COMPUTATIONAL PROBLEMS OF ELECTRICAL ENGINEERING

Vol. 3, No. 2, 2013

OPTIMIZATION OF ENERGY-SHAPING CONTROL OF PORT-CONTROLLED HAMILTONIAN SYSTEM

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Abstract: This paper raises the problem of finding the optimal parameters of a port-controlled Hamiltonian energy-shaping control system (ESCS). For solving this problem it is proposed to supplement the ESCS synthesis procedure with parameterization by shaping the desirable characteristic polynomial of a closed system. In order to verify this method, the synthesis of a modal regulation system and the ESCS controlled by a direct-current drive was carried out, and a number of comparative studies were conducted. The obtained results confirmed the feasibility and effectiveness of the application of the proposed structurally parametrical synthesis procedure of the ESCS.

Key words: energy-based approaches, energy-shaping control, port-controlled Hamiltonian system, structurally parametrical synthesis, direct-current drive.

1. Introduction

The complexity and nonlinearity of modern electromechanical systems and control laws have led to the search for new, simple and at the same time effective methods of control system (CS) synthesis. Some of them form the group of the energy-based approaches, which are based on physical laws and include the energy-shaping control [1]. Its prospects are confirmed by the large number of modern scientific publications, including [2 - 9]. The main advantages of energy-shaping control systems (ESCS) are their simplicity and clearness of configuration, because the synthesis procedure and the CS parameters are related to energy variables, it makes the role of these parameters in the control system evident. Typically, in such systems a number of parameters remain available to be configured [6, 8, 9], significantly complicating the system configuration procedure. Despite the great variety of ESCS synthesis options, only for some of them the guidelines for choosing parameter values can be found [5, 6]. But there are ESCSs with the application of evolutionary strategies, which are exceptions [7].

The inability to find at once the optimal values for all ESCS parameters during the synthesis procedure has a negative influence on the prevalence of these CSs. Thus, the problem of developing new methods intended for optimizing the ESCSs according to a given criterion arises on these grounds.

2. Analysis of recent publications

Energy-shaping control system synthesis

In general, the procedure of ESCS synthesis consists in decomposing a system into simpler subsystems interlinked in some way, and finding such additional subsystems and interconnections that the total energy of closed-loop system would attain a minimum in the equilibrium point [1]. This equilibrium point is the aim of the control and is defined by a reference signal.

In order to simplify the synthesis procedure, a controlled object is considered to be a port-controlled Hamiltonian system (PCHs) [1]:

$$\begin{cases} \dot{\vec{x}}(t) = [\mathbf{J}(\vec{x}) - \mathbf{R}(\vec{x})]\dfrac{\partial H}{\partial \vec{x}} + \mathbf{G}(\vec{x})\cdot\vec{u}(t) \\ \vec{y}(t) = \mathbf{G}^{\mathrm{T}}(\vec{x})\dfrac{\partial H}{\partial \vec{x}} \end{cases}, \quad (1)$$

where $\vec{x}(t)$ is a state vector, which consists of system inertia pulses, $\mathbf{J}(\vec{x})$ and $\mathbf{R}(\vec{x})$ are interconnection and damping matrices respectively, $H(\vec{x}) = 0.5\vec{x}^{\mathrm{T}}\mathbf{D}^{-1}\vec{x}$ is the energy function of the system, $\mathbf{D}$ is the diagonal matrix of inertias, $\mathbf{G}(\vec{x})$ is a port matrix, $\vec{u}(t)$ and $\vec{y}(t)$ are vectors of input and output system energy variables.

According to [5], ESCS synthesis comes to writing the mathematical model of the object in the PCHs form (1), selecting CS matrixes and solving the following matrix equation:

$$[\mathbf{J}_{\mathrm{d}}(\vec{x}) - \mathbf{R}_{\mathrm{d}}(\vec{x})]\frac{\partial (H_{\mathrm{d}} - H)}{\partial \vec{x}} = = [\mathbf{J}_{\mathrm{a}}(\vec{x}) - \mathbf{R}_{\mathrm{a}}(\vec{x})]\frac{\partial H}{\partial \vec{x}} + \mathbf{G}(\vec{x})\cdot\vec{b}(t), \quad (2)$$

where $\mathbf{J}_{\mathrm{d}}(\vec{x}) = \mathbf{J}(\vec{x}) + \mathbf{J}_{\mathrm{a}}(\vec{x})$ and $\mathbf{R}_{\mathrm{d}}(\vec{x}) = \mathbf{R}(\vec{x}) + \mathbf{R}_{\mathrm{a}}(\vec{x})$ are the interconnection and damping matrices of the desired system, $H_{\mathrm{d}}(\vec{x})$ is the desired energy function, which attains its minimum in the equilibrium point $\vec{x}_0$, $\vec{b}(\vec{x}) = \vec{u}$ is the vector of input system energy variables formed through feedback, $\mathbf{J}_{\mathrm{a}}(\vec{x})$ and $\mathbf{R}_{\mathrm{a}}(\vec{x})$ are the interconnection and damping matrices of the CS.

The elements of the regulator matrix $\mathbf{J}_{\mathrm{a}}$ and the final equations of ESCS regulators were found as the results of synthesis [2 - 9]. However, during the synthesis some elements of regulator matrices ($\mathbf{J}_{\mathrm{a}}$ and $\mathbf{R}_{\mathrm{a}}$) could be "free" [2, 3, 5 - 9]. They are intended for adjusting the CS and currently are selected manually.

Synthesis of modal regulation system

One of the most common structurally parametrical methods of CS synthesis for the linear systems, allowing us to find the optimal values of regulator parameters at once, is the synthesis of full-state vector control systems in general and modal regulation systems (MRS) in particular [10].

As we know, the MRS synthesis procedure begins with writing the mathematical model of the controlled object in the state space (SS) [10]:

$$\begin{cases} \dot{\vec{x}}_1(t) = \mathbf{A}\vec{x}_1 + \mathbf{B}\vec{u}_1(t) \\ \vec{y}(t) = \mathbf{C}\vec{x}_1 \end{cases}, \qquad (3)$$

where $\vec{u}_1$ and $\vec{y}$ are the vectors of input and output variables, $\vec{x}_1$ is the state vector, $\mathbf{A}$, $\mathbf{C}$ and $\mathbf{B} = \mathbf{B}_{\mathrm{r}} + \mathbf{B}_{\mathrm{d}}$ are the matrices of the object (input and output ones, respectively), $\mathbf{B}_{\mathrm{r}}$ and $\mathbf{B}_{\mathrm{d}}$ are the input matrixes of reference and disturbance.

The next step is to write down the transfer function (TF) of the desired closed-loop system (Fig. 1) [10]:

$$W_{MRS}(s) = \frac{\vec{y}(t)}{\vec{u}_{\mathrm{r}}(t)} = \left(s \cdot \mathbf{E} - \mathbf{A} + \mathbf{B}_{\mathrm{r}}\mathbf{K}\right)^{-1}\mathbf{B}_{\mathrm{r}}, \qquad (4)$$

where $\vec{u}_{\mathrm{r}}$ is the reference vector (of controlling impacts), and $\mathbf{E}$ is the identity matrix, $\mathbf{K}$ is the feedback matrix.

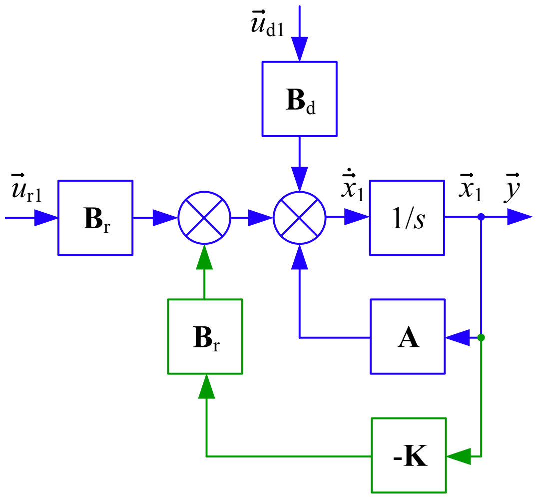

Fig. 1. MRS
(blue – object under control, green – MRS regulators).

Then the expressions of CS regulator parameters can be found from equality of the coefficients at identical degrees s of the characteristic polynomial of the transfer function (TF) (4)

$$H_{\mathrm{CT\_MRS}}(s) = \det\left(s \cdot \mathbf{E} - \mathbf{A} + \mathbf{B}_{\mathrm{r}}\mathbf{K}\right) \qquad (5)$$

and the desired characteristic polynomial that corresponds to the optimal standard form of the transient function:

$$\mathrm{H}_{\mathrm{CT\_dis}}(s) = s^n + \alpha_1\omega_0' s^{n-1} + \ldots + \alpha_n {\omega_0'}^n, \qquad (6)$$

where $\alpha_1, \ldots, \alpha_n$ are the coefficients defining the shape of the transient process, and ω_0' is the geometric mean-root determining a system response.

3. Objectives

The main purpose of this article is to complement the well-known ESCS synthesis procedure with the method of finding the optimal values of its free parameters, and to test the obtained procedure of ESCS structurally parametrical synthesis, as well.

4. Parametric synthesis of ESCS

We propose applying the above-described method of finding MRS coefficients by forming the desired characteristic polynomial to the ESCS. However, for this, the desired characteristic polynomial of the closed-loop ESCS should be found first.

It is known that the desired model of asymptotically stable closed-loop Hamiltonian systems (the object under control and ESCS regulators) is described by the following matrix equation [1]:

$$\dot{\vec{x}}(t) = \left[\mathbf{J}_{\mathrm{d}}(\vec{x}) - \mathbf{R}_{\mathrm{d}}(\vec{x})\right]\frac{\partial H_{\mathrm{d}}}{\partial \vec{x}}. \qquad (7)$$

Substituting the expressions of $\mathbf{J}_{\mathrm{d}}$ and $\mathbf{R}_{\mathrm{d}}$, and also well known equations $\vec{x} = \vec{y}\,\mathbf{D}\mathbf{G}^{-1}$ and $\frac{\partial H_{\mathrm{d}}}{\partial \vec{x}} = (\vec{x} - \vec{x}_0)\mathbf{D}^{-1}$ in equation (7), we obtain the matrix equation for composing the detailed structural diagram of the desired closed-loop ESCS (Fig. 2).

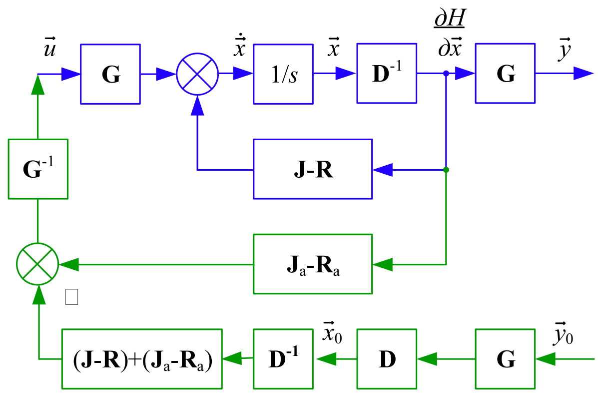

Fig. 2. ESCS
(blue – object under control, green – ESCS regulators).

The conclusion that follows from Fig. 2 is that, despite the visual complexity of representation, the ESCS is a system which regulates by the deviation and it deals with linear systems in much the same way as with the MRS. However, due to the regulation elements in the reference loop, the ESCS will have significant advantages while working with nonlinear systems.

As it is shown in Fig. 2, the input signal of the CS is the desired value of output coordinates $\vec{y}_0$. Thus, the matrix TF of the desired system takes the form:

$$W_{\mathrm{d}}(s)=\frac{\vec{y}}{\vec{y}_0}=-(s\cdot\mathbf{D}-(\mathbf{J}_{\mathrm{d}}-\mathbf{R}_{\mathrm{d}}))^{-1}\cdot(\mathbf{J}_{\mathrm{d}}-\mathbf{R}_{\mathrm{d}}). \quad (8)$$

Then the characteristic polynomial of the CS will be the following:

$$\begin{aligned}\mathrm{H}_{\mathrm{CT\_ESCS}}(s)&=\det[s\cdot\mathbf{D}-(\mathbf{J}_{\mathrm{d}}-\mathbf{R}_{\mathrm{d}})]=\\&=\det[s\cdot\mathbf{D}-(\mathbf{J}-\mathbf{R})-(\mathbf{J}_{\mathrm{a}}-\mathbf{R}_{\mathrm{a}})]\end{aligned}. \quad (9)$$

Equating the expressions at the same s degrees of the desired characteristic polynomial (6) and the synthesized characteristic polynomial system (9), we obtain the equations for finding the ESCS parameters.

It should be noted, that we will always be interested in the TF of the system in terms of only one final output coordinate (for example: $W_{i/i_0}, W_{\omega/\omega_0}, W_{\varphi/\varphi_0}$). This TF will be a diagonal element of the matrix TF (8) and will contain the operator s in its numerator. It is why TF zeros will always impact the dynamics of the system.

Therefore, according to [11], the characteristic polynomial of the desired transition function of the system should be always adjusted by multiplying it (with lower order) by the numerator of the TF (8):

$$\begin{aligned}\mathrm{H}'_{\mathrm{CT\_dis}}(s)&=\left(s^{n-1}+\ldots+\alpha_{n-1}\omega_0'^{\,n-1}\right)\cdot\\&\cdot\left\{\frac{[\lambda_{n1}\ldots\lambda_{nn}]\cdot[(\mathbf{J}_{\mathrm{d}}-\mathbf{R}_{\mathrm{d}})]^{\langle n\rangle}}{-[(\mathbf{J}_{\mathrm{d}}-\mathbf{R}_{\mathrm{d}})]_{nn}}\right\},\end{aligned} \quad (10)$$

where λ is the minor of the TF (8) denominator $[s\cdot\mathbf{D}-(\mathbf{J}_{\mathrm{d}}-\mathbf{R}_{\mathrm{d}})]$, and n is the system order.

5. Verification of the proposed approach on the example of a DC electric drive

In order to verify the effectiveness of the structurally parametrical ESCS synthesis and to compare it with the MRS synthesis, the synthesis of the CS controlling a simple linear system with a DC electric drive (a semi-conductor power converter (PC) and a DC motor (DCM) with separate excitation) was carried out using both approaches.

If the small time constant of the PC is neglected, the mathematical model of the PC-DCM system will be the following:

$$\begin{cases}L_{\mathrm{a}}\dfrac{\mathrm{d}i_{\mathrm{a}}}{\mathrm{d}t}=u_{\mathrm{c}}k_{\mathrm{PC}}-C\omega-R_{\mathrm{a}}i_{\mathrm{a}}\\J\dfrac{\mathrm{d}\omega}{\mathrm{d}t}=Ci_{\mathrm{a}}-Ci_{\mathrm{L}}\end{cases}, \quad (11)$$

where L_{a} and R_{a} are the armature winding inductance and resistance, u_{c} is control voltage, k_{PC} is a PC transfer coefficient, $C=\mathrm{k}\Phi$ is a DC motor constant, ω is motor angular speed, i_{a} is the armature current, J is the moment of inertia of the drive, $i_{\mathrm{L}}=T_{\mathrm{L}}/C$ is the static load current, and T_{L} is a static torque.

MRS of DC electric drive

Let's write down the elements of the object under control and the control system in the form (3):

$$\vec{x}_1=\begin{bmatrix}i_{\mathrm{a}}\\\omega\end{bmatrix},\quad \vec{u}_1=\begin{bmatrix}u_{\mathrm{c}}\\-i_{\mathrm{L}}\end{bmatrix},\quad \vec{y}=\begin{bmatrix}i_{\mathrm{a}}\\\omega\end{bmatrix},$$

$$\mathbf{A}=\begin{bmatrix}-R_{\mathrm{a}}/L_{\mathrm{a}}&-C/L_{\mathrm{a}}\\C/J&0\end{bmatrix},\quad \mathbf{B}_{\mathrm{r}}=\begin{bmatrix}k_{\mathrm{PC}}/L_{\mathrm{a}}&0\\0&0\end{bmatrix},$$

$$\mathbf{C}=\begin{bmatrix}1&0\\0&1\end{bmatrix},\quad \mathbf{K}=\begin{bmatrix}k_{11}&k_{12}\\k_{21}&k_{22}\end{bmatrix},$$

where $k_{11},\ldots,k_{22}$ are the MRS parameters.

Then the TF of the speed ω relative to the u_{c} will have the form:

$$W_{\mathrm{MRS}}(s)=\frac{\omega}{u_{\mathrm{c}}}=$$

$$=\frac{R_{\mathrm{a}}k_{\mathrm{PC}}}{\dfrac{JR_{\mathrm{a}}L_{\mathrm{a}}}{C}s^2+\left(\dfrac{JR_{\mathrm{a}}R_{\mathrm{a}}}{C}+\dfrac{JR_{\mathrm{a}}k_{\mathrm{PC}}k_{11}}{C}\right)s+(R_{\mathrm{a}}C+R_{\mathrm{a}}k_{\mathrm{PC}}k_{12})}$$

and the characteristic polynomial will be the following:

$$H_{\mathrm{CT\_MRS}}(s)=s^2+\frac{R_{\mathrm{a}}+k_{\mathrm{PC}}k_{11}}{L_{\mathrm{a}}}s+\frac{C(C+k_{\mathrm{PC}}k_{12})}{JL_{\mathrm{a}}}. \quad (12)$$

Equating the expressions (6) and (12) at the same s degrees, we obtain the following equations for the optimal parameters of MRS regulators:

$$\begin{cases}k_{11}=-(R_{\mathrm{a}}-\alpha_1L_{\mathrm{a}}\omega_0')/k_{\mathrm{PC}}\\k_{12}=-(C^2-JL_{\mathrm{a}}\omega_0'^{\,2})/Ck_{\mathrm{PC}}\end{cases}. \quad (13)$$

ESCS by the DC electric drive

Given object (11), being written as the PCHs (1), will have the following elements:

$$\vec{x}=\begin{bmatrix}L_{\mathrm{a}}i_{\mathrm{a}}\\J\omega\end{bmatrix}=\mathbf{D}\begin{bmatrix}i_{\mathrm{a}}\\\omega\end{bmatrix},\quad \vec{u}=\begin{bmatrix}u_{\mathrm{c}}k_{\mathrm{PC}}\\-Ci_{\mathrm{L}}\end{bmatrix},\quad \vec{y}=\begin{bmatrix}i_{\mathrm{a}}\\\omega\end{bmatrix},$$

$$\mathbf{D}=\begin{bmatrix}L_{\mathrm{a}}&0\\0&J\end{bmatrix},\quad \mathbf{J}=\begin{bmatrix}0&-C\\C&0\end{bmatrix},\quad \mathbf{R}=\begin{bmatrix}R_{\mathrm{a}}&0\\0&0\end{bmatrix}. \quad (14)$$

Let's set the following forms of CS matrices:

$$\mathbf{J}_{\mathrm{a}}=\begin{bmatrix}0&J_{12}\\-J_{12}&0\end{bmatrix},\quad \mathbf{R}_{\mathrm{a}}=\begin{bmatrix}r_{11}&0\\0&r_{22}\end{bmatrix}, \quad (15)$$

where J_{12}, r_{11} and r_{22} are the CS regulator parameters.

Substituting the matrices (14) and (15) into equation (6) we obtain the following equations for the ESCS regulator using the system of the PC-DC motor:

$$\begin{cases} u_c^* k_{PC} = -(i_a - i_{a0})r_{11} + (\omega - \omega_0)J_{12} + \omega_0 C + R_a i_{a0} \\ i_{a0} = \dfrac{(\omega - \omega_0)}{J_{12} - C} r_{22} - \dfrac{T_L - J_{12} i_a}{J_{12} - C} \end{cases}.$$

As the controlled object is linear and there is no need to change the interconnection structure in the desired ESCS, let us take $J_{12} = 0$. Then the ESCS regulators will have the following form:

$$\begin{cases} u_c^* k_{PC} = -(i_a - i_{a0})r_{11} + \omega_0 C + R_a i_{a0} \\ i_{a0} = \dfrac{-(\omega - \omega_0)r_{22} + T_L}{C} \end{cases}. \quad (16)$$

Let's find analytical expressions for determining parameters r_{11} and r_{22} according to the procedure mentioned above. First let us write the TF of the desired ESCS:

$$W_{d\_\omega}(s) = \frac{\omega}{\omega_0} = $$

$$= \frac{r_{22} L_a s + \left(C^2 + r_{11} r_{22} + r_{22} R_a\right)}{J L_a s^2 + \left(J r_{11} + J R_a + L_a r_{22}\right)s + \left(C^2 + r_{11} r_{22} + r_{22} R_a\right)},$$

then its characteristic polynomial will have the form:

$$H(s) = s^2 + \frac{J r_{11} + J R_a + L_a r_{22}}{J L_a} s + \frac{C^2 + r_{11} r_{22} + r_{22} R_a}{J L_a}. \quad (17)$$

According to [11], modifying the desired characteristic polynomial by equation (10) we obtain:

$$\mathrm{H}'_{CT\_dis} = s^2 + \frac{C^2 + r_{11} r_{22} + r_{22} R_a + L_a r_{22} \omega'_0}{r_{22} L_a} s + \\ + \frac{C^2 + r_{11} r_{22} + r_{22} R_a \omega'_0}{r_{22} L_a}. \quad (18)$$

Equating expressions (17) and (18) at the same degrees s, we obtain the following equations of the optimal parameters of ESCS regulators:

$$\begin{cases} r_{11} = R_a + L_a \omega'_0 - \dfrac{1}{2}\dfrac{L_a}{J}\left(J\omega'_0 + \mathrm{k}\right) \\ r_{22} = \dfrac{1}{2}\left(J\omega'_0 + \mathrm{k}\right) \end{cases}, \quad (19)$$

where $\mathrm{k} = \sqrt{J\left(4C^2 + J L_a \omega_0'^2\right) / L_a}$.

Selecting the desired distribution of the roots of the characteristic equation (H_{CT_dis} form and ω'_0), we can find necessary MRS and ESCS regulator settings.

6. Computer simulation

In order to verify the effectiveness of the ESCS with the found parameters, a series of comparative investigations of the MRS, the ESCS configured manually, and the ESCS with parameters found from equations (19) were conducted.

These studies were carried out by computer simulation in MATLAB/Simulink. The DC motor had the following parameters: P_n = 1 kW, n_n = 3000 rpm, U_n = 220 V, I_n = 6 A, R_a = 3.29 Ohm, p = 1, J = 0.048 kg·m^2, C = 0.4 Wb and L_a = 0.07 mH. The PC transfer coefficient was k_{PC} = 22.

The MRS was synthesized for the standard form of the roots distribution of the 2nd order Butterworth characteristic polynomial, with the mean-root ω'_0 = 38. The ESCS parameters were also found from the condition for providing the transition process by Butterworth for two cases: 1) with above-mentioned ω'_0 = 38; 2) with ω'_0 = 45, because the desired characteristic polynomial, which defines the TF of the system, must be adjusted (eq.10) and therefore initially is chosen with the lower order. The last one will provide the same overshoot as the MRS. The previous experience [9] shows that using only adjustable coordinate damping is enough to provide a satisfactory transient. As a result, only mechanical damping r_{22} was used for manual configuration. So, the CS operation with the following regulator settings was examined:

1. $\mathrm{MRS}_{\omega0'=38}$: k_{11} = 0.021; k_{22} = 0.317;
2. $\mathrm{ESCS}_{\omega0'=38}$: r_{11} = 3.083; r_{22} = 1.966;
3. $\mathrm{ESCS}_{\omega0'=45}$: r_{11} = 3.112; r_{22} = 2.282;
4. $\mathrm{ESCS}_{man,r22}$: r_{11} = 0; r_{22} = 1.08.

The studies were conducted according to the following algorithm. At the initial time the step input command signal for the motor acceleration to ω = 0.05 ω_n with no load was provided. After reaching a steady-state mode at t = 0.3 s, the motor was given an augmentation of nominal load torque to the value $T_L = T_n$ (Fig. 3). At the point of time t = 0.6 s the motor began the acceleration up to prenominal speed ω = 0.95 ω_n without load, and then at t = 0.9 s, once again, the command signal abruptly increased, and the motor acceleration took place up to $\omega = \omega_n$ followed by adding the nominal load (Fig. 4).

The main subjects of investigation were: system response, static error on low and high speeds, parametric sensitivity of the system, and the system behavior in the absence of load information, as there is a component T_L in the ESCS equations (16).

According to these investigations (Fig. 3 - 6, Table) the following conclusions can be made:

1) ESCS with found parameters provides: the prescribed optimal form of the transition process, double response speed compared to MRS and $\mathrm{ESCS}_{man,r22}$; CS astaticism of the command signal and the load (Fig.3, 4, Table);

2) the investigations of the sensitivity of parameter changes showed the following: the R_a increasing leads to deterioration of the CS dynamic and static indicators, the most sensitive are MRS and $ESCS_{man,r22}$ (Fig. 5); the reduction of L_a causes only a slight overshoot decrease in all systems; the reduction of C leads to slowing down dynamics and increasing the static error in all CSs proportionally to speed (Fig. 6).

3) in the absence of information about the disturbance of T_L and its influence on the ESCSs a static error appears, being always negative and not exceeding 4.3% ω_n (Fig. 3, 4).

CS quality comparison

			MRS ω_0'=38	**ESCS ω_0'=38**	**ESCS ω_0'=45**	**ESCS man,r_{22}**
at low speed	accel. at 5%ω_n	t_r, c	0.077	0.05	0.042	0.084
		δ, %	0.8	0	0	0
	nom.load adding	t_r, c	0.077	0.069	0.065	0.125
		δ, %	18.75	0	0	0
at high speed	accel. at 5%ω_n	t_r, c	0.078	0.048	0.042	0.082
		δ, %	22	0	0	0
	nom.load adding	t_r, c	0.077	0.069	0.065	0.125
		δ, %	0.5	0	0	0
at low speed and 1.2 R_a	accel. at 5%ω_n	t_r, c	0.091	0.055	0.046	0.12
		δ, %	0.5	0	0	0
	nom.load adding	t_r, c	0.093	0.068	0.065	0.119
		δ, %	17. 5	0	0	4.6
at low speed and 0.8 C	accel. at 5%ω_n	t_r, c	0.093	0.062	0.053	0.1
		δ, %	1.2	0.86	0.77	2.3
	nom.load adding	t_r, c	0.1	0.077	0.072	0.141
		δ, %	16.2	0.86	0.77	2.3

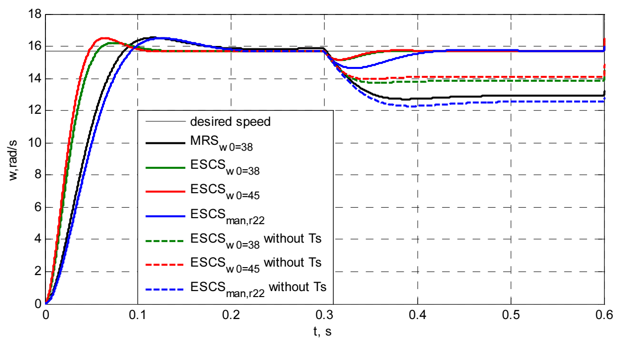

Fig. 3. Time dependences of CS low speed operation with information about T_L and without it.

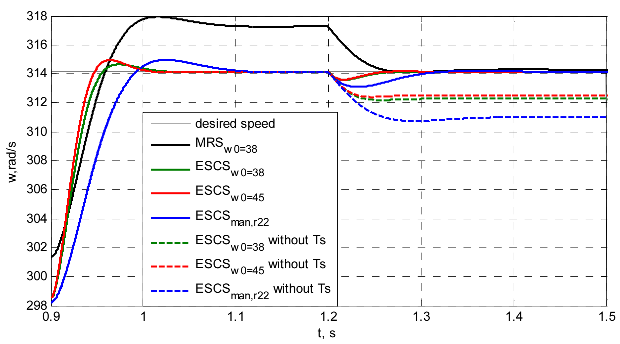

Fig. 4. Time dependences of CS high speed operation with information about T_L and without it.

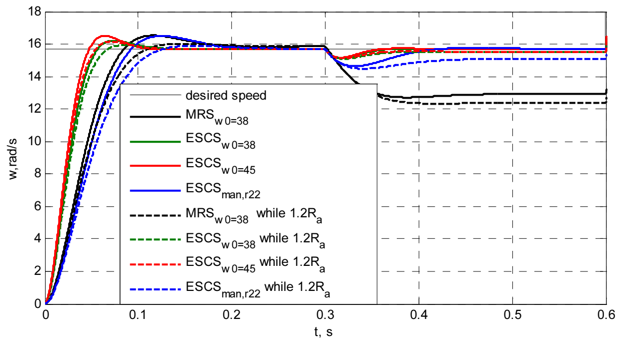

Fig. 5. Time dependences of CS operation at R increased by 20%.

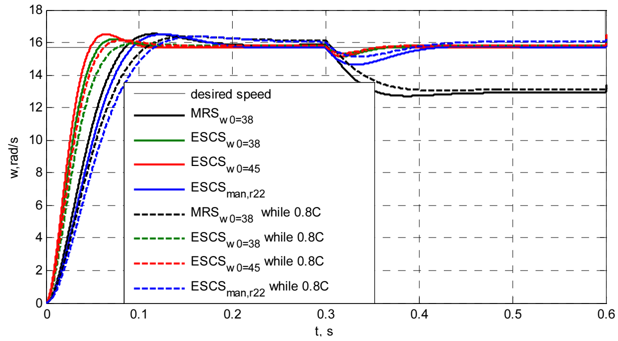

Fig. 6. Time dependences of CS operation at C reduced by 20%.

7. Conclusion

The proposed procedure of structurally parametrical ESCS synthesis uses the principle of forming the desired characteristic polynomial of the closed-loop CS. It allows us to get the ESCS with the optimal settings for a given criterion. On the one hand, these ESCSs with ready-optimal regulators eliminate the need for the most difficult initial setup of the system (to provide the necessary transition). On the other hand, their parameters are related to the physical coordinates of the system and the procedure of the final system configuration is significantly simplified. These two advantages will facilitate the spread of ESCS applications and energy-based approaches in general. For the same purpose, further research should be focused on the verification of applying this procedure to the synthesis of the CSs provided by complex nonlinear objects.

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ОПТИМІЗАЦІЯ ЕНЕРГОФОРМУЮЧОГО КЕРУВАННЯ ГАМІЛЬТОНОВОЮ СИСТЕМОЮ З КЕРОВАНИМИ ПОРТАМИ

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Розглянуто проблему знаходження оптимальних щодо заданого критерію параметрів системи енергоформуючого керування (СЕФК) у гамільтоновому представленні. З метою її вирішення запропоновано доповнити процедуру синтезу СЕФК параметризацією шляхом формування бажаного характеристичного поліному замкненої системи. Для перевірки підходу проведено синтез системи модального регулювання та СЕФК електроприводом постійного струму, а також низку порівняльних досліджень, в результаті чого підтверджено доцільність та ефективність застосування запропонованої процедури структурно-параметричного синтезу СЕФК.

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