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Correction of rotor rotation irregularity of permanent magnet synchronous motor in a controlled synchronous mode

Voronin S.G., Kurnosov D.A., Korobatov D.V.*, Kulmukhametova A.S.

South Ural State University, 76, Lenin Avenue, Chelyabinsk, 454080, Russian Federation

Abstract

While the permanent magnet synchronous motor (PMSM) operation in the synchronous mode rotor speed average value coincides with current frequency in the windings by definition. However instantaneous value of rotation speed can differ from the average one significantly in the process of oscillations occurring in the PMSM rotor and stator electromechanical system. This article describes a refined mathematical model of permanent magnet synchronous motor (PMSM) operating in the synchronous rotation mode allowing to explore rotor speed oscillations arising in the synchronous mode. On the basis of the mathematical model the article provides a theoretical foundation and the example of specific implementation of one of the oscillation damping ways of the PMSM rotor with permanent-magnet excitation in the synchronous mode by introducing a current feedback to the impact on the stator phase voltage. The transfer function of the compensating device, affecting the voltage phase on the motor windings and providing a significant reduction of PMSM rotor rotation irregularity is synthesized on the basis of matrix transfer function of interrelationship between output variables and input signals.

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Keywords: permanent magnet synchronous motor, oscillations damping, synchronous operating mode of PMSM ;

1. Task description

It is comparatively simple to implement the vector control system with the help of permanent-field synchronous motors if it has a rotor angular position sensor with fine resolution. If however such sensor is absent due to structural and space limitations, then only indirect rotational positional sensing on signals of current and voltage sensors is

* D.A. Kurnosov. Tel.: +7-912-479-5600
E-mail address: kurnosovda@susu.ac.ru

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possible. The complex algorithms involving lots of computing resources are used for it [1, 2]. Meanwhile in some cases when a resistive torque on a motor shaft is changing insignificantly, it is possible to implement a simplified form of vector control – so called controlled synchronous operating mode [3]. While implementation such mode three-phase sinusoidal voltage is energized on a motor stator winding as in a classical synchronous motor. It provides a steady vector rotation of stator field. In order to leave the rotor motor in the synchronous mode, signals from rotor position discrete sensor (RPS) are used, for instance, based on Hall sensors installed in the motor air gap. The coarse control of rotor angular position to stator is carried out according to the signals from discrete RPS. If this angular deviation reaches some critical value, motor source voltage is changed in the way that to bring this deviation to required value [4]. In a steady mode when there are no grand disturbances, motor rotor is rotating at a speed of stator field rotation. However as it is known, the rotor of a synchronous motor is apt to oscillations for which reason in many cases a damping winding is installed on it in order to remove these oscillations. In motors with permanent-magnet excitation such winding significantly complicates the rotor configuration and not always solves oscillability problem as well as degrades general dynamic properties of the motor. This article provides a theoretical foundation and the example of specific implementation of one of the oscillation damping ways of the PMSM rotor in the synchronous mode by introducing a current feedback to the impact on the stator phase voltage.

2. Refinement of synchronous motor mathematical model in a small oscillation mode

We get a block scheme of PMSM in the synchronous rotation mode from a simplified mathematical motor model presented in [5,6] taking a commutating angle as variable (θ=var) in it. Then a block scheme gets a view of Fig. 1.

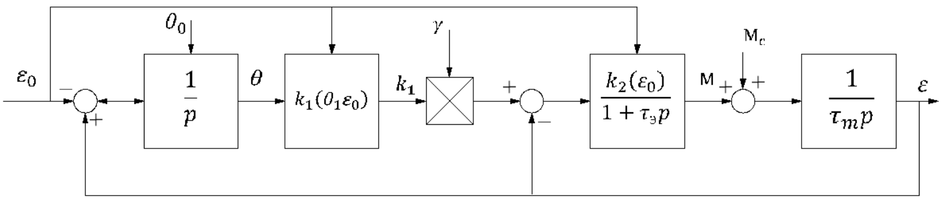

Fig. 1. Block scheme of PMSM in the synchronous rotation mode.

Fig. 1 shows: ε_0 is preselected synchronized relative rotor speed, where ideal unload speed (ω_0) as θ=0 is taken as basis speed value; p is operator of differentiation; $\tau_e = \omega_0 L/R$ is relative electromagnetic constant of phase winding; L,R is respectively total inductance and active resistance of phase winding; τm is relative value of electromechanical time constant equal to product of absolute constant (Tm) and idle speed; coefficients $k_1(\theta,\varepsilon_0)$ and $k_2(\varepsilon_0)$ are determined from equations 1, 2:

$$k_1(\theta,\varepsilon_0) = \cos\theta + \varepsilon_0\tau_e\sin\theta\,, \tag{1}$$

$$k_2(\varepsilon_0) = 1/[1+(\varepsilon_0\tau_e)^2]. \tag{2}$$

As it is seen from the block scheme, the PMSM model is non-linear both towards to input signals and to output variables. This circumstance significantly complicates the analysis of dynamic and static modes of PMSM. Let us conduct linearization of mathematical model. We should implement a standard method of linearization with Taylor expansion of non-linear functions in the vicinity of reference trajectory and truncation till linear terms [7]. As a result of quite cumbersome transformations we get a linearized block scheme of PMSM as Fig. 2.

Compared to the scheme on Fig. 1 the regulation possibility of phase to neutral voltage by actuating signal γ is taken into consideration in this block scheme. Besides, it is denoted:

$$k_3(\bar\theta,\bar\gamma,\bar\varepsilon_0) = \bar\gamma(\bar\varepsilon_0\tau_e\cos\bar\theta - \sin\bar\theta), \tag{3}$$

$$k_4(\bar{\varepsilon},\bar{\theta},\bar{\gamma},\bar{\varepsilon}_0)=\frac{\tau_e[\bar{\gamma}\sin\bar{\theta}-\bar{\gamma}\bar{\varepsilon}_0\tau_e(2\cos\bar{\theta}+\bar{\varepsilon}_0\tau_e\sin\bar{\theta})+2\bar{\varepsilon}_0\bar{\varepsilon}\tau_e]}{[1+(\bar{\varepsilon}_0\tau_e)^2]},$$

$$\bar{\theta}=\bar{\vartheta}+\bar{\theta}_0.$$

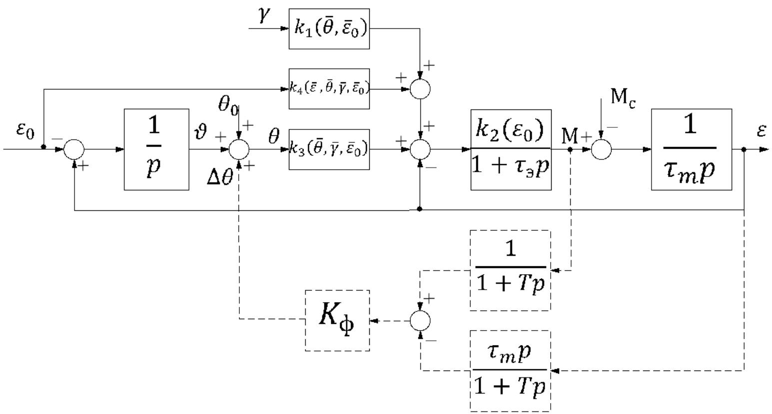

Fig. 2. Linearized block scheme of PMSM in the synchronous rotation mode.

The reference coordinate values are marked by dashes on top relative to which linearization is being implemented.

Linearized model presented in state space can be written over as (equations are written in deviations relative to system reference trajectory):

$$\dot{x}=Ax+Bu,$$
$$y=Cx+Du.$$

Here in addition to state vectors $x=(\mu,\varepsilon,\vartheta)^T$ and input signals $u=(\gamma,\theta_0,\varepsilon_0,\mu_c)^T$vector of output variables is introduced$y=(\mu,\varepsilon,\theta)^T$. For matrixes A, B, C and D it is correctly

$$A=\begin{bmatrix}\frac{-1}{\tau_e} & \frac{-1}{\tau_e[1+(\bar{\varepsilon}_0\tau_e)^2]} & \frac{\bar{\gamma}[\bar{\varepsilon}_0\tau_e\cos\bar{\theta}-\sin\bar{\theta}]}{\tau_e[1+(\bar{\varepsilon}_0\tau_e)^2]}\\ \frac{1}{\tau_m} & 0 & 0\\ 0 & 1 & 0\end{bmatrix},$$

$$B=\begin{bmatrix}\frac{\cos\bar{\theta}+\bar{\varepsilon}_0\tau_e\sin\bar{\theta}}{\tau_e[1+(\bar{\varepsilon}_0\tau_e)^2]} & \frac{\bar{\gamma}[\bar{\varepsilon}_0\tau_e\cos\bar{\theta}-\sin\bar{\theta}]}{\tau_e[1+(\bar{\varepsilon}_0\tau_e)^2]} & \frac{\bar{\gamma}\sin\bar{\theta}-\bar{\gamma}\bar{\varepsilon}_0\tau_e[2\cos\bar{\theta}+\bar{\varepsilon}_0\tau_e\sin\bar{\theta}]+2\bar{\varepsilon}_0\tau_e\bar{\varepsilon}}{[1+(\bar{\varepsilon}_0\tau_e)^2]^2} & 0\\ 0 & 0 & 0 & -\frac{1}{\tau_m}\\ 0 & 0 & -1 & 0\end{bmatrix},$$

$$C=\begin{bmatrix}1&0&0\\0&1&0\\0&0&1\end{bmatrix},$$

$$D=\begin{bmatrix}0&0&0&0\\0&0&0&0\\0&1&0&0\end{bmatrix}.$$

The state vector and output vector views will be as follows

$$x(p) = (pE - A)^{-1}Bu(p),$$

$$y(p) = [C(pE - A)^{-1}B + D]u(p).$$

The association matrix between output variables and input signals under zero initial conditions is called a matrix transfer function and designated as

$$W(p) = C(pE - A)^{-1}B + D. \tag{4}$$

It is represented by a matrix with the following components:

$$W(p) = \begin{bmatrix} W_{11}(p) & W_{12}(p) & W_{13}(p) & W_{14}(p) \\ W_{21}(p) & W_{22}(p) & W_{23}(p) & W_{24}(p) \\ W_{31}(p) & W_{32}(p) & W_{33}(p) & W_{34}(p) \end{bmatrix}, \tag{5}$$

where $W_{ij}(p) = y_i(p)/u_j(p)$ is scalar transfer functions, tying two coordinates. For instance, $W_{11}(p)$ ties an electromagnetic motor torque μ with actuating signal $\theta_0$and it is as follows

$$W_{12}(p) = \frac{\mu(p)}{\theta_0(p)} = \frac{\tau_m p^2 \bar{\gamma}(\sin\bar{\theta} - \bar{\varepsilon}_0 \tau_e \cos\bar{\theta})}{[1 + (\bar{\varepsilon}_0 \tau_e)^2](\tau_e \tau_m p^3 + \tau_m p^2) + p + \bar{\gamma}(\sin\bar{\theta} - \bar{\varepsilon}_0 \tau_e \cos\bar{\theta})}.$$

Other transfer functions will differ only in numerator, tying other coordinates.

The matrix transfer function (5) can be used both for analytic survey of dynamic processes and for compensating devices synthesis. Its analysis allows to express different strategies of valve electric drive control for all its operating modes. Let us deal with one of it.

3. The practical implementation of corrective action in the electric motor drive

Let us study a synchronous operating mode of PMSM. For improving accuracy of speed control while load fluctuations we introduce into control law a component, depending on the electromagnetic torque variation. Such additional feedback in relation to supported speed rate and amount of load should correct either amplitude (γ) or phase (θ_0) of PMSM source voltage. Let us implement the latest correction variant. Technically such implementation is quite simple. Information about load torque value of the motor can be obtained with the help of reduced observer [8] in accordance with equitation

$$\hat{\mu}_c(p) = W_\varepsilon(p)\varepsilon(p) + W_\mu(p)\mu(p),$$

where $W_\varepsilon(p), W_\mu(p)$ is corrective transfer functions by corresponding variables. The latest can be chosen in the following view

$$W_\varepsilon(p) = \frac{-\tau_m p}{1 + Tp}, \qquad W_\mu(p) = \frac{1}{1 + Tp}.$$

Here time constant T is entitled to setting.

Based on this information the compensating device generates the actuating signal in the form of phase shift of basic impulses, stating the frequency of motor source voltage. Then, phase of motor source voltage by signals of the compensating device can be shifted inertialess back and forth, changing the angle current value θ. On the block scheme (Fig. 2) a functional implementation of the compensating device is shown by dotted lines. At the same time a phase-shifting device is accepted as inertialess with the transfer factor Kф. It is obvious that changing the view and parameters values W(p) we can effect dynamic properties of the electric motor drive.

Below on Fig. 3 the results of valve electric drive operation modelling in the synchronous mode with the additional correction are presented. Modelling was conducted with following initial data: $\gamma = 1$, $\varepsilon_0 = 0.5$, $\tau_e = 0.1$, $\tau_m = 5$, $T = 0.01$. At the time t=80 load torque rise was carried out ($\Delta\mu_c = +0.4$), and at the time t=110 loss of load torque was performed ($\Delta\mu_c = -0.4$). On Fig. 3 the diagrams of speed $\varepsilon(t)$, of load torque $\mu_c(t)$ and of commutating angle variations $\theta_0(t)$ are presented.

For illustrative purposes on one fig. 3 two speed performance curves are given: the one – without introduction of the additional correction (without feedback), the other – with introduction into control loop of PMSM the corrective feedback up to moment variation (with feedback). The introduction of this feedback while altering the load torque to 0.4 ea. causes commutating angle alternation approximately to 0.6 ea. The diagrams demonstrate a high efficiency of such additional corrective feedback, velocity error is reduced from 33% to 1.7%, i.e approximately in twenty times.

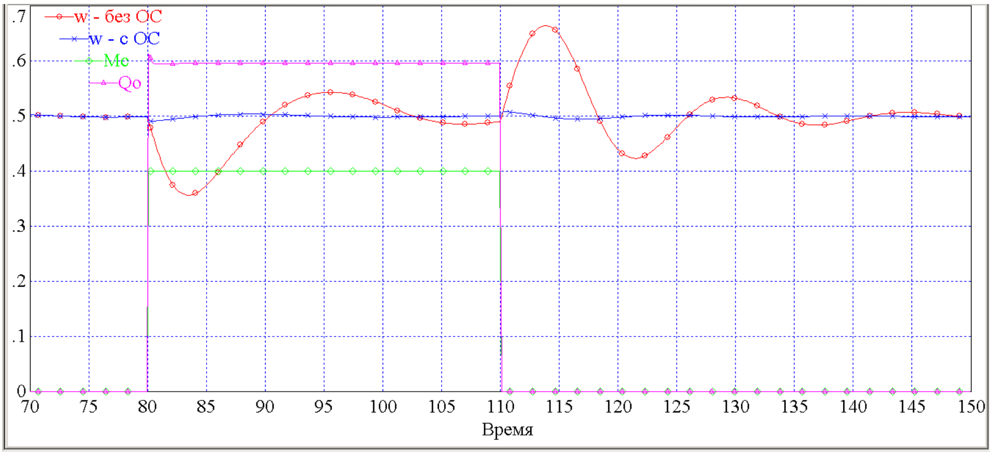

Fig. 3. The results of permanent-magnet synchronous motor operation modelling in a synchronous mode.

As a result of optimal adjustment of such feedback, which can be carried out by involvement of corresponding matrix components (5), it is possible to achieve a practical invariance of valve electric drive to load torque variations.

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References

[1] C. Busca, Open loop low speed control for PMSM in high dynamic application, Denmark, Aalborg university, 2010.
[2] S.G. Voronin, D.A. Kurnosov, A.S. Kul'mukhametova, Vector control of permanent-magnet synchronous motors, Russian Electrical Engineering 84, Issue 10 , pp 581–585.
[3] D.V. Korobatov, A.S. Kulmukhametova, A.A.Shevchenko, Controlled synchronous mode in a ventilator, Electrical equipment and systems: collection of scientific papers. 20 (2012) 79–82.
[4] A.S. Kulmuhametova, D.V. Korobatov, Implementation of vector control and synchronous mode SMPM, Proceedings of the International Scientific and Technical Conference in 3 tons "State and Prospects of Electrotechnology". 3 (2013) 111–113.
[5] S.G. Voronin, D.V. Korobatov, R.T. Kiyakpaev, A.S. Kulmuhametova, Dynamic models of the electric motors at different combinations of parameters, Proceedings of the Academy of Electrical Sciences. 2011 58–63.

[6] S.G. Voronin, D.A. Kurnosov, P.O. Shaburov, A.S. Kulmuhametova, Mathematical model of dynamic processes in the electric drive of valves, “Electrical Equipment and Systems ": collection of scientific papers. 20 (2012) 132–140.
[7] N.D. Yegupova, Methods of classical and modern control theory: Analysis and statistical dynamics of automatic control systems, Moscow, 2000.
[8] S.G. Voronin, D.A. Kurnosov, D.V. Korobatov, P.O. Shaburov, A.S. Kul’mukhametova, Electromagnetic and Resistance Torque on a Synchronous Motor Shaft with Permanent Magnet Excitation, Russian Electrical Engineering. 83(2) 61–63.