Control Systems for DC motor as Port-Controlled Hamiltonian System

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Abstract – One of the newest methods of control system design for DC motor as a part of electromechanical systems are energy-based approaches. The regulation in such systems is realized by forming energy function of the system. This article contains comparative analysis of simulation results of existing control systems, their applications and basic principles explanation. It was shown that using mechanical damping provides highly effective control and there are still many possibilities to increase energy-shaping system's efficiency.

Key words – DC motor, energy-based approach, control system, energy-shaping control system, structural and parametric synthesis, comparison, systems of modal regulation, cascade control systems.

I. Introduction

DC machines are the keystone of world industry. Simplicity in exploitation and regulating, as well as in control systems building, allows to get high quality properties of response, static precision, durability and reliability of synthesized control systems, and also the setup simplicity for most of them. Among them the most common excitation type of DC motors (DCM) are shunt-connected, as it provides conditional linearity of work characteristic, simplified calculation methods, and a smooth asymptotic transition process in case of sudden system parameters change. Despite numerous benefits their usage is associated with additional energy and funds losses on rectifier and collector, but these loses may be decreased by a proper control.

Nowadays there are numerous control systems developed for DCM. One of the most common of them are Systems of Modal Regulation (SMR) and Cascade Control Systems (CCS).

SMR forms control signal based on task signal, which is corrected by feedback signals (for DCM they are represented by current and speed). Each one of the signals flows through certain scale coefficient. These systems are especially common among unpretentious systems, as "raw" setup can be performed quite fast, but precise one is extremely sophisticated [1].

CCS consequently regulates every circuit of the system, starting from internal one. Thus, by engaging consequent correctors of certain type (P, PI, etc.) it becomes possible to strictly form behavior of every circuit (for DC motors these circuits are current and speed ones), so it give wide regulation possibilities [2]. These systems have standard general setup algorithm, according to which each scheme parameter is consequent formed. However in complicated systems, or ones with specially interconnected parameters setup procedure would be extremely difficult up to impossible.

So, there appears an actual task – to develop new control systems for DCM electromechanical systems (EMS), which would, at the same time, provide realization of control laws and be easy and clear to set up.

II. Energy-shaping control

One of the most perspective methods of control system design are physical control theory approaches. Exactly such are energy-based approaches, which are based on physical laws of energy transfer and conversion [3].

In general, any task for electromechanical system contains demand in certain filling it with energy. For example, for motor (as being the simplest EMS) it becomes the sum of magnetic and mechanical energies, accumulated during work parameters presetting. So reaching certain rotation speed is impossible without fulfilling system with rotational kinetic energy ($J\omega^2/2$) in mechanical part, and it is reached and held by certain momentum, caused by electrical current in rotor circuit, which in itself couldn't flow without fulfilling the circuit with magnetic energy ($Li^2/2$). The total energy of the system is called Hamiltonian, and is mathematically formulated quite differently. Mostly it is showed the following way:

$$H(\mathrm{x}) = \lambda^2 / 2J + p^2 / 2L\,,$$

where $\lambda = iL$, $p = \omega J$ – are energy system variables, representing its status (which is described as vector $\mathbf{x}(t)$).

Hamiltonian is the keystone of energy-shaping control methods, and serves to describe established status of system as well as dynamic one, considering dynamic parameters of system, and also the difference between current status and desired one (task). That's why, to simplify ESCS synthesis procedure, control object as well, as automatic control system itself are representing as port-controlled Hamiltonian system (PCHs) [4]:

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

where $J(x) = -J^T(x)$ is a skew-symmetric matrix which reflects the interconnection structure of the system, $R(x) = R^T(x) \geq 0$ is a symmetric positive semi-definite matrix which reflects the dissipation in the system, $G(x)$ is the port matrix, and $u(t)$ and $y(t)$ are vectors of input and output system energy variables.

Energy-shaping methods in themselves consist in supplying the system with the amount of energy we need, excluding dissipations, the energy needed to fulfill energy capacities, to form response by feedbacks and other properties of exact system.

According to [4], energy shaping control system (ESCS) synthesis procedure is reduced to the writing of the mathematical model of the object in the PCHs (1) form, the selection of the control system matrix and, thanks to the energy shaping principles, interconnection and damping assignment, to the solving of the following matrix equation:

$$\left[J(x)+J_a(x)-\left(R(x)+R_a(x)\right)\right]\frac{\partial\left(H_d-H\right)}{\partial x}= \\ =\left[J_a(x)-R_a(x)\right]\frac{\partial H}{\partial x}+G(x)\cdot b(x) \quad (2)$$

where $H_a(x)$ is the energy function of the control system, $J_a(x)$ and $R_a(x)$ are matrix of additionally injected factitious interconnections and factitious damping, provided by the control system.

By the method, given in [5], the ESCS for DCM, based on simplified model, has been got:

$$u=-r_{11}\left(i_{\mathrm{a}}-i_{\mathrm{a}}^{*}\right)-R_{\mathrm{a}}i_{\mathrm{a}}+C\Phi\omega_0, \quad (3)$$

where u_a^* – armature voltage, r_{11} – electrical damping coefficient, i_{a} – armature current, i_a^* – desired armature current, R_a – armature circuit resistance, $C\Phi$ – feedback EMF coefficient, ω_0 – desired working speed.

This “basic” ESCS is setup-simple and has large durability, but its regulative possibilities are current-based. Therefore, this control system was offered to be complemented with integrator [5].

To improve ESCS (3) in literature it is offered to use more detailed models, to connect some functional branches for static and dynamic properties correction, and make some more possible improvements [6, 7]. One of the newest ones is based on “mechanical” damping adding [8]. It complements (3) with the following question:

$$i_{\mathrm{a}}^{*}=i_{\mathrm{a}}^{*}-\left(\omega-\omega_0\right)r_{22}/C\Phi. \quad (4)$$

This kind of system allows influencing on both, current response form, as well as the one displaying speed.

III. Comparative research results

In order to analyze in detail ESCS, there have been conducted a set of comparative researches of ESCS with different regulators, SMR and CCS (PI regulators for both loops). There have been researched the response of systems in cases of rapid task and load changes, within small and larger borders, on small and prenominal speeds, also sensitivity to the changes of main parameters have been tested: increasing rotor resistance, weakening of magnetic flux, and decreasing of rotor inductivity. Static and dynamic characteristics of systems were researched too, as well as linearity of their dynamics.

According to the results, the following conclusions could be made:

1) All of the ESCSs, in order to provide complete static precision, require information about load or its estimator; they provide linearity of dynamics, are less sensitive to parameters than SMR, but more than CCS.

2) Basic ESCS (3) and the one with integrator have worse dynamic characteristics than other systems.

3) The integral part in basic ESCS with integrator allows to improve the static of the system, however it restricts the setup flexibility sufficiently (it also causes large overregulating) and also get rid of natural stability, typical for all of ESCSs.

4) The modified ESCS with mechanical (4) and electrical (3) damping has wide setup possibilities, which allows to adapt the system to specific properties of any technological process, also outmatches SMR and does not give up to CCS if to speak about static and dynamic characteristics.

5) The modified ESCS with only mechanical damping (with $r_{11}=0$) provides the same static and dynamic characteristics as well; becomes simpler, but less flexible in setting up.

Conclusion

The ESCSs of DCM with mechanical damping are simple in setting up, provide high static and dynamic characteristics, and asymptotic stability.

The new energy-shaping synthesis methods are still in development, but control systems on their basis have already matched classic systems. Considering all of these facts as well as possibilities of their further development and combining with classic methods, the usage of more detailed and complicated models of controlled objects it is rational to develop them in future.

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