LATVIAN JOURNAL OF PHYSICS AND TECHNICAL SCIENCES
2010, N 2

10.2478/v10047-010-0005-2

OPTIMIZATION OF CONTROL PROCESSES OF DIGITAL ELECTRICAL DRIVE SYSTEMS

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The aim of the work is solution of the problems associated with synthesis of the digital speed regulators both for DC and AC thyristor electrical drives. The investigation is realized based on the parameters of continuous technological equipment (e.g. paper-making machine) by taking into account elastic transmission links of the drive systems. Appropriate frequency characteristics and transient processes are described.

Key words: *dc/ac electrical drives of paper-making and metallurgical machines, digital control of electrical drives.*

1. INTRODUCTION

Nowadays, digital control systems play important role in metallurgical mills and paper-machines [1]. Modern electrotechnical companies motorize electrical drives with digital controllers, which ensure high production quickness and efficiency and thus the quality of output products.

The main purpose of the paper is connected with the problem of finding the optimal controllers with rigid and elastic mechanical shafts, both for dc and ac drives. The results of theoretical investigations were verified by MatLab simulation of transient processes going in the drive systems under consideration.

2. REGULATORS FOR DC ELECTRICAL DRIVE SYSTEMS

It is known that differential equations for the motor with a rigid mechanical shaft can be expressed as [1, 2]:

$$\begin{cases} \Delta\varepsilon_T = K_e \Delta\nu + \dfrac{1}{K_a}(T_a \dfrac{d\Delta\mu}{dt} + \Delta\mu); \\ \Delta\mu - \Delta\mu_{ST} = T_M \cdot \dfrac{d\Delta\nu}{dt}, \end{cases} \tag{1}$$

where $\Delta\varepsilon_T, \Delta\mu, \Delta\nu$ and $\Delta\mu_{ST}$ – relative increments in the voltage of thyristor converter, torque, static load, and rotation velocity of the drive, respectively;

K_e, K_a – the gain coefficients of the motor;

T_a, T_M – the electromagnetic and mechanical time constants of the drive system, respectively.

To describe our mathematical model of the thyristor convertor we use the equation [1, 3]:

$$T_T \frac{d\varepsilon_T}{dt} + \varepsilon_T = K_T \cdot \Delta \upsilon_c, \tag{2}$$

where K_T – the gain coefficient of the converter;

T_T – the time constant of the filter at the converter input, and

$\Delta \upsilon_c$ – the output voltage of the speed regulator (i.e. corrector).

Equations (1) and (2) define the common transfer function of the drive object (with optimized contour of current):

$$W_{DC0}^{*}(s) = \frac{1}{K_i \cdot T_M \cdot s(2T_{\Sigma 2} \cdot s + 1)}, \tag{3}$$

where K_i – a transfer coefficient of the current circuit;

$T_{\Sigma 2}$ – an equivalent time constant of the current circuit.

To study the operation of an appropriate digital drive system we assume the following numerical values for parameters: $K_i = 0.1$, $T_{\Sigma 2} = 0.01$ s, $T_M = 11.5$ s, and $T_0 = 0.05$ s (usually T_0 denotes the discretization period). Therefore, transfer function (3) in the form of *z*-operators will be presented as [4]:

$$W_{DC0}^{*}(z) = \frac{0.0275z + 0.0124}{z^2 - 1.08z + 0.082}. \tag{4}$$

The Bode diagrams built using (4) are shown on Fig. 1.

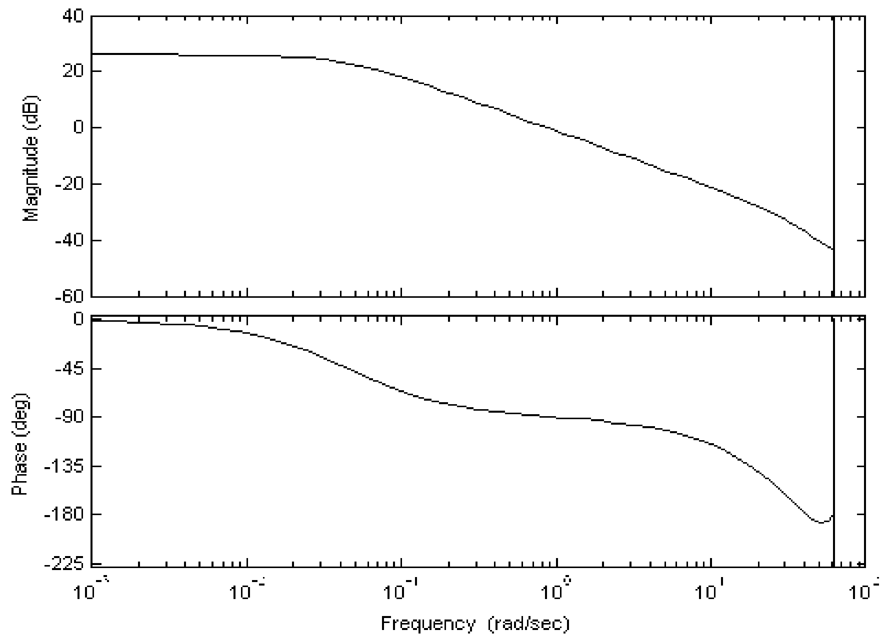

Fig. 1. Bode diagrams for the dc drive object with a rigid mechanical shaft.

Applying the method of frequency analysis to expression (4) (based on the Bode diagrams of Fig. 1) we can find the optimal transfer function for the regulator:

$$D_{DC}^{*}(z)=\frac{5z+1}{z}. \tag{5}$$

Using (5) we obtain the transfer function of a dc closed-loop drive system with digital control as

$$W_{DC}^{*}(z)=\frac{0.1375z^{2}+0.0895z+0.0124}{z^{3}-0.9425z^{2}+0.1715z+0.0124}. \tag{6}$$

The roots of characteristic equation (6) are: $z_1=0.3487$; $z_2=-0.05482$, and $z_3=0.6486$. It is clear that all these roots satisfy the condition $|z_i|<1, i=\overline{1;3}$ indicating the dynamical stability of the considered digital system. On Fig. 2 a transient process of the drive system (6) is presented.

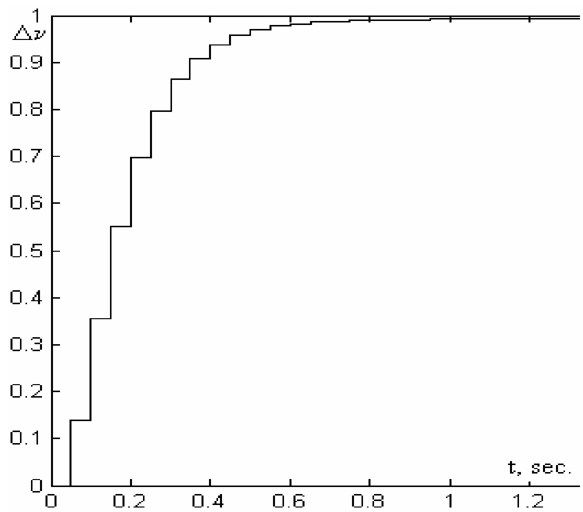

Fig. 2. The transient process in the dc drive system according to transfer function (6).

The second step in the drive optimization relates to the dc electrical drives with elastic mechanical shafts. Taking into account this property of the mechanical shaft of an electrical drive, we can express the motion equations of a thyristor dc drive as

$$\begin{cases} \Delta\mu-\Delta\mu_e=T_1\dfrac{d\Delta\nu_1}{dt}; \\ \Delta\mu_e-\Delta\mu_{ST}=T_2\dfrac{d\Delta\nu_2}{dt}; \\ \Delta\mu_e=\dfrac{1}{T_c}\int(\Delta\nu_1-\Delta\nu_2)dt+\dfrac{T_d}{T_c}(\Delta\nu_1-\Delta\nu_2), \end{cases} \tag{7}$$

where T_1 and T_2 – the mechanical time constants of inertial masses of the motor and the mechanism;

$\Delta\nu_1$ and $\Delta\nu_2$ – the increments in angular velocities of the motor and the mechanism;

$\Delta\mu_e$ – the elastic moment increment of the mechanical shaft of the drive;

T_d and T_c – the time constants characterizing the viscous friction and rigidity of the mechanical shaft, respectively.

From system (7) we find the transfer function of an object:

$$W_{DC0}^{**}(s) = \frac{k_0(b_0 s^2 + b_1 s + 1)}{a_0 s^4 + a_1 s^3 + a_2 s^2 + a_3 s + 1}, \tag{8}$$

where $K_0 = \dfrac{1}{K_i T_M}$;

$b_0 = T_2 T_c$;

$b_1 = T_d$;

$a_0 = \dfrac{2T_{\Sigma 2} T_1 T_2 T_c}{T_M}$;

$a_1 = \dfrac{T_1 T_2 T_c}{T_M} + 2T_{\Sigma 2} T_d$;

$a_2 = 2T_{\Sigma 2} + T_d$;

$T_M = T_1 + T_2$.

Assuming the following numerical values for the above parameters to be: $T_1 = 1.5$ s; $T_2 = 10$ s; $T_d = 0.002$ s, and $T_c = 0.0004$ s, we can conclude that the expression of transfer function (8) in this case will be:

$$W_{DC0}^{**}(s) = \frac{0.87(0.004s^2 + 0.002s + 1)}{s(0.00001s^3 + 0.00056s^2 + 0.022s + 1)}. \tag{9}$$

Therefore, the transfer function of a discretely controlled object with z-operators described by (9) could be written as

$$W_{DC0}^{**}(z) = \frac{0.01686(z + 0.99167)}{(z - 0.725)(z - 1)[(z - 0.986)^2 + 0.59^2]} \cdot$$

$$\cdot [(z - 0.9964)^2 + 0.4868^2]. \tag{10}$$

On Fig. 3 Bode diagrams according to (10) are presented.

By frequency analysis, using Eq. (10) and Bode diagrams of Fig. 3, we define the transfer function of an optimal digital regulator and its parameters for the DC drive with an elastic link:

$$D_{DC}^{**}(z) = \frac{10(z - 1)[(z - 0.986)^2 + 0.59^2]}{[(z - 0.9964)^2 + 0.4868^2]}. \tag{11}$$

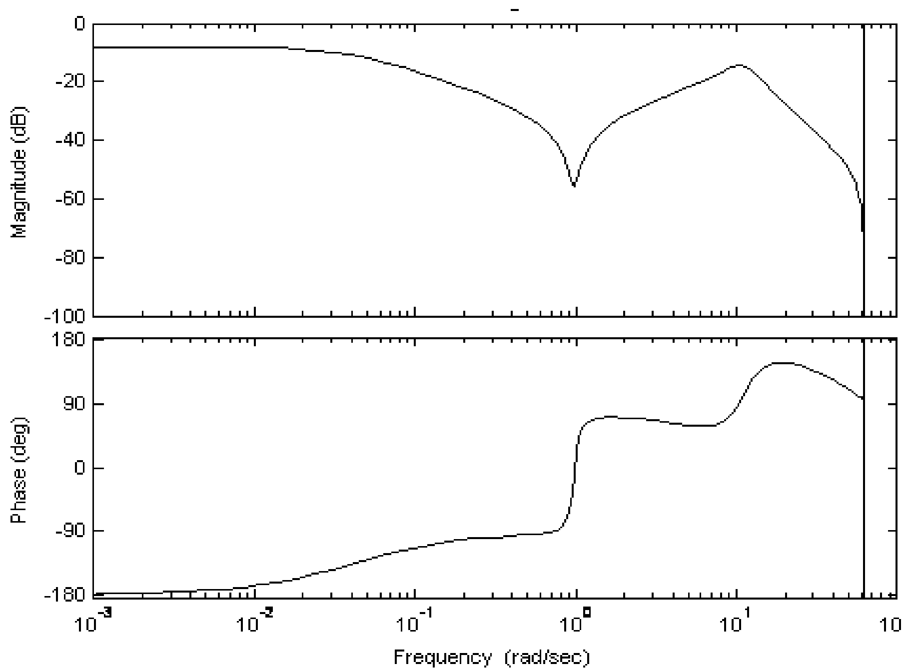

Fig. 3. Bode diagrams for the dc drive object with elastic mechanical shaft.

Using (11) it is not difficult to obtain the transfer function of a closed-loop thyristoric drive system taking into account the elastic properties of the mechanical shaft:

$$W_{DC}^{**}(z) = \frac{0.1686z + 0.1672}{z^2 - 0.5564z + 0.1672}. \tag{12}$$

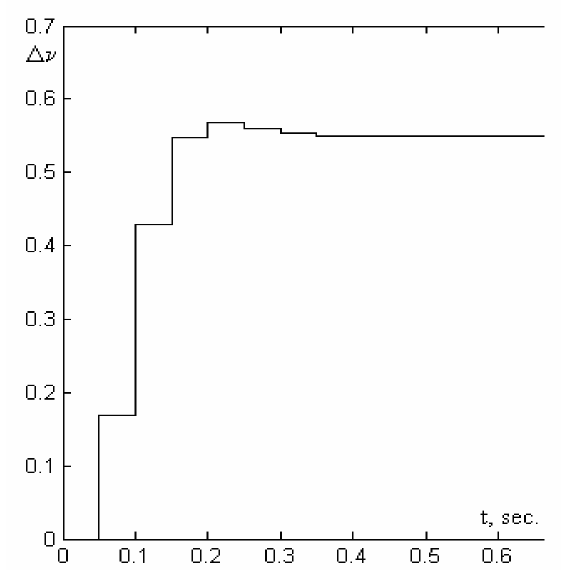

Fig. 4. The transient process in the dc drive system according to transfer function (12).

The roots of characteristic equation (12) are: $z_{1;2} = 0.278 + i \cdot 0.3$. Since $\left| z_{1;2} \right| = 0.42 < 1$ we can conclude that the drive system is dynamically stable. On Fig. 4 a transient process corresponding to the closed-loop drive system according to (12) is presented.

3. REGULATORS FOR AC ELECTRICAL DRIVE SYSTEMS

Here we will consider a mathematical model of a discretely controlled asynchronous electric drive with adjustable voltage. First of all we should write the differential equations for the motor with a rigid mechanical shaft:

$$\begin{cases} T_{EM} \dfrac{d\Delta\mu}{dt} + \Delta\mu = 2 \cdot \Delta\upsilon_{\phi}; \\ \Delta\mu - \Delta\mu_{CT} = T_M \dfrac{d\Delta\nu}{dt} + \dfrac{1}{\delta_B} \cdot \Delta\nu, \end{cases} \tag{13}$$

where $\Delta\upsilon_{\phi}$, $\Delta\mu$, $\Delta\mu_{CT}$, $\Delta\nu$ – the relative increments in the motor phase voltage, torque, static load and the rotation velocity of the drive;

T_{EM} and T_M – electromagnetic and mechanical time constants of the drive;

δ_B – a relative drop in the drive velocity.

Using expressions (13) and (2) for the thyristor converter of an ac motor, we can easily define the general transmission function of the drive object with *s*-operators as

$$W_0(s) = \frac{K_0}{a_0 s^3 + a_1 s^2 + a_2 s + 1}, \tag{14}$$

where $K_0 = 2K_T \cdot \delta_B$;

$a_0 = T_T \cdot T_{EM} \cdot \delta_B \cdot T_M$;

$a_1 = T_T \cdot T_{EM} + T_{EM} T_M \delta_B + T_T \cdot \delta_B \cdot T_M$;

$a_2 = T_T + T_{EM} + T_M \cdot \delta_B$.

Given the parameters $K_T = 25$; $\delta_B = 0.11$; $T_T = 0.01$ s; $T_{EM} = 0.075$ s; $T_M = 11.5$ s, we decompose (14) into simple rational fractions in the form [4]:

$$W_0(s) = \sum_{i=1}^{3} \frac{A_i}{s + \alpha_i}, \quad i = \overline{1;3} \tag{15}$$

where $A_1 = 0.6743$; $A_2 = 5.3329$; $A_3 = 4.6587$; $\alpha_1 = -100$; $\alpha_2 = -13.33$ and $\alpha_3 = -0.7805$. The transfer function corresponding to (15) can be written in the *z*-operational form as

$$W_0(z) = \sum_{i=1}^{3} \frac{A_1(1-d_i)}{z-d_i}, \tag{16}$$

where $d_i = e^{-\alpha_i T_o}$; T_0= 0.01 s; $d_1 = 0.3676$; $d_2 = 0.8754$; $d_3 = 0.9921$.

Using the numerical values, we can rewrite (16) in the form:

$$W^*_{AC0}(z) = \frac{7.384 \cdot 10^{-4} z^2 + 0.002261z + 0.0004181}{z^3 - 2.235z^2 + 1.555z - 0.3194}. \tag{17}$$

Performing the frequency analysis according to (17) we will define the optimal regulator with the transfer function:

$$D^*_{AC}(z) = \frac{30z - 26.4}{z}. \tag{18}$$

Using (18) we obtain the transfer function of the closed-loop asynchronous drive system with digital control:

$$W^*_{AC}(z) = \frac{0.0222z^3 + 0.0483z^2 - 0.0471z - 0.011}{z^4 - 2.212z^3 + 1.6033z^2 - 0.3665z - 0.011}. \tag{19}$$

The transient process corresponding to (19) is shown on Fig. 5.

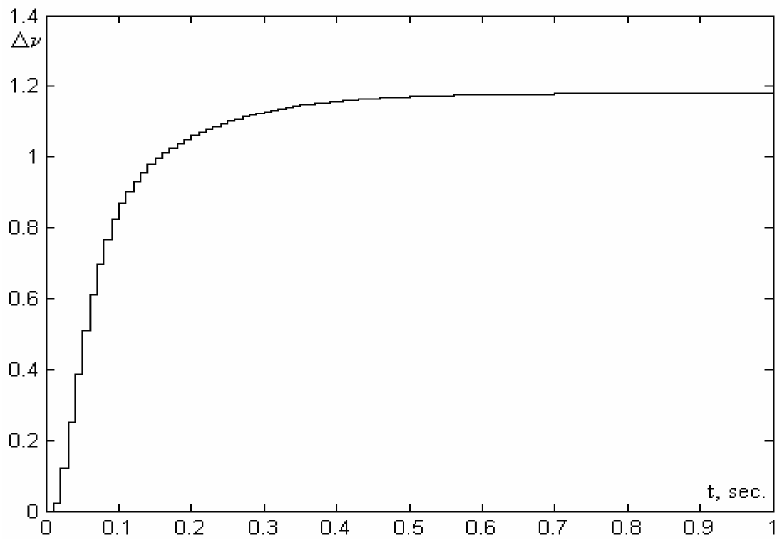

Fig. 5. The transient process in the ac drive system according to transfer function (19).

The characteristic equation (19) has the following four roots: $z_1 = -0.02676$; $z_2 = 0.8708$; $z_{3;4} = 0.6839 \pm i0.06454$. Since for the obtained roots the condition $|z_i| < 1$ is fulfilled, our drive system (without elasticity) is dynamically stable.

Now, taking into account the elastic properties of the mechanical shaft of the drive, we will rewrite the motion equations of the asynchronous motor in the following form:

$$\begin{cases} \Delta\mu - \Delta\mu_e = T_1 \dfrac{d\Delta\nu_1}{dt} + \dfrac{1}{\delta_B}.\Delta\nu_1; \\ \Delta\mu_e - \Delta\mu_{CT} = T_2 \dfrac{d\Delta\nu_2}{dt}; \\ \Delta\mu_e = \dfrac{1}{T_c}\int(\Delta\nu_1 - \Delta\nu_2)dt + \dfrac{T_d}{T_c}(\Delta\nu_1 - \Delta\nu_2), \end{cases} \tag{20}$$

where T_1 and T_2 – the mechanical time constants of inertial masses of the motor and mechanism;

$\Delta\nu_1$ and $\Delta\nu_2$ – the increments in angular velocities of the motor and the mechanism;

$\Delta\mu_e$ – an elastic moment increment of the mechanical shaft of the drive;

T_d and T_c – the time constants characterizing the viscous friction and rigidity of the mechanical shaft.

By (20) we easily define the transfer function of the object of the elastic drive as

$$W^{**}_{AC0}(s) = \frac{k_0(b_0 s^2 + b_1 s + 1)}{a_0 s^4 + a_1 s^3 + a_2 s^2 + a_3 s + 1}, \tag{21}$$

where $b_0 = T_2 T_c$; $b_1 = T_d$;
$a_0 = T_1 T_2 T_c \delta_B \cdot T_T \cdot T_{EM}$;
$a_1 = [T_2 T_c + (T_1 + T_2)\delta_B T_d](T_T + T_{EM}) + T_1 T_2 T_C \delta_B$;
$a_2 = (T_T + T_{EM})[(T_1 + T_2)\delta_B + T_d] + [T_2 T_C + (T_1 + T_2)\delta_B T_d]$;
$a_3 = (T_1 + T_2)\delta_B + T_d + T_T + T_{EM}$;
the values of T_1, T_2, T_c and T_d are as above.

The numerical computation of (21) gives:

$$W^{**}_{AC0}(s) = \frac{0.022 s^2 + 0.014 s + 5.5}{0.0001 s^4 + 0.0022 s^3 + 0.1149 s^2 + 1.352 s + 1} \tag{22}$$

Transformation of (22) in the z-operational form can be presented as

$$W^{**}_{AC0}(z) = \frac{0.01 z^3 - 0.01 z^2 - 0.0086 z + 0.01}{z^4 - 3.694 z^3 + 5.903 z^2 - 3.311 z + 0.8025}. \tag{23}$$

By the frequency analysis we will define the optimal parameters (numerical values) of a digital controller:

$$D^{**}_{AC}(z) = \frac{[(z - 1.51)^2 + 1.17^2]}{[(z - 0.9825)^2 + 0.2663^2]} \ . \tag{24}$$

It is not difficult to obtain the transfer function of the closed-loop asynchronous drive system taking into account the elastic properties of the mechanical shaft:

$$W_{AC}^{**}(z) = \frac{0.01z + 0.0965}{z^2 - 0.65z + 0.3}. \tag{25}$$

The roots of the characteristic equation (25) are: $z_{1;2} = 0.325 \pm i \cdot 0.44$. Since $|z_i| < 1$, $i = \overline{1;2}$ the dynamic stability of the drive system is observed (the transient process is shown on Fig. 6).

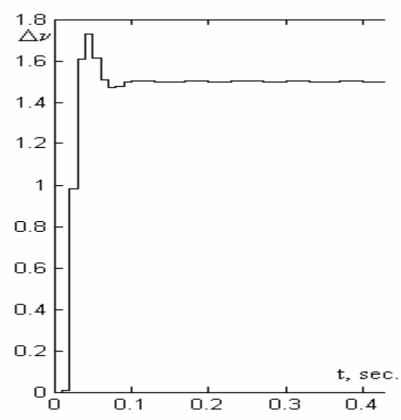

Fig. 6. The transient process in the AC drive system according to transfer function (25).

4. CONCLUSION

The computer investigations of the considered drive have shown that the duration of a transient process is 1.0 s for a rigid shaft, and within 0.2 s (owing to a relatively difficult correction) for an elastic shaft with permissible vibrations.

ACKNOWLEDGMENT

I am grateful to the Referee for her/his corrections.

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DIGITĀLO ELEKTRISKO PIEDZIŅU SISTĒMU
KONTROLES PROCESU OPTIMIZĀCIJA

J. Dochviri

K o p s a v i l k u m s

Darbā izskatītas problēmas saistītas ar elektrisko iekārtu DC un AC (līdzstrāvas un maiņstrāvas) tiristoru elektrisko piedziņu digitālo ātrumu regulatoru sintēzi. Izpēte tiek realizēta uz tehnoloģisko iekārtu (piemēram, papīra ražošanas mašīna) parametriem, ņemot vērā piedziņu sistēmu elastīgo transmisiju saites. Aprakstīti atbilstošie frekvences raksturlielumi un pārejas procesi.

30.08.2009.