Control Systems of Permanent Magnet Synchronous Machine as Port-Controlled Hamiltonian System

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Abstract – One of the most perspective methods of control system design for permanent magnet synchronous 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. The energy-shaping control systems with present regulation elements provide worse response compare with classical systems and are hard to be configured. The main aims of this article are quick view of current energy-shaping control systems, overcoming disadvantages of them and popularization of energy-based approaches in general.

Key words – permanent magnet synchronous machine, energy-based approach, vector control, energy-shaping control system, structural and parametric synthesis.

I. Introduction

One of the most perspective methods of control system design for permanent magnet synchronous motor as a part of electromechanical systems are physical control theory approaches, based fundamental physical laws. Exactly such are energy-based approaches, which are based on physical laws of energy transferring and conversion [1].

First of all, to simplify such energy-shaping control system (ESCS) synthesis procedure, control object and automatic control system could be represented as port-controlled Hamiltonian systems (PCHs) [2]:

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

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

Then, in general, synthesis ESCS will consists in decomposing the system into simpler subsystems interlinked in some way, and finding such additional interconnections and subsystems, and such intensity of their interactions (IDA) [3] that total energy of a closed loop system $H_d(\mathbf{x})$ would attain a minimum in the desired (defined by the asking signal) equilibrium point $\mathbf{x}_0$. The desired system will be asymptotically stable.

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

$$\begin{aligned}&[\mathbf{J}(\mathbf{x})+\mathbf{J}_a(\mathbf{x})-(\mathbf{R}(\mathbf{x})+\mathbf{R}_a(\mathbf{x}))]\frac{\partial(H_d-H)}{\partial \mathbf{x}}= \\ &=[\mathbf{J}_a(\mathbf{x})-\mathbf{R}_a(\mathbf{x})]\frac{\partial H}{\partial \mathbf{x}}+\mathbf{G}(\mathbf{x})\cdot\mathbf{b}(\mathbf{x})\end{aligned}, \qquad (2)$$

where $H_a(\mathbf{x})$ is the energy function of the control system, $\mathbf{J}_a(\mathbf{x})$ and $\mathbf{R}_a(\mathbf{x})$ are matrix of additionally injected factitious interconnections and factitious damping, provided by the control system

II. Energy-Shaping Control Systems

The literature offers a large number of ESCSs for PMSM based systems (Fig.1), with different mapping of control system matrix $\mathbf{J}_a(\mathbf{x})$ and $\mathbf{R}_a(\mathbf{x})$, and also combinations of different energy-based approaches of between themselves and with the known classical approaches.

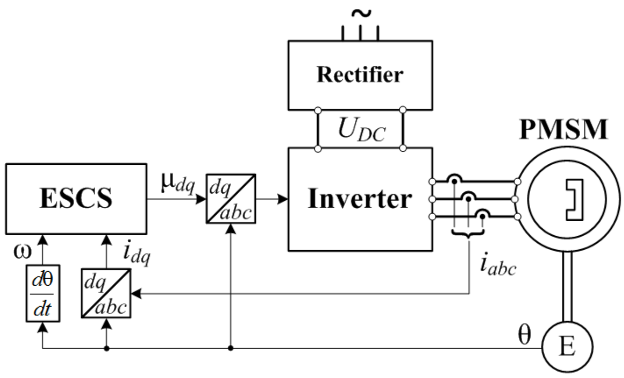

Fig. 1. General function scheme of PMSM control

The most common are ESCSs with different structures of $\mathbf{J}_a(\mathbf{x})$ and $\mathbf{R}_a(\mathbf{x})$, which use electrical damping. Such control systems have next drawbacks: the regulation is not carried out by the main control magnitude (velocity); nonlinearity of controlled object make setting up more difficult; there is no algorithm for configuring such control systems; also in the formation of a control system desired equilibrium point existing selections of controlled matrix involved elements that are completely independent of signal errors, which leads to errors in determination of this point and delaying the transition process.

One of the simplest energy-based control systems is ESCS only with passivation [5]. This system was deprived of the possibility to take into account windings losses in the formation of the desired equilibrium point and any additional regulatory possibilities.

Other decision was combination of classic and passivation regulators [6]. However, this system was losing the main advantage of energy-based management approaches - namely physical interpretation. Setting up of such systems was reduced to selection of classic parameters of applied regulators.

One of the most successful areas of energy-based control was energy balancing forming. Initially it was developed for Lagrangian systems and then applied to the Hamiltonian [6]. This ESCS was directed to compensate nonlinearities in controlled object, ensuring asymptotic stability of the closed-loop system and including the possibility of combining ESCS with classic controls similar to previous one. Despite the large number of control system parameters, which significantly complicates the procedure for setting up, the shortcomings of such system include the providing of errors in the desired equilibrium point formation and the sensitivity to parametric changes.

Besides there was attempt to synthesize digital passive control system by forming interconnections and desired damping. For use in digital systems, ESCS was improved by addition of corrective elements [7]. Adjustment of desired power function here is carried out to neutralize errors associated with the operation of a digital system. The large number of complex corrective elements in the system complicates the procedure of multiparameter setting up, and also don't suggests asymptotic stability of the system, which is inherently providing by all ESCS. Another drawback of this control system is that it does not provide an optimal formation of the desired equilibrium point.

One of the most successful was combination of ESCS with perturbations damping principle of L2-gain [8]. The resulting system provide significant forcing of transients and reduce static error in the absence of moment information. The main disadvantage of this system is that the main regulating parameter is in the mechanical and electrical processes control loops at once. On one hand, it makes impossible separate regulation of transient mechanical and electrical parts of the axis d and the axis q, on the other hand - impose restrictions on the use of this parameter adjustment. Another disadvantage of using such damping system is a high sensitivity to a change in control signal error. Reaction to this change leads control system to restrictions zone and as a result, the system becomes uncontrollable. It should also be noted that the introduction of such damping does not apply to energy approaches.

According to known systems drawbacks (low efficiency in control, complexity of understanding and configuration), the most simple and affective are ESCSs with interconnections and damping forming.

III. ESCS with Mechanical Damping

Existing ESCSs not always provide appropriate quality of response and have no clear algorithm of setting up. Therefore, it was proposed to use mechanical damping, provided by control system through electrical part. This mechanical damping would correct process of desired velocity forming to improve static and dynamic characteristic of the system [9]. We also suggest to carry out parametric synthesis of ESCS by finding parameters of its regulators through forming transfer function of desired the closed-loop port-control Hamiltonian system. There are some obstacles in providing such method connected to differential elements appearance in control loop, but they could simply be neutralized [9].

Such ESCSs are easy in configuration (there parametric synthesis), they provide acceleration of transition process, linearity of the dynamics of the whole system, possibility of regulators forming depending on the task.

Conclusion

ESCS with existing regulatory elements are complex to set up and provide worse quality of the transition process in comparison with classical control systems, and therefore their use is ineffective.

The proposed ESCS with electric and mechanical damping makes it possible to carry out effective regulation of electromechanical system based on PMSM and can be easily synthesized by a procedure of structural and parametric synthesis.

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