Speed regulation in vector control systems of synchronous motor drive

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Abstract. This article examines speed control systems in AC electric motors based on a permanent magnet synchronous motor. Special focus will be on the methods of parametric synthesis of controllers for controlling the speed of a synchronous motor with permanent magnets by deviation. The developed automatic engine control system should provide fixation, processing, robustness to signal, and parametric disturbances. The article also presents the results of digital modelling of a vector control system for a permanent-magnet synchronous motor and comparative analysis of these methods for synthesizing an engine control system based on the results.

1. Introduction
Conducted researches [1] show that a permanent magnet synchronous motor has an efficiency factor that is on average 2% higher than a highly efficient asynchronous motor on conditions that the stator has the same design and the same frequency converter controls the motors. Also, a permanent magnet synchronous motor (PMSM), in comparison with other motors, has the best performance in terms of power / volume, moment / inertia. In the scientific literature on the topic [2], [3], [4], two fundamentally different principles for controlling an AC electric motor, in particular, PMSM, are discussed.

The first of these principles is called frequency regulation. Its key feature is the maintenance of the U/f ratio, a certain constant value, depending on the parameters of the machine. This method is simple, but it only allows provides low requirements for dynamics. If the requirements for the automatic control systems are high speed, high control accuracy, and low overshoot, then it is preferred to use vector engine control. The electric machine model, following the principle of vector control, is represented by a system of bounded vectors of the main controlled variables, not only the values of these vectors but also their directions are taken into account.

The synthesis task is simplified by the introduction of auxiliary coordinate systems. In such systems, the directions of the vectors of electric and electromagnetic quantities in each phase are decomposed into components in such a way as to simplify the control system of this electric machine as much as possible.

2. Mathematical description of the control object
Permanent magnet synchronous machines have a substantial air gap and a low saturation level. Therefore, when considering the mathematical description of a PMSM, mathematical models are often used without considering the nonlinearity of the magnetic circuit. In addition to this, there are many assumptions necessary for applying the principle of superposition, which is used for describing magnetic and electromagnetic fields from different sources.
2.1. The mathematical description of the PMSM in a fixed coordinate system

The mathematical description of the PMSM in a two-phase fixed coordinate system (α-β) is based on the Edith Clarke transformation, the equation of electromagnetic moment and the basic equation of motion of the electric drive. It is presented in the system of equations (1):

\[
\begin{align*}
    u_{\alpha} &= R_{\alpha}i_{\alpha} + L_{c} \frac{di_{\alpha}}{dt} - \omega_{r}\Psi_{2,\beta} \\
    u_{\beta} &= R_{\beta}i_{\beta} + L_{c} \frac{di_{\beta}}{dt} + \omega_{r}\Psi_{2,\alpha} \\
    M_{e} &= \frac{3}{2} Z_p \psi_{r}\Psi_{1,\beta} - \psi_{1,\alpha}i_{\alpha} \\
    \frac{d\omega_{r}}{dt} &= \frac{1}{J} M_{e} - M_{r}
\end{align*}
\]  

(1)

\( u_{\alpha}, \ u_{\beta}, \ i_{\alpha}, \ i_{\beta} \) - PMSM stator voltage and current in the α and β axes; \( R_{\alpha}, \ L_{c} \) - active resistance and inductance of the stator winding; \( \Psi_{1} \) - flux linkage.

As known from the theory of electrical machines, the \( L_{c} \) value present in the system of equations (1) in a fixed coordinate system (α-β) is periodically changing. It depends on the design characteristics of the stator. Under such conditions, it is advisable to switch to a rotating coordinate system (d-q), since this inductance can be decomposed into the direct-axis and quadrature-axis components, which are constants.

2.2. The mathematical description of the PMSM in a field-oriented coordinate system

In order to make the transition to the mathematical description of the PMSM in a moving field-oriented coordinate system (d-q), in addition to the Edith Clarke transformation, it is necessary to perform the Park transformation, modify the equation of electromagnetic moment in accordance with the new coordinate system, the basic equation of motion of the electric drive remains unchanged. The mathematical description of the PMSM in the moving coordinate system (d-q) is represented by the system of equations (2):

\[
\begin{align*}
    u_{d} &= R_{d}i_{d} + L_{d}i_{d} + \Psi_{2, p} - \omega_{r}Z_{p}L_{q}i_{q} \\
    u_{q} &= R_{q}i_{q} + L_{q}i_{q}p + \omega_{r}Z_{p}L_{q}i_{d} + \Psi_{2} \\
    M_{e} &= \frac{3}{2} Z_p \psi_{r}\Psi_{1,\beta} - \psi_{1,\alpha}i_{\alpha} \\
    \frac{d\omega_{r}}{dt} &= \frac{1}{J} M_{e} - M_{r}
\end{align*}
\]  

(2)

Speed transient response does not meet the requirements for quality rating; therefore, it is necessary to synthesize a PMSM automatic control system to obtain the desired dynamics.

3. Synthesis of PMSM automatic control system

3.1. Synthesis of current and speed regulators by the classical technique of subordinate control

This method of constructing multi-circuit automatic control systems has a wide implication. It is repeatedly described in the literature [5, 6]. There are no signicant differences between methodology for the synthesis of regulators for PMSM from other types of electric motors.

The transfer function of the current and speed controllers is derived using standard settings for modular and symmetric optimums.

Figure 1 shows the block diagram of the PMSM automatic control systems. Figure 2 shows the transients responses of the currents on the axes (d-q) and speed when starting at idle, followed by a surge and shedding of the load.
The possibility of deriving the transfer functions of the regulators by other methods is studied to improve the quality of transients response.

3.2. Synthesis of current regulators for automatic control systems of a PMSM by localization method

The idea of the localization method is to compensate for the perturbing effect with a large coefficient. It needs to localize it using the velocity vector, “deep” feedback control loops and separation of the motion of control processes [7]. For the parametric synthesis of current controllers by the localization method, the block diagram of the current control loop, shown in Figure 3, is used.

The setpoint value (Fig. 3) is formed using the equation of the desired motions. For convenience, the transfer function of the differentiating filter is presented in this form.
\[ D_f \ p = T_f p + 1 \]

Next, the current closed-loop transfer function is written down.

\[ W_{oc} p = \frac{\left( k_p + k_i p \right) k_{FC} \frac{1}{R_i} T_p + 1}{1 + \left( k_p + k_i p \right) k_{FC} \frac{1}{R_i} T_p + 1} \]

After mathematical transformations, the characteristic polynomial of PMSM can be expressed, which is written in the following form:

\[ D_{cc} p = \frac{T_q T_f R_i}{k_i K_{FC}} p^3 + \frac{T_q + T_f R_i}{k_i K_{FC}} p^2 + \frac{k_i K_{FC} + R_i}{k_i K_{FC}} p + 1 \]

Based on the modal synthesis method, the characteristic polynomial, reduced to the standard form, can be equated to the normalized polynomial [8]. By setting its coefficients and the time constant of the differentiating filter, it is possible to unambiguously determine the proportional and integral coefficients of the automatic control systems PMSM current regulator.

\[
\begin{align*}
    k_i &= \frac{T_q + T_f}{T_q T_f K_{FC} A_{zn}} R_i \\
    k_p &= \frac{T_{cc} A_{zn} k_i K_{FC} - R_i}{K_{FC}}
\end{align*}
\]

\( A_{zn} \) – coefficients of the normalized polynomial characterizing the desired form of the transients response, and \( T_{cc} \) – coefficient of the normalized polynomial characterizing the desired performance.

3.3. Synthesis of automatic control systems PMSM speed controllers by localization method

When considering the speed controller of the synchronous electric drive, a similar technique of structural and parametric synthesis is used. Figure 4 shows the block diagram of the speed control loop.

![Figure 4. Block diagram of the speed control loop for automatic control systems of a PMSM](image_url)

The same assumptions apply for the synthesis of the speed control loop as for the synthesis of the current control loop. However, the time constant of the differentiating filter in the speed control loop must significantly exceed the same time constant in the current control loop in order to be able to present a closed current loop as an inertialess link based on the idea of dividing movements into “fast” and “slow”.

The closed-loop speed transfer function can be expressed as

\[ W_{cs} p = \frac{\left( k_p + k_i p \right) K_{T_{pp}} \frac{3}{2} Z_p \Psi_z \frac{1}{J_p}}{1 + \left( k_p + k_i p \right) K_{T_{pp}} \frac{3}{2} Z_p \Psi_z \frac{1}{J_p} T_{f p} + 1} \]

The characteristic polynomial of closed-loop speed control is expressed in the following form:
Equating the obtained characteristic polynomial to a standard normalized third-degree polynomial, the desired coefficients of the PI controller are determined:

\[
D(s) = \frac{2JT_i K_{i, ph}}{3k Z_p \psi_2} s^3 + \frac{2J + T_J}{3k Z_p \psi_2} s^2 + \frac{k_p}{k_i} + 1
\]

\[
k_i = \frac{2J + T_J}{3J^2 T_J^2 Z_p \psi_2 A_{1n}^2}
\]

\[
k_p = T_{cc} A_{2n} k_i
\]

$A_{1n}, A_{2n}$ – coefficients of the normalized polynomial characterizing the desired transient response shape; they may be equal or not equal to the coefficients of the characteristic polynomial from the previous paragraph. $T_{cc}$ – the coefficient of the normalized polynomial characterizing the desired speed that should differ from the same coefficient to observe the separation of the rates of movement.

3.4. Investigation of parametric disturbance
Let us consider the ability of the synthesized automatic control systems to compensate for a parametric disturbance. By parametric disturbance is meant the ability of a parameter in a mathematical description to vary in a certain range of values. In this paper, the stator resistance changing in the system of equations (2) is considered, due to heating of the windings as the result of the flow of active current. 40% increase in stator resistance is considered for classical automatic control systems and automatic control systems synthesized by the localization method. The effect of changes in active resistance is shown in Figure 5.

Figure 5 shows a fragment of the current transients at the end of the dynamic model as the most significant. The dashed line for both automatic control systems indicates a transient with increased active resistance.

As can be seen from Figure 5, an increase in the stator resistance drags the end of the dynamic mode, which worsens the performance of both automatic control systems. However, for automatic control systems synthesized by the localization method, the negative effect is noticeably less. At other time intervals, the effect of an increase in stator resistance is negligible for both automatic control systems.

4. Comparative analysis
The initial testing of the synthesized algorithms of a multi-loop vector control system of the synchronous electric drive allows evaluating the correctness of its operation and the correctness of structural, parametric synthesis. Figure 6 shows the transients response on the currents in the axes (d-q) and the speed of the automatic control systems of a PMSM.
5. Conclusion
A comparative analysis of the methods for the root distribution of the vector control systems of the synchronous electric drive, synthesized by the classical method for a system of a subordinate control and the localization method, is carried out. The PMSM vector control system, built on the principle of the localization method, has less overshoot, higher speed, less oscillation, therefore, the values of the quality rating of the transient response of the PMSM correspond to the requirements in comparison with the classical system of a subordinate control. Calculation of regulators by the localization method can be performed as an alternative to the classical method of calculating regulators using the standard settings method.

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