it can be ignored, for example, for mechanisms...
with a large moment of inertia of the drive. There are also known ways to compensate for CEMF through the use of positive feedbacks in the current controller circuit [15]. A detailed analysis of electromechanical systems with elastic links [16,17] revealed a significant relationship between the CEMF and the nature of the oscillatory processes. In [18], using the example of a two-mass electromechanical system, which described the dynamic properties of the digging mechanism of a walking excavator, the results of research on the control of elastic oscillations based on feedback on the force in the cable were presented, the synthesis of which was carried out by solving the inverse problem of dynamics in accord with prescribed nature of controlled motion. In this case, the CEMF of the dc machine was not taken into account.

In this work, the effect of the CEMF of the dc machine on the parameters of the synthesized control system of elastic oscillation in a two-mass electromechanical system is investigated.

2. Object and method of investigation

The research will be carried out on the example of an electromechanical system of a digging mechanism of a dragline equipped with a high-speed thyristor converter with a two-loop feedback automatic control system [19]. We represent the mechanical part of this system with an accuracy sufficient for practice by a two-mass computational scheme with lumped masses, and an elastic link in the form of a weightless thread with constant coefficients of stiffness and viscous friction. Taking into account the accepted assumptions, the linearized system of differential equations will have the following form:

\[
J_1 \ddot{\phi}_1 s = M_{dv} - \frac{c_{12} \Delta \phi_{12}}{s} - b_{12} \Delta \phi_{12} \quad (1); \quad J_2 \ddot{\phi}_2 s = \frac{c_{12} \Delta \phi_{12}}{s} + b_{12} \Delta \phi_{12} - M_c \quad (2); \quad M_{dv} = C_e I_a \quad (3);
\]

\[
E_{dv} = C_e \phi_1 \quad (4); \quad I_a = \frac{E_p - E_{dv}}{T_a s + 1} k_a \quad (5); \quad \frac{(k_{CR} T_{CR} s + 1)(T_a s + 1)k_p}{T_{CR} s (T_p s + 1)} (U_{cr} - I_a k_{cs}) = E_p \quad (6);
\]

\[
(U_{ref} - k_{ss} \phi_1) k_{SR} = U_{cr} \quad (7).
\]

Where \( J_1 \) is the inertia of the shaft two motors, and equivalent moment of inertia gearbox and drums; \( J_2 \) is the inertia of the actuator; \( c_{12} \) is the stiffness of cable; \( b_{12} \) is viscous friction of cable; \( M_{dv} \) is the drive torque; \( M_c \) is the load torque; \( \phi_1 \) and \( \phi_2 \) are angular velocities of the masses; \( \Delta \phi_{12} = \phi_1 - \phi_2 \) are the velocities of the elastic deformation; \( C_e \) is the voltage constant; \( E_{dv} \) is the dc machine voltage; \( E_p \) is the converter voltage; \( k_a \) is the gain of the armature circuit; \( T_a \) is the time constant of the armature circuit; \( k_p \) is the converter gain; \( T_p \) is the converter time constant; \( k_{cs} \) is the gain of the current sensor; \( k_{CR} \) is the gain of the current controller; \( T_{CR} \) is the time constant of the current controller; \( U_{cr} \) is the voltage at the input of the current controller; \( k_{ss} \) is the gain of the speed sensor; \( k_{SR} \) is the coefficient of the speed controller; \( U_{ref} \) is the reference voltage; \( s = \frac{d}{dt} \) is a Laplace operator [18].

Introducing the value of the elastic force in the form \( M_{12} = \frac{c_{12} + b_{12} s}{s} \Delta \phi_{12} \) and solving the equations (1) and (2) under the condition \( M_c = 0 \), we obtain the equation of motion of the mechanical part of the system

\[
M_{12} s^2 + b_{12} J_{12} M_{12} s + \omega_{12}^2 M_{12} = \frac{c_{12} + b_{12} s}{J_1} M_{dv}, \quad (8)
\]
where \( \omega_{12} = \sqrt{\frac{c_{12}(J_1 + J_2)}{J_1 J_2}} \) is the natural oscillations of a two-mass mechanical system; \( J_{12} = \frac{J_1 + J_2}{J_1 J_2} \) is the inertia moment ratio.

Using the approach proposed in [18], we accept the law of change of the force in the cable in the following form

\[
M_{12} = e^{a t} (\cos \beta t + \sin \beta t),
\]

(9)
in which the parameters \( \alpha \) and \( \beta \) are selected based on the characteristic polynomial of equation (8) at a given relative damping coefficient \( \xi = 0.707 \), which ensures maximum response time with minimum overshoot.

Solving the inverse problem, according to the algorithm described in [18], based on expression (8) we find the law of change of the drive torque, which ensures the prescribed nature of motion

\[
M_{dv} = C_1 e^{a t} \cos \beta t + C_2 e^{a t} \sin \beta t.
\]

(10)

Constants \( C_1 \) and \( C_2 \) at functions of time are equal:

\[
C_1 = \frac{J_1 (c_{12} + b_{12} \alpha - b_{12} \beta K_2)}{(c_{12} + b_{12} \alpha)^2 + b_{12}^2 \beta};
\]

\[
C_2 = \frac{J_1 (c_{12} + b_{12} \alpha - b_{12} \beta K_1)}{(c_{12} + b_{12} \alpha)^2 + b_{12}^2 \beta},
\]

where \( K_1 = \alpha^2 + 2 \alpha \beta - \beta^2 + b_{12}^2 J_{12} (\alpha + \beta) + \omega_{12}^2 \) and \( K_2 = \alpha^2 - 2 \alpha \beta - \beta^2 + b_{12}^2 J_{12} (\alpha - \beta) + \omega_{12}^2 \).

Substituting (10) in (1), (3), and (4), taking into account (8), we will successively determine the laws of change of the electromechanical system coordinates \( \phi_1 \), \( I_a \) and \( E_{DV} \).

\[
\dot{\phi}_1 = B_1 e^{a t} \cos \beta t + B_2 e^{a t} \sin \beta t.
\]

(11)

Here \( B_1 = \frac{\alpha(C_1 - 1) - \beta(C_2 - 1)}{J_1 (\alpha^2 + \beta^2)} \) and \( B_2 = \frac{\beta(C_1 - 1) + \alpha(C_2 - 1)}{J_1 (\alpha^2 + \beta^2)} \).

\[
E_{DV} = C_e \dot{\phi}_1 = C_e B_1 e^{a t} \cos \beta t + C_e B_2 e^{a t} \sin \beta t.
\]

(12)

\[
I_a = \frac{M_{DV}}{C_e} = \frac{C_1}{C_e} e^{a t} \cos \beta t + \frac{C_2}{C_e} e^{a t} \sin \beta t.
\]

(13)

Let us find the law of change \( E_p \), taking into account the effect of the CEMF. In [18], when synthesizing the control system, the CEMF of the dc machine was not taken into account, therefore, further relations will differ, but the method of their calculations will remain the same.

Expressing from (5) \( E_p \) and substituting laws (12) and (13) into the obtained equality, after the operation of differentiation and some transformations, we obtain

\[
E_p = L_1 e^{a t} \cos \beta t + L_2 e^{a t} \sin \beta t,
\]

(14)
in which \( L_1 = \frac{[T_a (C_1 \alpha + \beta C_2) + C_1]}{C_e k_a} + C_e B_1 \) and \( L_2 = \frac{[T_a (C_2 \alpha - \beta C_1) + C_2]}{C_e k_a} + C_e B_2 \).

Continuing the calculations, we determine the law of voltage change at the input of the current controller \( U_{CR} \), dividing the variables \( U_{CR} \) and \( E_p \) in (6), and knowing the law \( E_p \), we obtain \( U_{CR} \) in the form
\[ U_{CR} = G_1 e^{\alpha t} \cos \beta t + G_2 e^{\alpha t} \sin \beta t , \] (15)

unknown coefficients in which are determined based on the following relationships:

\[ G_1 = \frac{N_1 (k_{CR} T_{CR} \alpha + 1) - k_{CR} T_{CR} \beta N_1)}{k_p (k_{CR} T_{CR} \alpha + 1)^2 + (k_{CR} T_{CR} \beta)^2} \]
\[ G_2 = \frac{N_2 (k_{CR} T_{CR} \alpha + 1) + k_{CR} T_{CR} \beta N_1)}{k_p (k_{CR} T_{CR} \alpha + 1)^2 + (k_{CR} T_{CR} \beta)^2} \]

The time effect of the system is assumed to be equal into account the

\[ N_1 = T_{CR} T_p (M_1 \alpha + M_2 \beta) + T_{CR} M_1 + k_{CS} k_p k_{CR} T_{CR} \frac{C_1 \alpha + C_2 \beta}{C_e} + \frac{k_{CS} k_p C_1}{C_e} , \]
\[ N_2 = T_{CR} T_p (M_2 \alpha - M_1 \beta) + T_{CR} M_2 + k_{CS} k_p k_{CR} T_{CR} \frac{C_2 \alpha - C_1 \beta}{C_e} + \frac{k_{CS} k_p C_2}{C_e} ; \]

\[ M_1 = L_1 \alpha + L_2 \beta \quad \text{and} \quad M_2 = L_2 \alpha - L_1 \beta . \]

with the known law of change the current controller voltage \( U_{CR} \) (15), we find the law of changing the voltage control \( U_{ref} \) using equations (7) and (11)

\[ U_{ref} = P_1 e^{\alpha t} \cos \beta t + P_2 e^{\alpha t} \sin \beta t . \] (16)

Unknown constants are found from expressions: \( P_1 = \frac{G_1}{k_{SR}} + k_{SS} B_1 \) and \( P_2 = \frac{G_2}{k_{SR}} + k_{SS} B_2 \).

We synthesize the structure and parameters of the control system based on the feedback principle. For this purpose, we compose a system of equations for the force in the cable and its derivative

\[ \begin{bmatrix} M_{12} = e^{\alpha t} \cos \beta t + e^{\alpha t} \sin \beta t \\ M_{12} p = (\alpha + \beta) e^{\alpha t} \cos \beta t + (\alpha - \beta) e^{\alpha t} \sin \beta t \end{bmatrix} . \]

Expressing the time functions from the system in terms of the force and its derivative and substituting the obtained values into (16), we obtain the control in the form

\[ U_{ref} = (k_f p + k_A) M_{12} . \] (17)

The feedback gains in (17) are \( k_f = \frac{P_1 - P_2}{2 \beta} \) and \( k_A = \frac{P_1 (\beta - \alpha) + P_2 (\alpha + \beta)}{2 \beta} . \)

3. Research and discussion

The effect of the CEMF of the dc machine on the parameters of the synthesized control system is estimated by numerical modeling of the electromechanical system of the excavator digging mechanism, with parameters close to the real mechanism \( J_1 = 572 \text{kg} \cdot \text{m}^2 , \quad J_2 = 60 \text{kg} \cdot \text{m}^2 , \quad c_{12} = 7500 \text{N} \cdot \text{m} / \text{rad} , \quad b_{12} = 150 \text{N} \cdot \text{m} \cdot \text{s} / \text{rad} , \quad C_e = 17.37 \text{V} \cdot \text{s} / \text{rad} , \quad k_a = 33 \Omega^{-1} , \quad T_a = 0.082 \text{sec} , \quad k_p = 120 , \quad T_p = 0.01 \text{sec} , \quad k_{SS} = 0.151 \text{V} \cdot \text{s} / \text{rad} , \quad k_{CS} = 0.00313 \text{V} / \text{A} , \quad T_{CR} = 0.25 \text{sec} , \quad k_{CR} = 0.328 , \quad k_{SR} = 8 . \)

The comparison will be carried out with a system in which gains of feedbacks are obtained without taking into account the CEMF of the dc machine [18]. Let us call the control system obtained taking into account the CEMF system 1, and without taking into account the CEMF - system 2. The coefficient of relative damping for both systems is assumed to be equal \( \xi = 0.707 ; \) in this case, the calculated values of the roots of the characteristic polynomial were \( \alpha = -8,3087 \) and \( \beta = 8,311 . \) The parameters of the speed and current controllers are synthesized according to the standard procedure,
with an uncompensated time constant of the thyristor converter $T_\mu = T_\nu = 0.01 \text{sec}$. The calculated values of the feedback gains for system 1 were $k_A = -0.00042333$ and $k_V = -0.000029$, for system 2 - $k'_A = -0.0002378$ and $k'_V = -0.000014708$. Comparing the gains, we note that in system 1 $k_A$ increased in 1.8 times, and $k_V$ in 2 times. Considering that the damping coefficient for the two systems was taken equal $\xi = 0.707$, an increase in the gains of feedback when taking into account the CEMF of the dc machine indicates an increase in the internal damping properties of system 1 compared to system 2. This circumstance was also noted in [17], in which it was shown that in the oscillating system the CEMF promotes an increase in damping properties and a decrease the amplitude of elastic oscillations.

This consequence allows us to draw the following conclusion. Since the CEMF increases the damping properties of the system then during the synthesis of the elastic oscillation control system, it is possible to reduce the adopted coefficient of relative damping $\xi$ by the magnitude of the effect of this connection. This can be done in the following way. Reducing the parameter $\xi$ in the synthesis of system 1, for example, to a value $\xi = 0.52$, we achieve approximate equality of the gains $k_A \approx k'_A = -0.0002378$ and $k_V \approx k'_V = -0.000014708$ with system 2, obtained without taking into account the CEMF. Then we recalculate the gains of feedback in system 2 [18] with a new value $\xi = 0.52$: $k'_A = -0.0001589$ and $k'_V = -0.000009518$.

Numerical modeling of equations (1) - (7) and (17) with feedback gains $k'_A = -0.0001589$ and $k'_V = -0.000009518$ was carried out in the Matlab Simulink software package for the starting and stopping modes of the electromechanical system in a linear setting.

Oscillograms of the transient processes of the force in the cable $M_{12}$ and the drive torque $M_{dv}$, the speed of the drive $\omega_1$ and the actuator $\omega_2$ for the options of feedbacks without taking into account the CEMF - 1 ($k'_A = -0.0002378$ and $k'_V = -0.000014708$) and taking it into account - 2 ( $k'_A = -0.0001589$ and $k'_V = -0.000009518$) are shown in Fig. 1a. and 1b.

![Oscillograms of transient processes](image)

**Figure 1.** Oscillograms of transient processes.

The analysis of oscillograms shows that taking into account the CEMF makes it possible to improve the quality of the transient processes of the actuator speed $\omega_2$ and the force in the cable $M_{12}$, the behavior of which approaches the adopted oscillatory law (9). The amplitude of the force $M_{12}$ in
system 2 increases by 17%, while the behavior of the actuator speed changes according to the prescribed law with an overshoot of 4%, which corresponds to the adopted damping coefficient \( \xi = 0.707 \). The amplitude of the drive torque \( M_{dv} \) practically does not change, however, there is a certain shift in oscillations and a delay in the transient process. It should be noted that taking into account the CEMF at the standard settings of the controllers of the control system and compensation of elastic oscillations based on feedbacks makes it possible to reduce the values of the gains and more fully use the damping capabilities of a standard electric drive.

4. Conclusion
The performed studies have shown a significant effect of the CEMF of the dc machine on the parameters of the elastic oscillation control system. It was found that taking into account the CEMF leads to an increase of the damping properties of the electromechanical system and an increase gains of the feedbacks. A method for the selection of these coefficients is proposed, based on their comparison with the coefficients obtained in an electromechanical system without taking into account the CEMF and an approximate assessment of its effect on the nature of the transient processes. With the standard settings of the control system controllers, taking into account the CEMF when synthesizing the control of elastic oscillations based on the concept of inverse problems of dynamics makes it possible to more fully take into account the damping properties of a standard electric drive and more rationally determine the gains of the feedbacks.

5. References
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