Synergetic Control for Electromechanical Systems

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Abstract

The paper is devoted to a problem of synergetic regulators synthesis for nonlinear electromechanical systems (EMS). The different variants of synergetic regulators synthesis for such EMS as DC electric drives, asynchronous electric drives and synchronous electric drives are presented. Synthesized vector regulators are constructed on basis of nonlinear mathematical models and ensure to peform the standard technological tasks: angle and angular speed stabilization, torque stabilization etc. Also examples of EMS using in mechanical oscillator mode and the task of EMS's power-saving control are considered.

KEYWORDS: electromechanical systems, synergetic control theory, automatic regulator, electric drives

1 Introduction

Electromechanical systems (EMS) play the key role in different fields of modern technical sphere. On other side, the 60% of this energy is transformed into the mechanical energy by electric drives which are executive basis of most industrial, transport and service sets and aggregates.

The modern requirements for EMS quality are becoming stricter. Besides the range of technological tasks broadens. This calls for necessity to search for more advanced control strategies for these objects. In this article the application of synergetic conception [1,2] for EMS control tasks is considered. This conception is characterized by supporting on "physical" essence of controlled processes, using the most adequate nonlinear mathematical models and analytic procedures of regulators synthesis.

2 Invariants of Electromechanical Systems

In synergetic control theory the requirements put on dynamic and static qualities of the systems being synthesized are represented in the form of a set of invariants. Invariants enter in the structure of invariant manifolds formed in the phase space of the object according to the method of synergetic synthesis. These manifolds serve as attractors of the closed-loop system.

For EMS we can determine a three invariants group: technological, energetic and electromagnetic. The typical invariants of EMS are presented in a table.

The form of **technological invariant** is determined by specific practical task solved by EMS in some technological process and characterizes the desired static or dynamic state of the controlled variables – mechanical speed, angle, torque.

Energetic invariants are correlations between object's coordinates characterizing most advantageous energetic modes of work (minimal energy losses, minimal energy consuming etc.)

The invariants of EMS connected to the constancy of the magnetic flux (**electromagnetic invariants**) deserve a special attention. The idea of stabilization of the magnetic state of the asynchronous machine found its application in the known asynchronous motors frequency control laws and has an indubitable practical importance.

Table

	Invariant type	Solving task
		Electromagnetic invariants
1.	$\psi_s = const$	Stator linkage stabilization
2.	$\psi_r = const$	Rotor linkage stabilization
3.	$\Phi = const$	Magnetic flux stabilization
		Energetic invariants
1.	$\Phi = \Phi_{opt}$	Optmal magnetic flux
2.	$s = s_{opt}$	Optmal sliding
		Technological invariants
1.	$\omega = \omega_0$	Speed stabilization
2.	$\Theta = \Theta_0$	Positioning task
3.	$M = M_0$	Torque stabilization
4.	$\omega = f_1(t)$	Maintaining the set function of time for the change of speed
5.	$\Theta = f_2(t)$	Maintaining the set function of time for the change of rotor angle
6.	$M = f_3(t)$	Maintaining the set function of time for the change of torque

Modern EMS is a complex technical and algorithmic means, constantly exchanging by energy and information and solving a common task of controlled electromechanical energy transformation.

Every EMS may be described by a system of nonlinear differential equations, have several control channels and be subject to external disturbances from environment (technological and natural).

The task of search for the structure and parameters of the regulator is a classical synthesis task. In our case it can be stated in the following way: *It is necessary to find a control vector* $\mathbf{u}(\mathbf{x})$ *as a function of phase coordinates ensuring motion of the nonlinear EMS from an arbitrary initial state* $\mathbf{x}^0$ *located at some allowed area to the set final state* $\mathbf{x}^k$.

Lets consider the synergetic control theory application for general types EMS regulators synthesis solving.

3 Synergetic Control for DC Electric Drives

At the present time DC electric drives (DCED) are the important functional elements of many technological processes in various branches of modern industry.

The most commonly used type of DC electric motors – DC electric motor with an independent excitation. It has two independent energy sources (two control channels) – one for the armature circuit and another one for the excitation circuit. Mathematical model of DCED with independent excitation may presented in form

$$\begin{aligned} \dot{x}_1(t) &= x_2; \\ \dot{x}_2(t) &= (x_3 x_4 - M_l)a_{21}; \\ \dot{x}_3(t) &= (u_1 - x_4 x_2 - a_{31} x_3)a_{32}; \\ \dot{x}_4(t) &= (u_2 - f_1(x_4))a_{41}. \end{aligned} \tag{3.1}$$

The relative values here denote: x_1 – drive's shaft rotation angle; x_2 – frequency (speed) of the shaft's rotation; x_3 – armature current; x_4 – magnetic flux of one pole; u_1 – armature voltage; u_2 – excitation winding voltage; M_l – load resistance torque on the motor's; $f_1(x_4)$ – function characterizing the saturation process in the motor's magnetic systems.

Lets consider synergetic synthesis procedure for these dynamic objects. According to the number of control channels two basic invariants could be selected. Generally one of them is technological (speed stabilization, positioning etc.) So it is expedient to select a parallel totality of invariant manifolds in the following form:

$$\begin{aligned} \psi_1 &= x_3 - \gamma_1(x_1, x_2) = 0; \\ \psi_2 &= x_4 - \gamma_2(x_1, x_2) = 0. \end{aligned} \tag{3.2}$$

To find a vector control law we must solve a system of general funcional equation of ADAR method [1,2]:

$$\begin{aligned} T_1\dot{\psi}_1(t) + \psi_1 &= 0; \\ T_2\dot{\psi}_2(t) + \psi_2 &= 0. \end{aligned} \tag{3.3}$$

taking into account the equations of model (3.1). This control law ensure a motion of the closed-loop system represented point to manifolds (3.2) intersection. On the intersection of manifolds $\psi_1 \equiv 0$ and $\psi_2 \equiv 0$ the functions γ_1 and γ_2 will determine the character of armature current and flux changing respectively, but DCED dynamics on this intersection is described by next differential equations:

$$\begin{aligned} \dot{x}_{1\psi}(t) &= x_{2\psi}; \\ \dot{x}_{2\psi}(t) &= (\gamma_1(x_{1\psi}, x_{2\psi}), \gamma_2(x_{1\psi}, x_{2\psi}) - M_l)a_{21}. \end{aligned} \tag{3.4}$$

Then after performing additional definition of the functions γ_1 and γ_2 basing on the set technological invariant and on the required performance indexes of DCED functioning we can give the control laws the specific form.

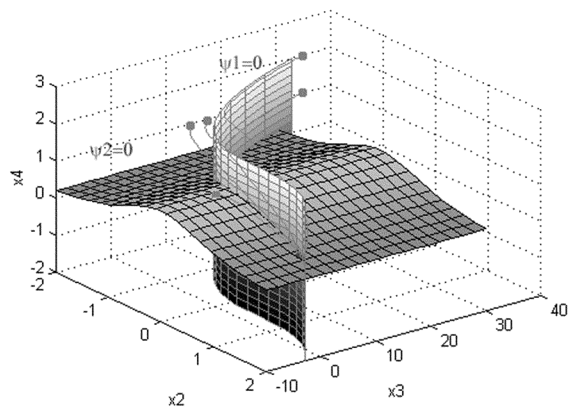

Figure 1: Phase portrait

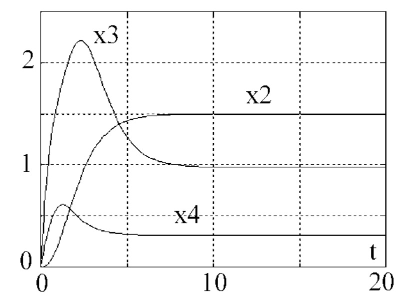

Figure 2: State variables transients

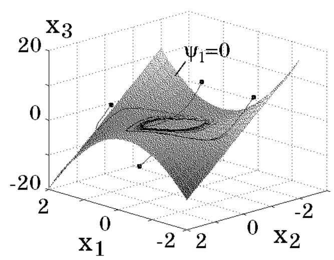

Figure 3: Phase portrait

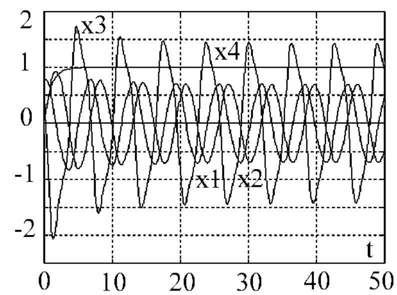

Figure 4: State variables transients

Synthesized control laws have a basic fundamental character because basing on them we can realize local vector regulators for any DCED that has a definite mechanical part (including a multi-mass one with flexible links) and a specified set of electrical converters.

Using of basic control laws allow to find the different variances of new control algorithms for DCED, ensuring performing of standard tasks of speed stabilization and positioning [3,4].

Figures 1 and 2 show the phase portrait and transients of the closed-loop system for the mode of acceleration to the speed higher than the nominal one. The modeling results confirm that the acquired control laws ensure asymptotically stable character of transients and are universal for and "speed" task. A mechanical oscillator is present in a number of technological tasks. From the point of view of synergetic synthesis the natural step in realization of such mode is the transformation of the equations of "remaining" dynamics of the system (3.3) on the intersection of invariant manifolds $\psi_1 \equiv 0$ and $\psi_2 \equiv 0$ to the form of one of the known auto-oscillating system: Van der Paul, Rellay etc. This can be done by the appropriate selection of the functions γ_1 and γ_2. So the attractor of the closed-loop system will be the cycle in the phase space that will be located on the intersection hyper-surfaces of 4th order: $\psi_1 \equiv 0$ and $\psi_2 \equiv 0$. Fig. 2 shows phase portrait of the closed-loop system in the space $X_2X_3X_4$. Fig. 3 shows transients of state variables. The structure of EMS shouldn't include special sine voltage generators. The EMS itself becomes a nonlinear

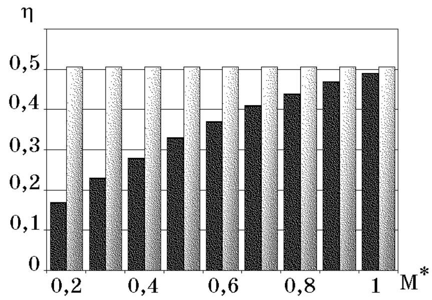

Figure 5: Efficiency diagram for DCED: $M_l = var$, $x_2 = x_{2nom}$

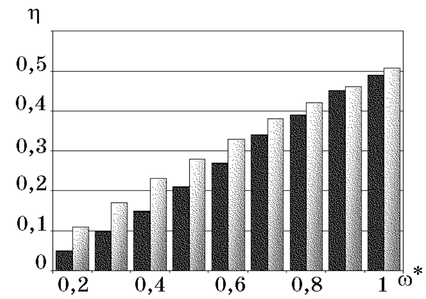

Figure 6: Efficiency diagram for DCED: $M_l = M_{lnom}$, $x_2 = var$

oscillating system because of the appropriate control strategy, i.e. because of the appropriate feedbacks.

An important result of our research that has an outstanding practical importance is the power-saving control strategies for DCED. Such regulators allow the most power-wise favorable modes of DCED functioning during performing various technological tasks.

Minimization of the power losses in DCED power channels is possible only if there is an active control of magnetic flux of the electric machine. For this purpose, one of the invariants of the synthesized system was selected in the form of a optimal flux linkage:

$$\Phi^2_{opt^*} = M_{l^*} \sqrt{\frac{k_{v^*}}{k_{b^*} + k_{s^*} \cdot \omega_*^{\beta}}}\,. \tag{3.5}$$

Here Φ_{opt^*}, M_{l^*}, ω_* – relative values of optimal flux, torque and rotation frequency, while k_{v^*}, k_{b^*}, k_{s^*} – relative values of the losses components in copper, excitation winding and steel.

Fig. 5 shows the efficiency diagrams of electromechanical transformation in DCED when load torque is chahged and speed is nominal. Here white is power-saving control and black is constant flux control. Fig. 6 shows the efficincy diagrams when speed is chahged and load torque is nominal.

Mathematical and natural modeling results let us say that application of power saving control algorithms allows us to essentialy reduce the total power losses compared to the standard scheme of supervised regulation at the constant flux.

4 Synergetic Control for Asynchrnous Drives

A perspective direction in modern controlled EMS is application of the systems with asynchrnous drives (AD). These drives are one of the most simple, reliable and economical. However the attempts to use these remarkable qualities of the asynchrnous motors in the controlled electric drives met serious difficulties. This was caused by the fact that AD are very complex electromechanical objects. Application of principles and methods of synergetic control theory allows to build the vector regulators for AD using there full nonlinear models of motion [3,4].

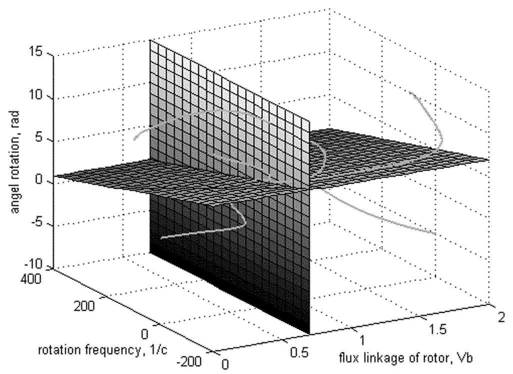

Figure 7: Phase portrait of closed-loop systems for AD positioning task

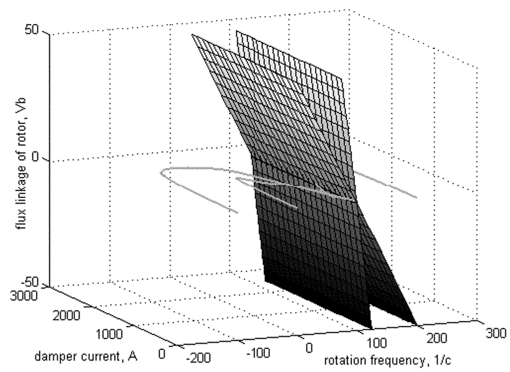

Figure 8: Phase portrait of closed-loop systems for AD speed control task

The mathematical model of an asynchronous drive (AD) with a shorted rotor can be presented in the xy rotating system of coordinates oriented along the rotor's flux linkage vector:

$$\begin{aligned}
&\dot{x}_1(t) = x_2;\\
&\dot{x}_2(t) = \frac{3}{2}\frac{p^2 L_m}{J L_r} x_3 x_5 - \frac{p}{J} M_l;\\
&\dot{x}_3(t) = \frac{r_r L_m}{L_r} x_4 - \frac{r_r}{L_r} x_3;\\
&\dot{x}_4(t) = -\frac{(r_r L_m^2 + r_s L_r^2) x_4 + r_r L_m x_3}{L_r (L_s L_r - L_m^2)} + x_2 x_5 + \frac{r_r L_m}{L_r}\frac{x_5^2}{x_3} + \frac{L_r}{L_s L_r - L_m^2} u_1;\\
&\dot{x}_5(t) = \frac{(r_r L_m^2 + r_s L_r^2) x_5 + L_r L_m x_3 x_2}{L_r (L_s L_r - L_m^2)} - x_2 x_4 - \frac{r_r L_m}{L_r}\frac{x_4 x_5}{x_3} + \frac{L_r}{L_s L_r - L_m^2} u_2.
\end{aligned} \tag{4.1}$$

where u_1, u_2 – projections of the stator voltage on the axes of the coordinate systems; x_4, x_5 – projections of the stator current on the coordinates axes; x_3 –modulus of the resulting flux linkage vector of the rotor; x_1, x_2 – angle and speed of the rotor; r_s, r_r – active resistances of the stator and rotor windings; L_s, L_r – full inductances of the stator and rotor windings; L_m – mutual inductance of the stator and rotor; p – number of pole pairs; J – reduced moment of inertia; M_l – load torque.

Using a procedure of synergetic synthesis allows to solve a the tasks of speed stabilization and positioning. Second invariant was $x_3 = const$. Selection of this electromagnetic invariant is caused by the fact that the most stiff mechanical characteristic of the AD can be achieve. Figures 7 and 8 show a phase portraits of closed-loop systems for AD positioning and speed control tasks. For power-saving control the next energetic invariant must be used:

$$x_3^2 = M_l \sqrt{\frac{k_1}{k_2 + k_3 x_2^{\beta}}}$$

Fig. 9 shows the efficiency diagrams of electromechanical transformation in DCED when load torque is chahged and speed is nominal. Here white is power-saving control and black is

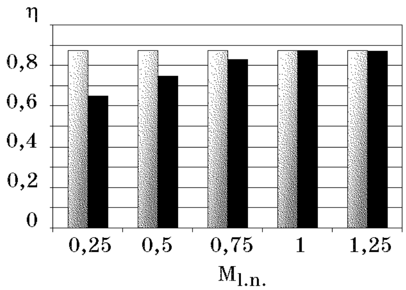

Figure 9: Efficiency diagram for AD: $M_l = var$, $x_2 = x_{2nom}$

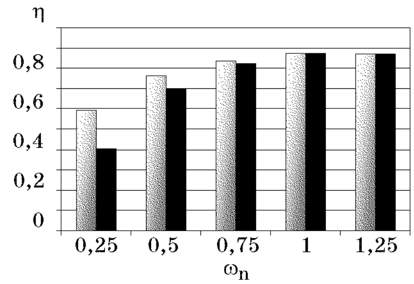

Figure 10: Efficiency diagram for AD: $M_l = M_{lnom}$, $x_2 = var$

constant rotor linkage control. Fig. 10 shows the efficincy diagrams when speed is chahged and load torque is nominal.

5 Synergetic Control for Synchronous Drives

In design of vector regulators in the tasks of synchronous drive (SD) control we use the mathematical model presented in the SD rotor's system of coordinates:

$$\begin{aligned} u_d &= L_d\frac{di_d}{dt} + L_{ad}\frac{di_f}{dt} - L_q i_q \omega_r + r_a i_d; \\ u_q &= L_q\frac{di_q}{dt} + L_d i_d \omega_r + L_{ad} i_f \omega_r + r_a i_d; \\ u_f &= L_f\frac{di_f}{dt} + L_{ad}\frac{di_d}{dt} + r_f i_f; \\ \frac{d\omega_r}{dt} &= \frac{1}{J}\left(L_{ad} i_f i_q + \left(L_d - L_q\right) i_d i_q - m_l\right); \end{aligned} \tag{5.1}$$

where r_a – active resistance of the armature winding; r_f – active resistance of the excitation winding; i_d, i_q – armature winding currents on the longitudinal and transverse axes; i_f – excitation winding current; $\omega_r = \omega_s$ – rotor's angular velocity equal to the synchronous speed; L_d, L_q – inductances of the armature windings on the longitudinal and transverse axes; L_f – inductance of the excitation winding; L_{ad} – mutual inductances among the windings on the longitudinal axis; u_d, u_q – stator windings voltages on the axes d and q.

Let's determine the types of invariants that should be satisfied by the synthesized SD control system. This object has three control channels, therefore, it can have not more than three invariants. First, we determine a technological invariant – SD's speed stabilization. Besides the technological invariants a certain number of requirements is put on the system. These requirements are associated with the static working modes. For example, ensuring the maximal electrical torque with a fixed modulus of the stator current, sustention of a particular value of $\cos\varphi$ etc. In synthesis of SD control systems, one of the important tasks is sustention of the constant excitation flux ($\psi_{ad} = const$). Accounting for $\psi_{ad} = L_{ad} i_f$, the task of excitation flux stabilization comes to the task of excitation current stabilization.

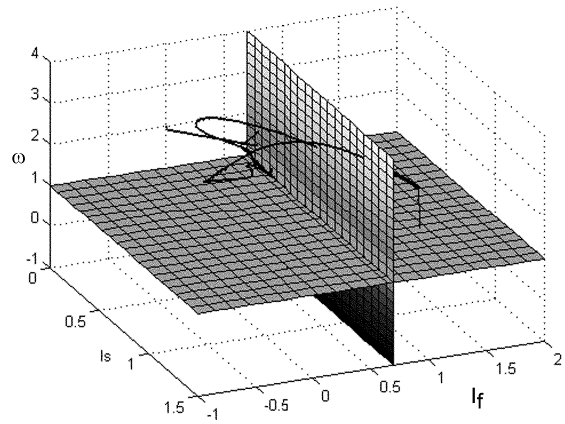

Figure 11: Phase portrait of closed-loop system

Basing on this we form the next electromagnetic invariant: $\phi_2 = i_f - i_{f0}$, where i_{f0} – the set stabilized value of the excitation current. It is known that to ensure the maximal electrical moment with a fixed stator current it is necessary to zero the longitudinal component of the stator current. So we can form the third electromagnetic invariant: $\phi_3 = i_d - i_{d0}$; $i_{d0} = 0$.

Fig. 11 shows a phase portrait of closed-loop system for considered invariant set.

6 Conclusion

The examples of vector regulators synthesis considering in this article reflect to small degree the new possibilities for perspective EMS constructors when they use progressive methods and principles of control theory. Supporting on "physical" essence of controlled processes, mobilization of all control channels, finding power-saving controls algorithms are the key to solving a problem of technological equipment maximal efficiency.

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