ISSN 1068-3712, Russian Electrical Engineering, 2015, Vol. 86, No. 5, pp. 296–303. © Allerton Press, Inc., 2015.
Original Russian Text © S.V. Tararykin, L.G. Kopylova, I.A. Tikhomirova, 2015, published in Elektrotekhnika, 2015, No. 5, pp. 62–70.

Structural and Parametric Synthesis and Optimization of Controllers of Selective-Invariant Electromechanical Systems with Harmonic Load Torque

S. V. Tararykin, L. G. Kopylova, and I. A. Tikhomirova

Ivanovo State Power Engineering University, Ivanovo, Russia

e-mail: journal-elektrotechnika@mail.ru

Received April 14, 2015

Abstract—Based on modal control methods, structural and parametric synthesis is carried out and an integrated assessment is given for quality factors for different types of astatic electromechanical systems that are constructed based on a combination of the harmonic disturbance internal model principle (selective invariance) with other principles of control theory (cascade control, subordinate control with series compensation, state control, polynomial output control, and separation of motion rates). Methods are proposed for comparison and structural optimization of systems synthesized by using a combination of the specified methods in accordance with a defined complex of main and additional quality criteria: optimization of the constant and harmonic components of load torque disturbances, the range of acceptable variations of the inertia moment of the mechanical part, the level of pulsations of output speed signals when noise is on its measuring channel, the maximum value of signals time delay in the power converter when the system is stable, and the total degree of regulator dynamic blocks. The results show how the selected quality factors that are the most important for a designer are emphasized when the designer applies a combination of different system generation principles, which makes it possible to reasonably choose the most effective structural solution.

Keywords: electromechanical system, harmonic disturbance compensation, internal model principle, synthesis and structural optimization of regulators, selective invariance

DOI: 10.3103/S1068371215050089

The use of individual applied technological machine devices and significant simplification of power transmissions between an electric motor (EM) and a main operating element (OE) has led to the latter becoming a common element of the mechanical part of electromechanical systems (EMSs). In addition, manufacturing, assembling, and mounting errors, as well as OE design features, result in generation of the typical harmonic disturbances of the EM load torque with a frequency equal to or several times its rotation speed, which can be presented in the first approximation [1] as

$$T_{\text{load}}(t) = T_0 + T_1 \sin(\omega_1 t), \qquad (1)$$

where T_0 is the constant component and T_1 and ω_1 are the OE torque vibration amplitude and rotation frequency.

The load-torque fluctuations of EMSs and, hence, the rotation frequencies of the technological device's operating elements have a significant effect on the output quality [2–4]. They have an effect on the manufacturing accuracy of the workpiece during metal working, the geometrical dimensions of elongated materials during processing in flow lines (fiber or wire diameter, thickness of films and different coatings), their weight indices (paper density, tissue density, etc.), the light transmission of optical light guides, etc. This is confirmed by results of the relevant studies [1–4] performed on different-purpose technological machines with the use of the method of spectral coordinate analysis in a wide operating speed range.

Attempts to reduce the level of OE rotation frequency pulsations by controlling the follow-up EMS state and increasing the overall loop gain lead to an increase in EM current boosts and a corresponding decrease in the dimension of the linear range of systems operation during the optimization of control actions, as well as to reduction of their noise resistance [4].

Of the known approaches to solving the problem of compensation of external disturbances [3, 5–8], the most effective for the given conditions is the principle of selective invariance of automatic control systems (ACSs) to certain types of actions that is based on use of the internal disturbance model [3, 5–7]. Here, the selective-invariant system is understood as a system that provides the minimum stationary response to a specific type of disturbances, that is, harmonic disturbance in our case (1).

For disturbing action (1) consisting of constant and vibrational components, the corresponding Laplace image will be as follows:

$$T_{\text{load}}(s) = \frac{T_0}{s} + \frac{T_1\omega_1}{s^2 + \omega_1^2}, \quad (2)$$

where s is a Laplace variable, $\omega_1 = \Omega/i$, Ω is the EM rotation speed, and i is the gear ratio.

According to the selective invariance principle, the polynomial that forms mathematical disturbance model (2) and enters into the regulator transfer function (TF) denominator is determined here as

$$G'(s) = s(s^2 + \omega_1^2) = sG(s). \quad (3)$$

A control device with such a disturbance model obtains an integrational and a vibrational components that, under the effect of negative feedback (FB), collectively provide type-1 astaticism, i.e., a zero static error caused by the action of the constant torque component and the antiphase compensation of its harmonic component in the steady state operation regime. Generation of additional zeroes in the TF of the control action system is eliminated by a relevant out-of-loop signal former (a prefilter).

STATEMENT OF THE PROBLEM

Let us take a dc electromechanical system as the object of research. Its block diagram is shown in Fig. 1a, where the following value notations are used: U_c and U are the power converter control and input voltage and I_a is the EM anchor chain. The following identifiers of object parameters have also been assumed: $K_{\text{p.c.}}$ and $T_{\text{p.c.}}$ are the the transfer factor and response time of the power voltage converter, R_a and T_a are the active resistance and response time of the anchor chain, C is the structural EM constant, and J is the total reduced inertia moment of the EM rotor and OEs.

We consider the traditional indices of the control of rotation frequency and disturbance signals (control time, overcontrol, recovery time, etc.) with respect to load torque of type (1) as the main quality criteria for synthesized astatic ACSs.

Sensitivity to the mechanical part's parameter variations, noise resistance to flat-noise random signals in the velocity feedback channel, and resistance to power converter signal lagging that was not taken into account during the design, as well as the degree of the regulator complexity determined by the total degree of its dynamic blocks, are assumed to be additional quality criteria.

Within the framework of the aforementioned requirements, let us perform a structural and parametric synthesis and provide an integrated assessment of different structural solutions for EMSs generated based on a possible combination of the principle of the internal disturbance model (DM) or selective invariance to other ACS generation principles:

—subordinate control of coordinates with series compensation of control loops;

—cascade control (regulator construction) (CC);

—system state control (SC);

—output state control or polynomial control (PC); and

—separation of motion rates (localization) of subsystems (MRS).

Let us use the methods of modal control theory as a basis for EMS synthesis that provide the main quality indices by forming the respective distribution of the poles of the systems being generated.

Let us create and implement a general technique for comparison and structural optimization of different EMS types according to the specified complex of main and additional quality criteria.

GENERATION OF SELECTIVE AND INVARIANT ASTATIC EMSs USING DIFFERENT PRINCIPLES FOR ACS SYNTHESIS

To make the synthesizing procedures more understandable and enable comparison of results from different structural EMS implementations, let us assume a unified control object (CO) (Fig. 1a) with the following parameters: $K_{\text{p.c.}} = 22$, $T_{\text{p.c.}} = 0.001$ s, $R_a = 0.177\ \Omega$, $T_a = 0.02$ s, $C = 1.37$ Wb, $J = 0.2$ kg m^2, and $i = 10$.

Assume that it is required to provide a transient response time for a speed frequency control system in a linear range of its operation of no more than 50 ms with the absence of overcontrol and the zero static velocity error caused by load action of type

$$T_{\text{load}}(t) = 41.1 + 8.22\sin\left(\frac{\Omega}{i}t\right), \quad (4)$$

as well as the effective dynamic compensation of disturbance with a recovery time equal to the control time. Let us analyze the transient response of EMSs with the start being at a decreased rotation frequency $\Omega = 15.7$ rad/s (which corresponds to $\omega_1 = 15.7$ rad/s).

To increase the robust properties of synthesized ACSs (avoidance of generation of positive feedback or nonminimum phase blocks as part of controllers), let us neglect the relatively short-time constant $T_{\text{p.c.}}$ in calculations, according to recommendations [9]. As a result, the TF of the control object becomes

$$L_{\text{CO}}(s) = \frac{B(s)}{A(s)} = \frac{b_0}{s^2 + a_1 s + a_0} = \frac{42570.6}{s^2 + 50s + 2651}, \quad (5)$$

where $A(s)$ and $B(s) = b_0$ are a characteristic polynomial (CP) and an action polynomial.

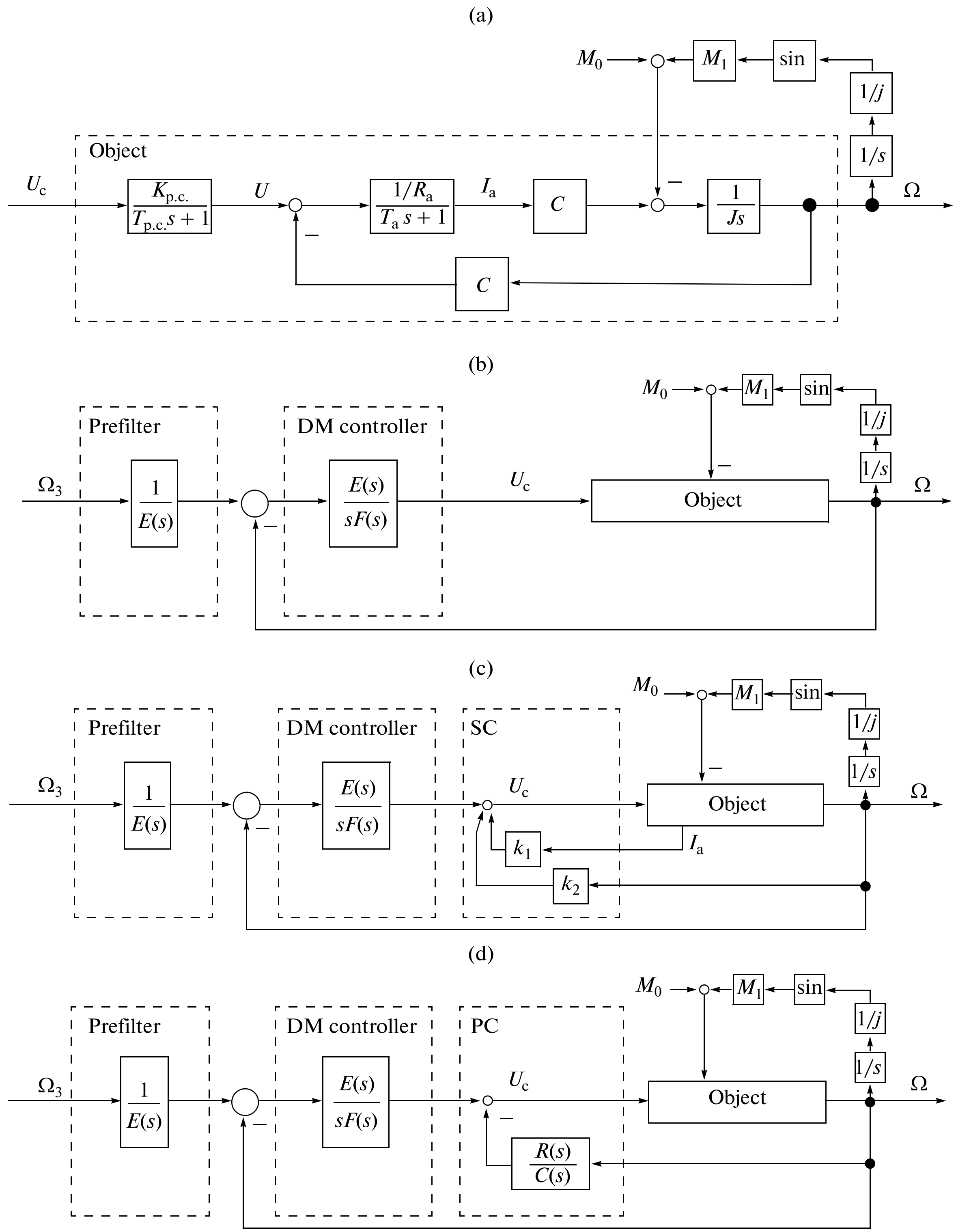

Fig. 1. Block diagrams of control object and different EMS types.

The EMS shown in Fig. 1b, where Ω_{set} is a set rotation speed value, is a traditional [3, 6] solution for the specified problem, which is structurally the simplest solution and requires only measurement of the CO output coordinate. It has one control loop with a combined polynomial controller (PC), that includes the DM and is further referred to as an SL(DMPC) (single-loop disturbance model polynomial controller).

Table 1

ACS no.	ACS type	Control principles applied	Controller structure and parameters
1	SL(DMPC)	PC, DM	$\frac{E(s)}{F(s)} = \frac{14.055s^4 + 4275.467s^3 + 68526.526s^2 + 57562089.6s + 2014679638.06}{s(s^2 + 1.57^2)(s + 1210)}$
2	DMPC/(SC)f	SC, MRS, PC, DM	$K = [-0.77\ \ -7.7];\ \frac{E(s)}{F(s)} = \frac{2700s^2 + 315881.04s + 12320100}{s(s^2 + 1.57^2)}$
3	DMPC/(PC)f	PC, MRS, DM	$\frac{R(s)}{C(s)} = \frac{0.0264s + 7.536}{0.0005s + 1},\ \frac{E(s)}{F(s)} = \frac{2700s^2 + 315881.04s + 12320100}{s(s^2 + 1.57^2)}$
4	P(DMPC/SC)	P, SC, PC, DM	$K = [-0.084\ \ -1.56];\ \frac{E(s)}{F(s)} = \frac{5.33s^3 + 1574.97s^2 + 157495.891s + 5906250}{s(s^2 + 1.57^2)}$
5	P(DMPC/PC)	P, PC, DM	$\frac{R(s)}{C(s)} = \frac{0.0123s + 0.593}{0.0005s + 1},\ \frac{E(s)}{F(s)} = \frac{5.33s^3 + 1574.97s^2 + 157495.891s + 5906250}{s(s^2 + 1.57^2)}$
6	K(DMPC/SC)	CC, SC, PC, DM	$K = [-0.14\ \ -4.64];\ \frac{E(s)}{F(s)} = \frac{2.85s^3 + 1369.9s^2 + 123284.61s + 4438668.94}{s(s^2 + 1.57^2)}$
7	K(DMPC/PC)	CC, PC, DM	$\frac{R(s)}{C(s)} = \frac{0.021s + 4.64}{0.005s + 1};\ \frac{E(s)}{F(s)} = \frac{2.85s^3 + 1369.9s^2 + 123284.61s + 4438668.94}{s(s^2 + 1.57^2)}$

A combined controller is synthesized here through the solution [6] of a polynomial equation of the form

$$A(s)sF(s) + B(s)E(s) = D(s), \tag{6}$$

where $E(s)$ and $sF(s)$ are the polynomials of the controller TF numerator and denominator at $F(s) = G(s)V(s)$, $V(s)$ is an auxiliary polynomial ensuring the controller's engineering feasibility, and $D(s)$ is a desired CP of the synthesized system ($E(s)$ is also assumed to be the out-of-loop prefilter CP).

According to the defined dynamics requirements and expressions (3)–(5), let us choose the sixth-order Newtonian polynomial as $D(s)$, with a root mean square value (RMS) $\Omega_0 = 210\ \text{s}^{-1}$, which corresponds to the response time 50 ms.

For such an EMS, expanded equation (6) of the synthesis of the minimum-order astatic PR [9] becomes

$$(s^2 + 50s + 2651)s(s^2 + 1.57^2)(s + \nu_0) + 42570.6$$
$$\times (e_4s^4 + e_3s^3 + e_2s^2 + e_1s + e_0) = (s + 210)^6.$$

Its solution under the specified conditions allows one to obtain the TF of the controller the type and parameters of which are given in the first row of Table 1.

This EMS can meet the set main quality criteria; however, it is characterized by a high degree of regulator complexity (the total degree of blocks is 8) and is likely to have increased noise sensitivity.

A significant simplification of the controller can be achieved in the EMS structure presented in Fig. 1c and is designated as PRDM-(SC)f. It includes a "fast" internal subsystem based on inertia-free SC, which is tuned to a fast response exceeding the defined dynamic requirements by five to seven times, as well as the outer loop with PC, that includes a disturbance model.

This structure is constructed based on a combination of SC, MRS, PC, and DM principles. The following calculation procedure can be proposed for synthesis of its controllers.

An inertia-free SC of the internal subsystem with high response time (7 ms) is synthesized based on the modal control method. For this purpose, the second-order Newton CP with $\Omega_{ob} = 572\ s^{-1}$ is assumed to be the desired one. Calculation of the current FB coefficient matrix and rotation speed yields the following result: $K = [-0.177\ -7.7]$.

When finding an external PR with DM, the basic polynomial synthesis equation is used [6]:

$$P(s)sF(s) + Q(s)E(s) = D(s), \quad (7)$$

where $P(s)$ and $Q(s)$ are the CP and the action polynomial of the internal subsystem TF.

The fast response time of the internal subsystem gives reason for considering it as an inertia-free one when synthesizing an external PC, i.e., for assuming the following expressions, taking into account the specified parameters: $P(s) = 1$, $Q(s) = \dfrac{b_0}{\Omega_{ob}^2}$.

According to the established dynamics requirements, a third-order Newton polynomial is chosen as $D(s)$, with an RMS value of $\Omega_0 = 117\ s^{-1}$, which corresponds to the set response time (50 ms).

In this case, synthesis equation (7) takes on the following expanded form:

$$s(s^2 + 1.57^2) + 0.13(e_2 s^2 + e_1 s + e_0) = (s + 117)^3.$$

Its solution allows one to obtain the transfer function of the external minimum-order regulator, the parameters of which are given in the second line of Table 1.

The EMS of this structure, which applies four of the above-mentioned control principles (Table 1), can meet the set main requirements in the case of a low level of complexity of the dynamic part of the controller (total degree of blocks equal to 5). However, it is likely to have an increased sensitivity to the action of all factors that were not taken into account during synthesis—in particular, to signal lagging in the power voltage converter (PVC).

The same MRS principle can be applied in EMSs when using only one output coordinate (Fig. 1d). In this case, the "fast" internal subsystem is implemented by the internal dynamic (PC)f with the numerator polynomial $R(s)$ and polynomial denominator $C(s)$ of its TF. As a result, the external control synthesis equation is

$$A(s)C(s) + B(s)R(s) = P(s). \quad (8)$$

When choosing the second-order Newton polynomial with RMS $\Omega_{ob} = 572\ s^{-1}$ and applying solution (8) to condition $C(s) = 1$, we obtain a derivative (PC)f with a TF $R(s) = 0.0264s + 7.536$ and assume the following form for its engineering feasibility: $C(s) = 0.0005s + 1$.

Calculation of the external DM PC is done in the same way as for the previous structure (Fig. 1b) in accordance with synthesis equation (7) subject to the inertia-free nature of the internal subsystem. The types and parameters of the controller TF for the EMS structure that is shown in Fig. 1d and referred to as DMPC/(PC)f are given in the third line of Table 1.

This EMS in which output coordinate dynamic derivatives are used can provide a higher loop gain and, hence, the best optimization of load torque disturbance; it may be expected, however, that this will simultaneously entail a significant reduction of system noise resistance.

It is possible to reduce EMS sensitivity to the effect of noise in measuring channels through slower adjustment of the internal rotation speed subsystem with SC and PC (Figs. 1c, 1d) and application of the series compensation principle. In this case, a moderately accelerated (by 2–2.5 times) internal subsystem is approximated by the aperiodic first-order block, after which an external PR with a DM is synthesized. In the present case, to synthesize an AC- or PC-based internal subsystem by Eq. (8), the desired second-order $P(s)$ polynomial is assumed in the Newtonian form, where $\Omega_{ob} = 267\ s^{-1}$, which corresponds to moderate response time (24 ms) and allows one to approximate its transfer function of the form

$$H_{int}(s) = \frac{Q(s)}{P(s)} = \frac{b_0/\Omega_{ob}^2}{Ts + 1} = \frac{0.6}{0.007s + 1},$$

when synthesizing the external operator.

In this case, synthesis equation (7) with fourth-order polynomial $D(s)$ in the Newton form and $\Omega_0 = 150\ s^{-1}$ takes on the following expanded form

$$(0.007s + 1)s(s^2 + 1.57^2) + 0.6(e_3 s^3 + e_2 s^2 + e_1 s + e_0) = (s + 150)^4.$$

The obtained expressions and parameters of TF polynomials and the FB coefficients of the controllers of both EMS types, referred to as P(DMPC/SC) and P(DMPC/PC), respectively, are given in Table 1.

However, one may assume that use of the series compensation principle accompanied by the errors of approximation of internal subsystems with lower-order blocks, will lead to a respective deterioration of the optimization of load torque disturbances, as com-

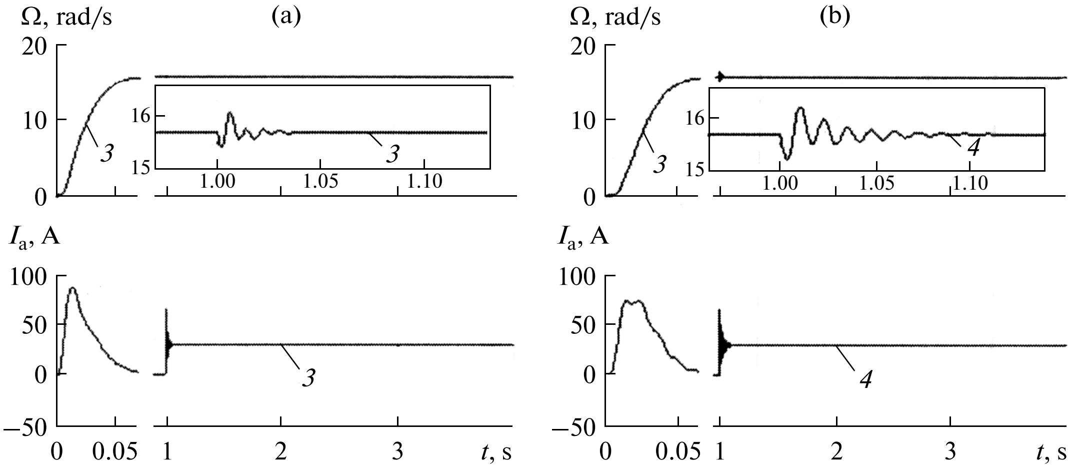

Fig. 2. Quality assessment for optimization of constant load torque: (a) 5 points; (b) 1 point.

pared with other EMS types. In addition, the total degree of the blocks of regulators of the analyzed systems increases to 6 and 7, respectively.

A certain compromise between the quality of optimization of disturbances acting in the direct channel (on the EM shaft) and the rotation speed measuring channel, with the level of the regulator complexity being preserved, can be provided by similar EMS structures, designated as K(DMPS/SC) and K(DMPS/PC). They are constructed according to the same cascade principle (Figs. 1c, 1d), but without approximation and reduction of the order of internal rotation speed control subsystem.

Synthesis of these EMS types is carried out in two stages in the direction from the outer loop of the system to the inner loop.

At the first stage, synthesis equation (7) is formulated, in which a desired five-order CP $D(s)$ is introduced in the right-hand member (in our case, in the Newtonian form with $\Omega_0 = 180\ s^{-1}$, corresponding to the response time of 50 ms). The general form of the desired CP of the second-order internal system is defined as $P(s)$ polynomial (the same Newtonian form as in our case), with an unknown value Ω_{ob}. In addition, as in the two previous EMS types, the introduction of an auxiliary $V(s)$ is not required. The polynomial $Q(s)$ is replaced by coefficient $b_0 = 42570.6$. It is necessary to determine the parameters of the $E(s)$ polynomial of the disturbance model controller, as well as the value of RMS of the polynomial $P(s) - \Omega_{ob}$.

For the synthesized EMS types, we obtain the expanded form of Eq. (7)

$$(s+\Omega_{ob})^2 s(s^2+1.57^2) + 42\,570.6(e_3 s^3 + e_2 s^2 + e_1 s + e_0) = (s+180)^5$$

its solution yields the values of $E(s)$ polynomial coefficients shown in Table 1 and the value $\Omega_{ob} = 450\ s^1$ that determines the compromise response time of the internal subsystem (15 ms).

At the second stage, the regulators of the external SC or PC subsystem are respectively synthesized for the EMS (Figs. 1c, 1d). The procedures of this synthesis are similar to the above-described procedures for (SC)f and (PC)f controllers, with the only difference being that the polynomial $P(s) = (s + 450)^2$ obtained at the first stage of synthesis is assumed to be a desired CP.

Complete information on the structures and parameters of controllers of all types of synthesized EMSs with the indication of control principles that form their basis is given in Table 1.

It is clear that each of the EMS types will have its own advantages and disadvantages not only due to the features of a specific CO, but also due to general regularities determined by the control principles being applied.

COMPARATIVE ANALYSIS OF QUALITY INDICES AND STRUCTURAL OPTIMIZATION OF SELECTIVE-INVARIANT EMSs

The research is conducted by setting up detailed computational experiments with the models of synthesized EMSs using the Matlab software package.

When optimizing a control action, the transient response of all types of EMSs is calculated; their identity and compliance with the specified requirements are verified. The quality of separate optimization is assessed (at a time point of $t = 1$ s) for the step variation of the constant load torque component (factor $T_=$) and the action of its harmonic component (factor $T_\sim$). The most common diagrams of the stated transient processes are shown in Figs. 2 and 3, where the curve numbers correspond to the ordinal numbers of EMS types in Table 1.

By performing multiple computational experiments with EMS models, the ranges of allowable vari-

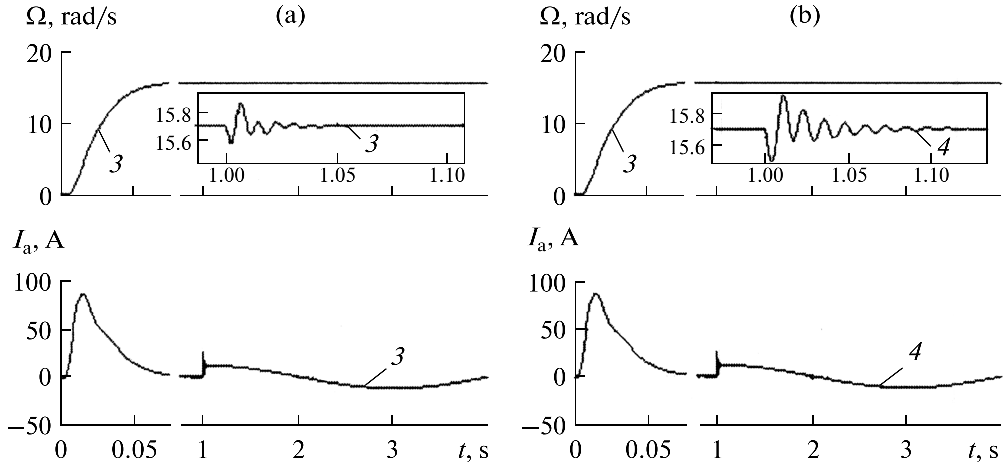

Fig. 3. Quality assessment for optimization of harmonic load torque: (a) 5 points; (b) 1 point.

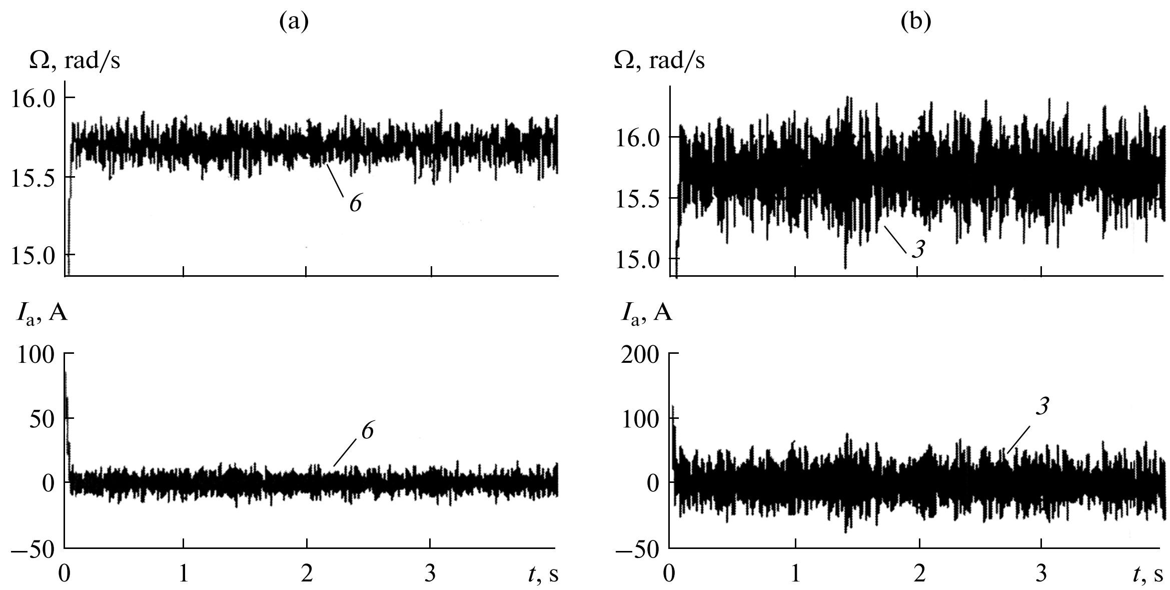

Fig. 4. Assessment of system response to introduction of disturbances into the velocity meter circuit: (a) 5 points; (b) 1 point.

ations of the mechanical part inertia moment (factor J = var) and the maximum values of signal (pure) time delay τ_{max} in the PVC (factor $e^{-\tau s}$, τ = var) that provide system stability are determined. The obtained values of the specified factors and the total degree of regulator dynamic blocks (factor N_{reg}) of synthesized EMSs are given in Table 2.

The noise resistance of EMSs (factor $P^{\sim}$) is assessed from the level of output velocity signal pulsations under the interference of additive noise in the form of "flat noise" with a power of $N = 0.00001$ W/Hz in its measuring channel. The most common velocity diagrams for different types of systems (Table 1) are shown in Fig. 4 in accordance with the accepted numbering.

The results of research in the form of diagrams of transient processes and numeric values of the stated factors, that were obtained in the course of experiments, are assessed by the traditional five-point scale using an expert method and are summarized in Table 3, where the overall quality assessment (Q_Σ) is given for each EMS, that was obtained with the equal significance of the aforementioned factors taken into account.

It should be noted that in our case, the operation of systems is not studied with significant changes in the operating velocities and frequencies of load torque harmonic disturbance, since these factors create their own problematics that should obviously be resolved by using additional adaptive control algorithms.

The results of research that reflect the level of fulfillment of the whole set of the defined requirements

Table 2

ACS no.	ACS type	EMS quality factors		
		J = var, kg m^2	$e^{-\tau s}$, τ = var, ms	N_{reg}
1	SL(DMPC)	[0.09; 0.38]	0.0014	8
2	DMPC/(SC)f	[0.08; 0.32]	0.0012	5
3	DMPC/(PC)f	[0.13; 0.38]	0.0008	6
4	P(DMPC/SC)	[0.17; 0.57]	0.0011	6
5	P(DMPC/PC)	[0.12; 0.22]	0.00096	7
6	K(DMPC/SC)	[0.09; 0.53]	0.0014	6
7	K(DMPC/PC)	[0.12; 0.65]	0.00092	7

Table 3

ACS no.	ACS type	EMS quality factors						
		$M_\sim$	$M_=$	J = var	$P_\sim$	e^{-ts}	N_{reg} complexity	Q_Σ
1	SL(DMPC)	3	3	4	3	5	1	19
2	DMPC/(SC)f	2	2	4	4	4	5	21
3	DMPC/(PC)f	5	5	2	1	1	4	18
4	P(DMPC/SC)	1	1	3	4	4	4	17
5	P(DMPC/PC)	1	1	1	3	3	3	12
6	K(DMPC/SC)	4	4	5	5	5	4	27
7	K(DMPC/PC)	5	5	5	2	2	3	22

demonstrate the advantages and disadvantages of each EMS type and allow designers to solve structural optimization problems based on the most preferable compromise scheme.

CONCLUSIONS

The proposed structural solutions of selective-invariant EMSs, as well as the adopted procedure for their research and the results illustrate how the values of quality indices are redistributed when applying different principles of ACS generation. This can serve as a basis for the structural optimization of follow-up high-accuracy EMSs that are exposed to load torque harmonic disturbances and the influence of other factors.

Use of a unified control object in different EMS types makes it possible to create equal conditions for their comparative analysis and demonstrate the general regularities and features of their synthesis, that are inherent in control systems for different COs.

ACKNOWLEDGMENTS

This study was conducted with state financial support provided by the Ministry of Education and Science of Russia, research (project) unique identifier RFMEFI57414X0070.

REFERENCES

1. Schoenfeld, R. and Habiger, E., *Automatisierte Elektroantriebe*, Berlin: Veb Verlag Technik, 1981.
2. Selezneva, V.V., Vibrodiagnostics according to processing results, in *Nadezhnost' i diagnostirovanie tekhnologicheskogo oborudovaniya: Sb. statei INMASh AN SSSR* (Reliability and Diagnosing for Technological Equipment. Collection of Scientific Papers of INMASh USSR Academy of Sciences), Moscow: Nauka, 1987.
3. Gudvin, G.K., Grebe, S.F., and Sal'gado, M.E., *Proektirovanie sistem upravleniya* (Control Systems Design), Moscow: BINOM. Laboratoriya znanii, 2004.
4. Kopylova, L.G. and Tararykin, S.V., The way to compensate harmonic disturbances at the loading moment in the following-up electromechanical systems and the elements of controller's structure optimization, *Vestn. Ivaovsk. Gos. Energ. Univ.,* 2012, no. 6.
5. Kulebakin, V.S., On the main problems and methods for increasing systems automated control quality, in *Tr. II Vses. soveshch. po teorii avtomaticheskogo regulirovaniya* (Proc. 2nd All-Union Meeting on the Theory of Automated Control), Moscow: Nauka, 1965, vol. 2.
6. Gaiduk, A.R., *Osnovy teorii sistem avtomaticheskogo upravleniya: Ucheb. posobie* (Foundations of Automated Control Systems. Student's Book), Moscow: Uchebnaya literatura, 2005.
7. Andrievskii, B.R. and Fradkov, A.L., *Izbrannye glavy teorii avtomaticheskogo upravleniya s primerami na yazyke MATLAB* (Selected Chapters of Automated Control Theory with Examples in MATLAB Environment), St. Petersburg: Nauka, 1999.
8. Zaitseva, M.V. and Parsheva, E.A., Robust control for linear object under disturbances and noises, *Mekhatron., Avtomatiz., Upr.*, 2011, no. 3.
9. Tyutikov, V.V. and Tararykin, S.V., *Robastnoe modal'noe upravlenie tekhnologicheskimi ob"ektami* (Robust Modal Control for Technological Objects), Ivanovo, 2006.

Translated by D. Zabolotny