American Journal of Electrical and Electronic Engineering, 2016, Vol. 4, No. 1, 16-22
Available online at http://pubs.sciepub.com/ajeee/4/1/3

DOI:10.12691/ajeee-4-1-3

Dynamics of Digital System of Two-Motor Electrical Drive with Elastic Transmissions

Jumber Dochviri*, Oleg Khachapuridze, Nana Beradze

Department of Electrical Engineering, Faculty of Power Engineering and Telecommunications, Georgian Technical University, 77, M. Kostava str., 0175 Tbilisi, Georgia
*Corresponding author: Jumber_Dochviri@yahoo.com

Abstract The appearance in recent years of the two-motor electric drives on the presses of high speed paper machines ensures increasing of the life of expensive press felts and improvement of production quality. The easiest and accurately acting from the different existing control systems of drives are two-motor drives with a total speed controller and individual thyristor converters for each motor separately. In this paper we study the dynamic characteristics of the system with a digital controller and correctors. The mathematical model of two-motor thyristor electric drive, taking into account the elastic properties of mechanical transmissions, is given. Applying the logarithmic frequency characteristics for tuning of digital controllers, correctors and current sensors of the drive system are given. The results of investigations of transient processes using the MATLAB sources are presented. This system guarantees maximum performance and proportional distribution of load between the motors without any additional controllers.

Keywords: *digital control, two-motor electrical drive, dynamics, automatic distribution of loading*

Cite This Article: Jumber Dochviri, Oleg Khachapuridze, and Nana Beradze, "Dynamics of Digital System of Two-Motor Electrical Drive with Elastic Transmissions." *American Journal of Electrical and Electronic Engineering*, vol. 4, no. 1 (2016): 16-22. doi: 10.12691/ajeee-4-1-3.

1. Introduction

In the modern paper machine presses widely applied DC two-motor thyristor electric drives with digital controls. Usually on large-sized paper machine sections are joined to the motors through long mechanical shafts. Since the paper machine drive systems are usually required to maximize the effect of fast transients, so elasticities of long mechanical shafts are mandatory factor [1,2,5]. To obtain the best results from the point of view of transients in the system under consideration we use digital controllers of P-I type.

Below on Figure 1 a functional diagram of a two-motor electric drive with digital controllers of the presses of paper machines.

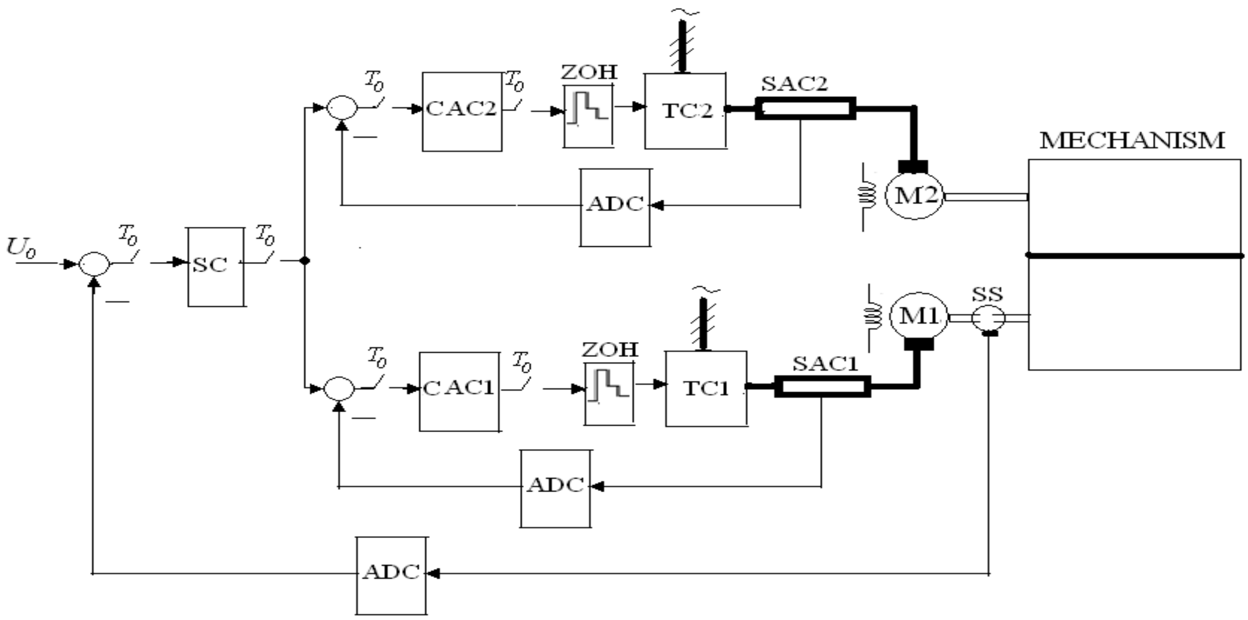


Figure 1. Block scheme of two-motor digital electrical drive

On the diagram (Figure 1) we have the following notations: U_0 governing signal; SC-digital speed controller of the drive; CAC1 and CAC2 -Digital controllers of motor current armature; SS, SAC1 and SAC2- sensors of the speed and current ofanchor; ZOH-zero-order hold; ADC-analog-to-discrete converter.

2. Mathematical Model of the Drive

Assuming no sliding between the working shafts of press of the paper machine and with elasticities of mechanical transmissions the equations of motion of the two-motor electric drive due to the principle of D'Alembert can be write as follows:

$$\begin{cases} M_1 - M_{e1} = J_1 \cdot d\omega_1 / dt; \\ M_2 - M_{e2} = J_2 \cdot d\omega_2 / dt; \\ M_{e1} + M_{e2} - M_M = J_M \cdot d\omega_M / dt; \\ M_{e1} = c_{12}\left(\phi_1 - \phi_M\right) + b_{12}(\omega_1 - \omega_M); \\ M_{e2} = c_{23}\left(\phi_2 - \phi_M\right) + b_{23}(\omega_2 - \omega_M), \end{cases} \tag{1}$$

where, M_1, M_2, M_{e1}, M_{e2} and M_M are moment of rotation of the DC-motor, elastic moment of mechanical transmission shaft and resistance moment of the mechanism reduced on the shaft of the main motor, respectively; J_1, J_2 and J_M are moments of inertia of the motors and mechanism; $\omega_1 = \frac{d\phi_1}{dt}, \omega_2 = \frac{d\phi_2}{dt}$ and $\omega_M = \frac{d\phi_M}{dt}$ are angular speeds of the motors and mechanism; ϕ_1, ϕ_2, ϕ_M are rotation angles of inertial masses of the electrical motors and mechanism; c_{12} and c_{23} is coefficients of elasticity of long mechanical shaft; b_{12} and b_{23} are the coefficients of attenuation of torsional vibrations from the internal viscous friction of a long shaft.

If we write the variables in the relative increments and use simple transformations in the (1), we get:

$$\begin{cases} \frac{d\Delta\nu_1}{dt} = \frac{1}{T_{M1}}(\Delta\mu_1 - \Delta\mu_{e1}); \\ \frac{d\Delta\nu_2}{dt} = \frac{1}{T_{M2}}(\Delta\mu_2 - \Delta\mu_{e2}); \\ \frac{d\Delta\nu_M}{dt} = \frac{1}{T_{MM}}(k_{L1} \cdot \Delta\mu_{e1} + k_{L2} \cdot \Delta\mu_{e2} - \Delta\mu_M); \\ \frac{d\Delta\mu_{e1}}{dt} = \frac{1}{T_{c1}} \cdot (\Delta\nu_1 - \Delta\nu_M) - \frac{T_{d1}}{T_{c1}} \cdot (\frac{1}{T_{M1}} + \frac{k_{L1}}{T_{MM}})\Delta\mu_{e1}; \\ \frac{d\Delta\mu_{e2}}{dt} = \frac{1}{T_{c2}} \cdot (\Delta\nu_2 - \Delta\nu_M) - \frac{T_{d2}}{T_{c2}} \cdot (\frac{1}{T_{M2}} + \frac{k_{L2}}{T_{MM}})\Delta\mu_{e2}, \end{cases} \tag{2}$$

Where: $\Delta\nu_1 = \frac{\Delta\omega_1}{\omega_{ST}}, \Delta\nu_2 = \frac{\Delta\omega_2}{\omega_{ST}}, \Delta\nu_M = \frac{\Delta\omega_M}{\omega_{ST}}$, $\Delta\mu_1 = \frac{\Delta M_1}{M_{M.ST1}}, \Delta\mu_2 = \frac{\Delta M_2}{M_{M.ST2}}, \Delta\mu_{e1} = \frac{\Delta M_{e1}}{M_{M.ST1}}$, $\Delta\mu_{e2} = \frac{\Delta M_{e2}}{M_{M.ST2}}$ and $\Delta\mu_M = \frac{\Delta M_{M.}}{M_{M.ST.\Sigma}}$ are relative increments of the angular speed of the motors and mechanism, moment of rotation of the motors, elastic moment of mechanical transmission shaft and resistance moment of the mechanism reduced on the shaft of the motor, respectively; $T_{M1} = \frac{J_1\omega_{ST}}{M_{M.ST.1}}$, $T_{M2} = \frac{J_2\omega_{ST}}{M_{M.ST.2}}$ and $T_{MM} = = \frac{J_M\omega_{ST}}{M_{M.ST.\Sigma}}$ are mechanical time constant of the motors and mechanism, respectively; $T_{c1} = \frac{M_{M.ST.1}}{c_{12} \cdot \omega_{ST}}$, $T_{c2} = \frac{M_{M.ST.2}}{c_{23} \cdot \omega_{ST}}$, $T_{d1} = \frac{b_{12}}{c_{12}}$ and $T_{d2} = \frac{b_{23}}{c_{23}}$ are time constants of long (elastic) shaft; $M_{M.ST.\Sigma} = M_{M.ST.1} + M_{M.ST.2}$ denotes total static moment from the mechanism; $M_{M.ST.1}, M_{M.ST.2}$ are static loadings on the motors; $k_{L1} = \frac{M_{M.ST.1}}{M_{M.ST.\Sigma}}$ and $k_{L2} = \frac{M_{M.ST.2}}{M_{M.ST.\Sigma}}$ coefficients of distribution of loading of the motors; ω_{ST} is base (static) values of angular speed of the drive.

To obtain transfer functions of mechanical part of the system under consideration from thesignal $\Delta\mu_1$ to signal $\Delta\nu_1$, also from $\Delta\mu_2$ to the $\Delta\nu_1$ let us rewrite equations (2) in the Cauchy form as follows:

$$\begin{cases} \frac{dx}{dt} = Ax + Bu; \\ y = Cx, \end{cases} \tag{3}$$

where: $x^T = \left[x_1 x_2 x_3 x_4 x_5\right]$; x_1, x_2, x_3, x_4 and x_5 denote states of angular speeds of the motors (x_1, x_2), of the mechanism (x_3), of elastic moments of connecting long shafts (x_4, x_5); *u*- input signal of the object ($\Delta\mu_1$, $\Delta\mu_2$); y -output signal of the object ($\Delta\nu_1$);

$$A = \begin{bmatrix} 0 & 0 & 0 & -\frac{1}{T_{M1}} & 0 \\ 0 & 0 & 0 & 0 & -\frac{1}{T_{M2}} \\ 0 & 0 & 0 & \frac{k_{L1}}{T_{MM}} & \frac{k_{L2}}{T_{MM}} \\ \frac{1}{T_{c1}} & 0 & -\frac{1}{T_{c1}} & -\frac{T_{d1}}{T_{c1}} \cdot \left(\frac{1}{T_{M1}} + \frac{k_{L1}}{T_{MM}}\right) & -\frac{T_{d1}}{T_{c1}} \cdot \frac{k_{L2}}{T_{MM}} \\ 0 & \frac{1}{T_{c2}} & -\frac{1}{T_{c2}} & -\frac{T_{d2}}{T_{c2}} \cdot \frac{k_{L1}}{T_{MM}} & -\frac{T_{d2}}{T_{c2}} \cdot \left(\frac{1}{T_{M2}} + \frac{k_{L2}}{T_{MM}}\right) \end{bmatrix};$$

$$B=\begin{bmatrix} \dfrac{1}{T_{M1}} \\ \dfrac{1}{T_{M2}} \\ 0 \\ 0 \\ 0 \end{bmatrix}; C=\begin{bmatrix}1 & 0 & 0 & 0 & 0\end{bmatrix}. \qquad (4)$$

From the system of equations (3) we can write a general formula for the transfer functions:

$$W(s)=C(sE-A)^{-1}\cdot B, \qquad (5)$$

where $s=d/dt$ -Laplace operator of differentiation; E is identity matrix with the dimension 5.

Substituting the matrices A and B from (4) into the expression (5), we define the transfer functions of the mechanical part of the drive with respect to the angular speed of the main (first) motor as follows [6]:

$$W_{01}(s)=\frac{\Delta\nu_1(s)}{\Delta\mu_1(s)}=\frac{k_{L1}\left[1+\dfrac{T_1^2 s^2(T_2^2 s^2+2\xi_1 T_2\, s+1)}{k_{L1}(T_{d1}s+1)(T_{d2}s+1)}\right]}{T_{M\Sigma}\cdot s\cdot N(s)}; \qquad (6)$$

$$M_{12}(s)=\frac{\Delta\nu_1(s)}{\Delta\mu_2(s)}=\frac{k_{L2}}{T_{M\Sigma}\cdot s\cdot N(s)}, \qquad (7)$$

where:

$$N(s)=1+\frac{T_{M1}T_{M2}T_3 s^2(T_4 s+1)}{T_{M\Sigma}(T_{d1}s+1)(T_{d2}s+1)}\times$$
$$\times\left[1+\frac{T_{MM}T_5^2(T_6^2 s^2+2\xi_2 T_6 s+1)}{T_{M1}T_{M2}T_3(T_4 s+1)}\right];$$

$$T_1=\sqrt{k_{L1}T_{M2}T_{c2}+(k_{L2}T_{M2}+T_{MM})T_{c1}};$$

$$T_2=\sqrt{T_{M2}T_{MM}T_{c1}T_{c2}}\,/\,T_1;$$

$$\xi_1=\frac{k_{L1}T_{M2}T_{c2}T_{d1}+(k_{L2}T_{M2}+T_{MM})T_{c1}T_{d2}}{2T_1^2 T_2};$$

$$T_3=k_{L1}T_{c2}+k_{L2}T_{c1};\; T_4=\frac{k_{L1}T_{c2}T_{d1}+k_{L2}T_{c1}T_{d2}}{T_3};$$

$$T_5=\sqrt{T_{M1}T_{c1}+T_{M2}T_{c2}};\; T_6=k_{L1}T_{c2}T_{d1}+k_{L2}T_{c1}T_{d2};$$

$$\xi_2=\frac{T_{M1}T_{c1}T_{d2}+T_{M2}T_{c2}T_{d1}}{2T_5^2 T_6};$$

$T_{M\Sigma}=k_{L1}T_{M1}+k_{L2}T_{M2}+T_{MM}$ is total mechanical time constant of the drive.

3. Optimization and Modeling of the System

Optimization of the electromechanical system will be done with the following parameters of the drive:

$$P_{M1}=200,kW; P_{M2}=50,kW; k_{L1}=0.8;$$
$$k_{L2}=0.2; T_{M1}=1.5,\text{sec.}; T_{M2}=0.7,\text{sec.};$$
$$T_{MM}=10,\text{sec.}; T_{d1}=T_{d2}=0.002,\text{sec.};$$
$$T_{c1}=0.0004,\text{sec.}; T_{c2}=0.00035,\text{sec.}$$

The transfer function of the object for the open loop system (without main feedback), i.e. transfer function from the output voltage of the SC to the angular speed of first (main) motor could be write as:

$$W_{OB}(s)=\frac{\Delta\nu_1(s)}{\Delta\upsilon_{SC}(s)}=\frac{W_{01}(s)+M_{12}(s)}{k_i(T_{\Sigma 2}s+1)}, \qquad (8)$$

where: $\Delta\upsilon_{SC}=\dfrac{\Delta U_{SC}}{U_{0.ST}}$ is relative increment of the output voltage of the SC; $U_{0.ST}$ -static value of governing signal; k_i -gain of the sensor of current armature ($k_i=0{,}1$); $T_{\Sigma 2}$ -non-compensating time-constant of the current loop.

Inserting values of parameters in the expressions (6) and (7) we get view of (8) as follows:

$$W_{OB.}(s)=\frac{0{,}48s^4+9{,}84s^3+}{s(0{,}00072s^5+0{,}2s^4+8{,}9s^3+}\rightarrow$$
$$\rightarrow\frac{+4150s^2+7000s+300000}{+786{,}6s^2+15560s+1110000)}. \qquad (9)$$

To express transfer function of (10) in the discrete z-transform form we use well known [3] approximation: $z=e^{T_0 s}\approx 1+T_0 s \;\Rightarrow s=(z-1)/T_0$, where sample time $T_0=0.01$ sec. and then we get:

$$W_{OB}(z)=\frac{0.017z^5-0.045z^4+0.046z^3-}{z^6-4.42z^5+8.2z^4-}\rightarrow$$
$$\rightarrow\frac{-0.017z^2-0.0059z+0.006}{-8z^3+4.17z^2-z+0.062}. \qquad (10)$$

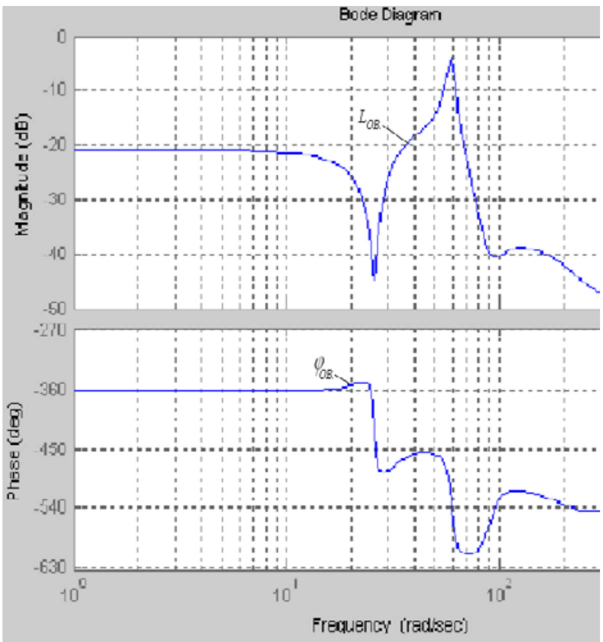


Figure 2. Bode diagrams of the object of the open system relative to the first motor

On Figure 2 are given Bode diagrams built via (10), where $L_{OB}(\omega)$ is an amplitude and $\phi_{OB}(\omega)$ is a phase characteristic of the object of current loop of armature relative to the first motor.

To synthesis of the optimal parameters of the speed controller (SC) of the drive we apply the method of frequency characteristics (i.e., via Bode diagrams). The resulting amplitude frequency characteristic has one resonance peaks at a frequency $\omega_e = 1/\sqrt{T_{M1} \cdot T_{c1}} = 60, \sec.^{-1}$ due to $J_M >> J_1, J_2$, i.e. $T_{MM} >> T_{M1}, T_{M2}$ (when T_{MM} is commensurate with T_{M1}, T_{M2} then usually $L_{OB}(\omega)$ has two resonance peaks, see e.g. [2]). Based on analysis of the obtained characteristics to suppress its resonance peak (in order to reach the maximum performance of the system) by the method pointed out in [7, 8] we choose the optimum correction filter as follows:

$$W_F(z) = \frac{0.013z^2 - 0.2863z + 0.1778}{z^2 - 1.708z + 0.7659}, \qquad (11)$$

On Figure 3 Bode diagrams corresponding to (11) are presented, where as we estimate resonant peak is suppressed.

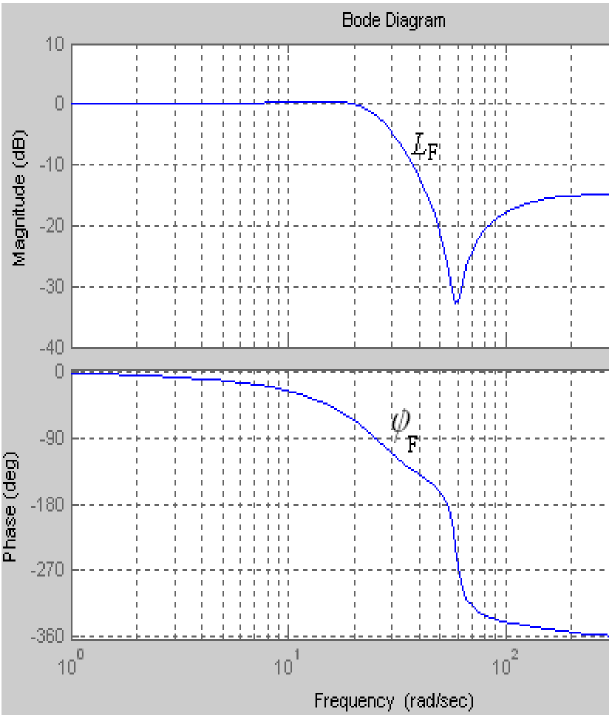


Figure 3. Bode diagrams of the adjusted filter according to the expression (11)

Applying frequency characteristics given on Fig.2 and Figure 3 in a first approximation, tuning of the speed controller SC can be done similarly to the electrical drive with rigid shaft according to the well-known , "symmetric optimum " [4]:

a) continuous form

$$W_{SC}(s) = \beta \cdot \frac{\tau s + 1}{\tau s} = 15 \cdot \frac{0.5s + 1}{0.5s}; \qquad (12)$$

b) discrete form

$$W_{SC}(z) = \beta \cdot \frac{z - a}{z - 1} = 15 \cdot \frac{z - 0.98}{z - 1}. \qquad (13)$$

On Figure 5 detailed block scheme of a digital system of the two-motor thyristor electric drive is given, taking into account elasticities of mechanical transmissions. On this scheme, in addition to the above used notations are following ones: K_{T1}, K_{T2}, T_{T1} and T_{T2} – gains and time constants TC1 and TC2; $K_{\iota 1}, K_{\iota 2}$ and $T_{\varphi 2}$ – gain and the time constants of sensors SAC1 and SAC2; K_{a1}, K_{a2}, T_{a1} and T_{a2} – and the coefficients of transmission and the time constants of the circuits of anchors of the electric motors M1 and M2; $T_{\varphi 1}$ – time constant of the filter after the sensor of speed; □ $\Delta\varepsilon_{T1}$ and $\Delta\varepsilon_{T2}$ – relative increments of output voltages TC1 and TC2; $\Delta\varepsilon_1$ and $\Delta\varepsilon_2$ - relative increments EMF motors; $\Delta\iota_{a1}$ and $\Delta\iota_{a2}$ - relative increments of the currents of armatures. In the form of relative increments currents of electrical motors are equal to their torques: $\Delta\iota_{a1} = \Delta\mu_1$; $\Delta\iota_{a2} = \Delta\mu_2$.

MATLAB/SIMULINK based simulations of the drive system controllers of the current of motor armature CAC1 and CAC2 were tuned due to the principle of "modular optimum" [1,2]. On Fig.6 a block diagram of the drive with numerical values of the parameters is given.

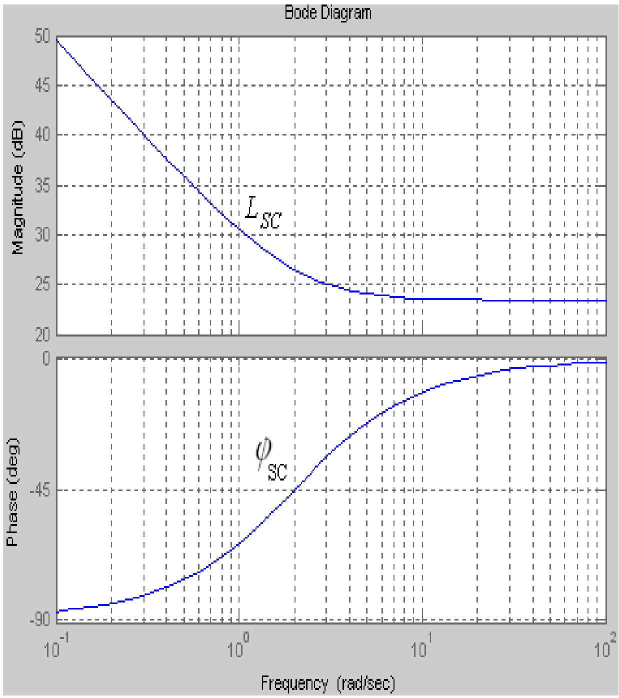


Figure 4. Bode diagram of a speed controller

On Figure 6 is represented computer structural diagram where to suppress the elastic vibrations of the inertial masses of the motors is used a digital filter of sequential and parallel type. The sequential filter is included in the output of the SC and is built due to the formula (11), that is done similar to [8]. Corresponding transient curves are shown on the Figure 7.

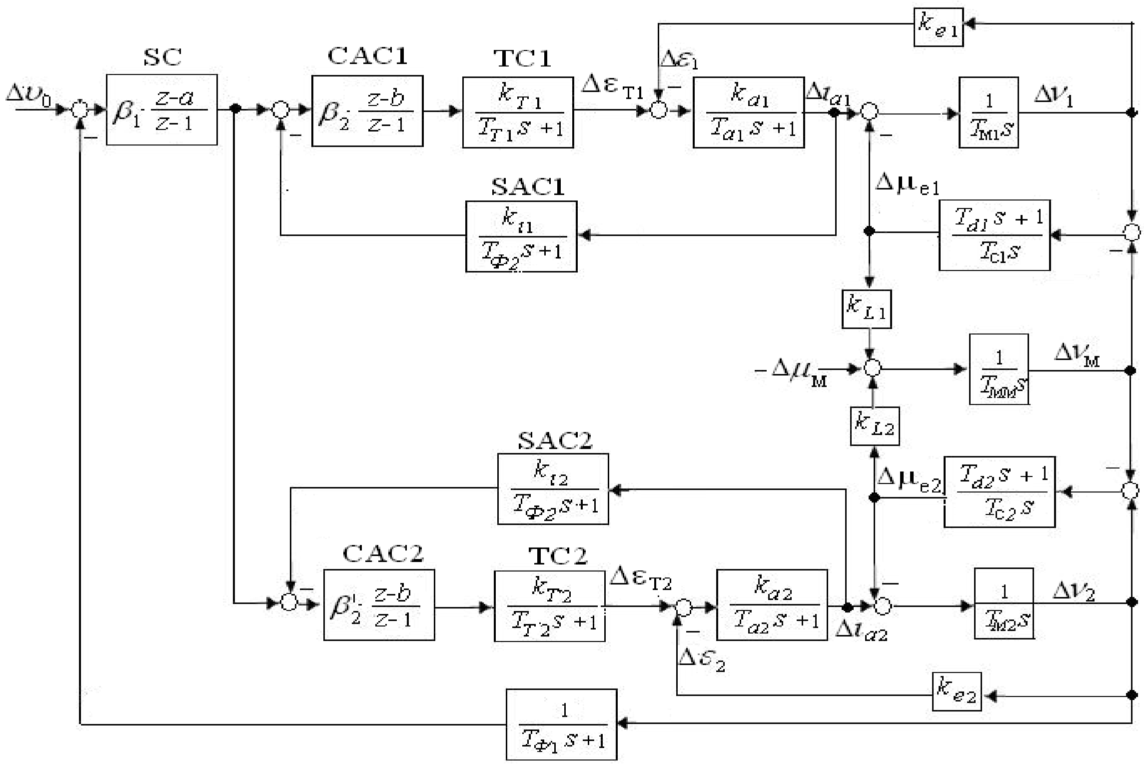


Figure 5. Structural scheme of two-motor drive with digital controllers

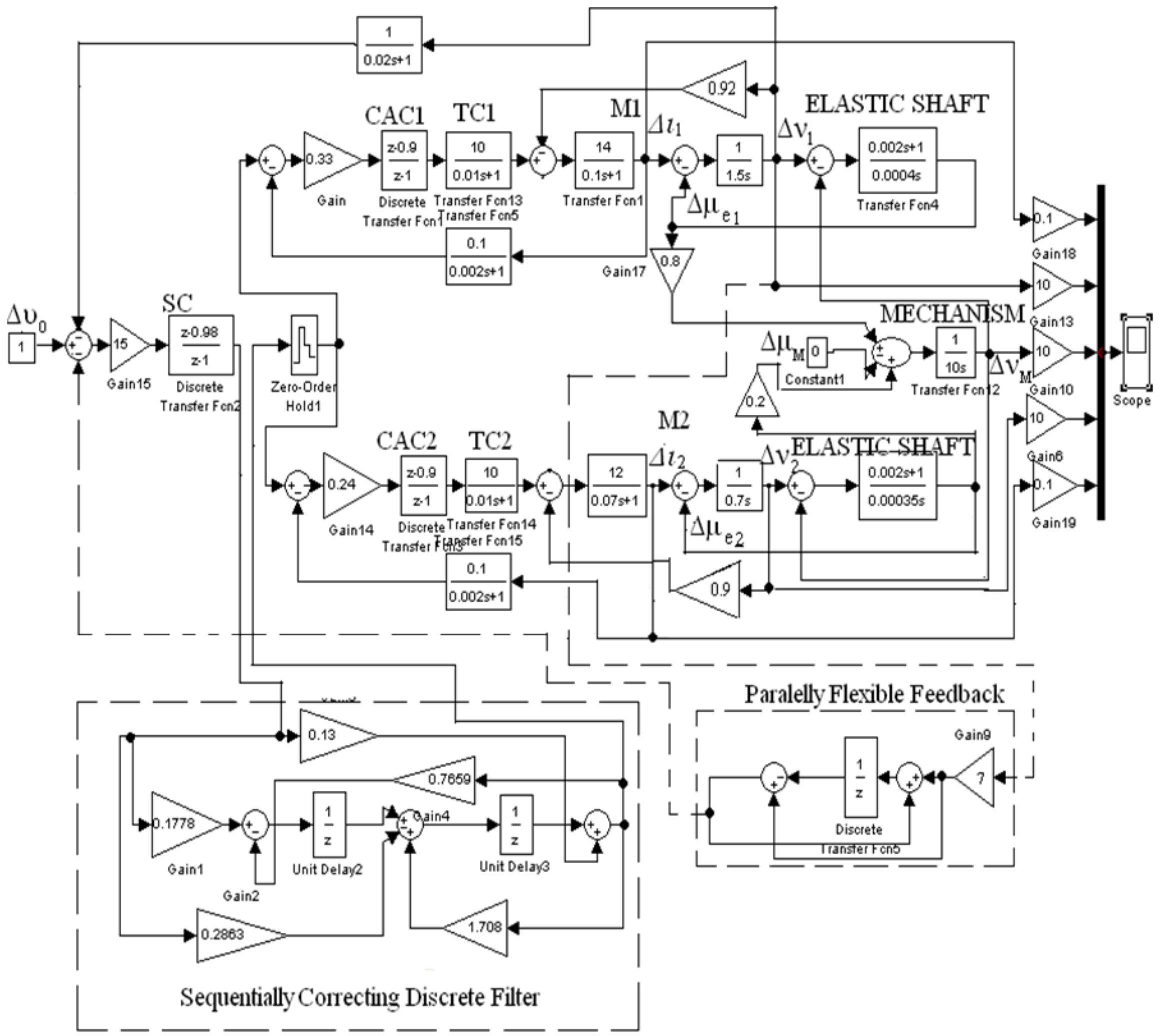


Figure 6. Numerical block diagram of digital system of two-motor electrical drive with correcting filters

If we use for the drive so-called parallel flexible feedback to suppress elastic vibrations from the first motor speed (see dashed filter on Figure 6) which has following transfer function:

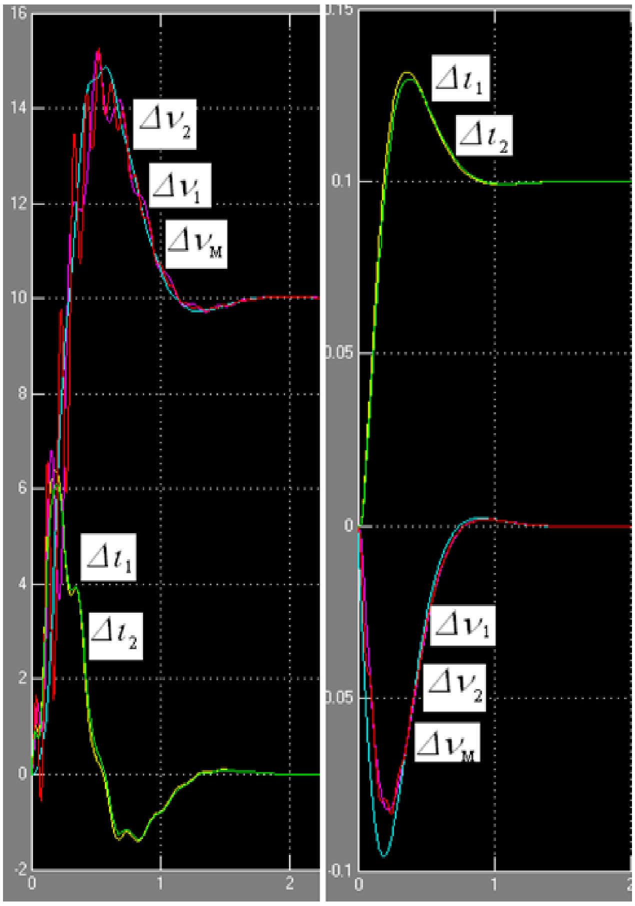
a) in the continuous form

$$W_{Flex.FB}(s) = \frac{\tau_0 \cdot s}{T_0 s + 1} = \frac{0.035 \cdot s}{0.005 \cdot s + 1}; \quad (14)$$

b) in the discrete form

$$W_{Flex.FB.}(z) = \frac{7 \cdot (z-1)}{z+1}, \quad (15)$$

then dynamic characteristics (from the view point of high-frequency oscillations of the second motor, Figure 8, a, b) are not the best with respect to the system with sequentially correction (Figure 7,a,b).



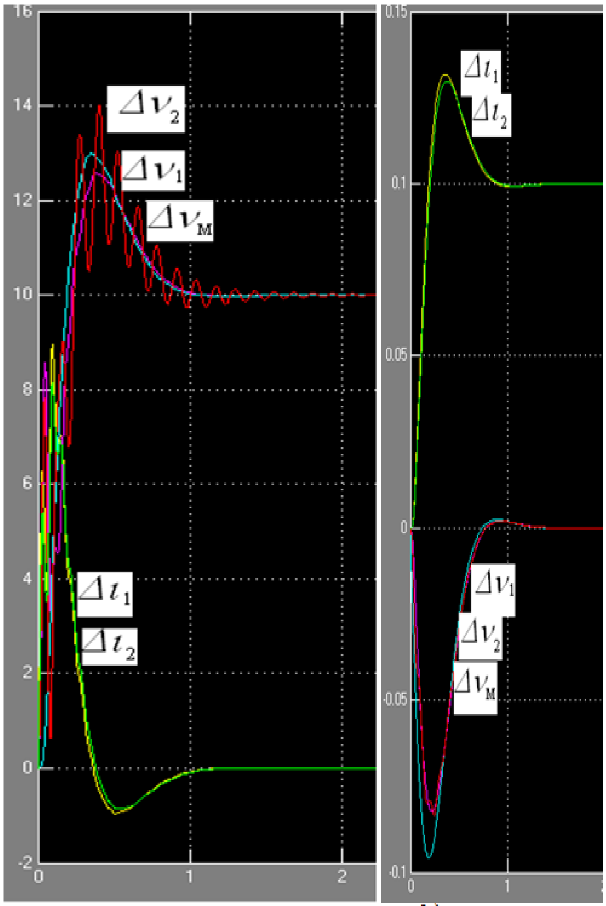
a) b)

Figure 7. Transient curves of thyristor electrical drive with sequentially included correcting filter: a) under stepwise change of control signal; b) under stepwise change of loading

However, in the drive system with a flexible feedback by closing the system via the speed of second motor of the drive we obtain significantly improved characteristics (Figure 9, a, b). In this case speed controller should have following transfer function:

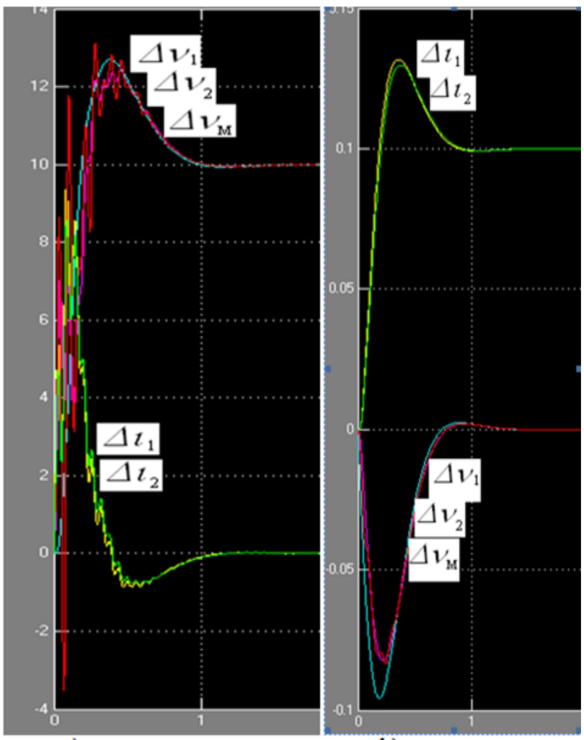
$$W_{SC}(z) = 10 \cdot \frac{z - 0.967}{z - 1}. \quad (16)$$

In all modes the equal changes of the currents of armatures of the motors confirm us that the suggested system provides high-precision proportional distribution of the load between the drive motors.



a) b)

Figure 8. Transient curves of thyristor electrical drive with paralelly included correcting filter- the system with one feedback of speed: a) under stepwise change of control signal; b) under stepwise change of loading



a) b)

Figure 9. Transient curves of thyristor electrical drive with paralelly include correcting filter- when the system is closed with two feedbacks of speed: a) under stepwise chang of control signal; b) under stepwise change of loading

4. Conclusions

1) The mathematical model of the two-motor thyristor electric drive with digital controls for paper machine of presses by taking into account elastic mechanical transmission are given. The system is equipped with a speed controller and individual thyristor converters for each motor separately. The scheme provides in a simple manner proportional distribution of the load between the motors.

2) Applying the method of state space of variables there are obtained generalized transfer functions of the object of control system of electrical drive with respect to the angular speed of the main (the first) electric motor.

3) On the basis of the frequency analysis expressions for tuning digital controllers of speed, currents of the motors and correctors of the system are given. Validity of the obtained parameters are confirmed via the MATLAB simulations.

Acknowledgement

The authors are grateful to the anonymous referee for his/her comments and suggestions.

The first author has been supported by the grant FR/7/3-160/14 from Shota Rustaveli National Science Foundation of Georgia.

References

[1] V. D. Baryshnikov, Y. A. Bortsov, et al.-Dynamics of Thyristor Electrical Drives of the Sections of Paper Machines // J. Russian Electrical Technology, 1973, v. 1, pp. 43-48.

[2] J. N. Dochviri-The Optimization of Transients in Multi-Motor Thyristor Electric Drives with Elastic Links for the Press Mechanisms of Continuous Technological Machines // J. Russian Electrical Technology. 2006, v. 2, pp. 34-42.

[3] K. Ogata-Discrete-Time Control Systems. Upper Saddle River, N.J.: Prentice hall, 1994.

[4] C. Kessler-Das Symmetrische Optimum // J. Regelungstechnik, 1958, v.6, pp. 395-400.

[5] E. Raatz-Regelung von Antrieben mit Elastischer Verbindung zur Arbeitsmaschinen // ENZ, 1981, A92, №4б pp. 211-216.

[6] J.N. Dochviri, O.G. Kervalishvili-The Dynamics of Two-Motor Electrical Drives with one Speed Regulator and Individual Thyristor Converters // Bull. Georgian Acad. Sci., 1978, v.91(2), pp. 421-424.

[7] A. Antoniou-Digital Filters: Analysis, Design and Applications// McGraw-Hill, New York, 1993.

[8] J. Dochviri, O. Khachapuridze, N. Beradze-A Digital Filter for Electrical Drive with Elastic Shaft // American Journal of Electrical and Electronic Engineering, 2015, v.3, №5, pp. 112-116.