Speed and Rotor Position Identification of Permanent Magnet Synchronous Motor Based on ADRC

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Abstract. Aiming at the accurate estimation of rotor speed and position of surface-mounted permanent synchronous motor, a scheme using extended state observer in the two-phase static frame is constructed. The conventional method estimating the rotor speed and position in two-phase synchronized rotation reference frame has the problem of error accumulation of the estimated rotor position which was calculated by angular velocity estimated value integral. This method avoids those problems and has advantages. The speed and current closed loop control system is constructed by using the auto disturbance rejection controller to replace the PI regulator. The simulation results validate the accuracy of the rotor speed and position is higher, and the system is stable and has good disturbance rejection performance.

1. Introduction

In the high-performance control algorithm of permanent magnet synchronous motor, it is generally necessary to detect the position and speed of rotor in real time. The traditional mechanical or photoelectric sensor not only increases the cost, but also increases the probability of fault occurrence and reduces the reliability of system operation. Therefore, speed sensorless control, which does not rely on sensors but can estimate the rotor position and speed online by detecting the current, voltage and other physical parameters of the motor, has become a research hotspot.

The active disturbance rejection control (ADRC) is a new control technology [1-3]. The extended state observer of ADRC system can observe the unknown variables which are difficult to measure in the control system, and it can suppress the internal and external disturbances through the compensation of the control variables to achieve a good control effect [4-6]. In this paper, the auto disturbance rejection control technology is applied to the rotor displacement angle estimation and speed control. It is proposed that the extended state observer in two-phase static coordinate system is better than that in two-phase rotating coordinate system, and the modeling and simulation are carried out in Simulink environment.

2. Mathematical model of ADRC

For systems with unknown functions:

\[ x^{(2)} = f_0(x, x^{(1)}, t) + f_1(x, x^{(1)}, w(t)) + bu \]  (1)

Where \( x, x^{(1)}, x^{(2)} \) are the variables of the system and their first and second derivatives. \( f_0, f_1 \) are known and unknown functions, \( w(t) \) are unknown disturbances, \( u \) are input variables, \( b \) is known constant. The ADRC control system shown in Figure 1 can be constructed [1-2].
Fig. 1 Structure of ADRC

Tracking differentiator (TD) is used to get the fast tracking signal and its derivative of given signal. Nonlinear states error feedback (NLSEF) is used to calculate the control amount before compensation according to the difference between the given tracking signal and the feedback signal. Extended state observer (ESO) is used to observe the related variables and unknown variables in the system, and to give the compensation value of the control variables, which is used to suppress the internal and external disturbances of the system.

The expression of ESO is as follows\(^{[1-2]}\):

\[
\dot{z} = -y + \beta_0 \cdot \text{fal}(\varepsilon, \alpha, \delta) + bu(t)
\]

The expression of \(\text{fal}(\varepsilon, \alpha, \delta)^{[1-2]}\):

\[
\begin{cases}
|\varepsilon| > \delta \\
|\varepsilon| \leq \delta
\end{cases}
\]

TD\(^{[1-2]}\):

\[
\begin{align*}
\varepsilon_0 &= v - v_1 \\
\frac{dv_1}{dt} &= -\beta_0 \cdot \text{fal}(\varepsilon_0, \alpha_0, \delta)
\end{align*}
\]

NLSEF\(^{[1-2]}\):

\[
\begin{align*}
\varepsilon_{01} &= v_1 - z_1, \varepsilon_{02} &= v_2 - z_2 \\
u_0 &= K_0 \cdot \text{fal}(\varepsilon_{01}, \alpha_{01}, \delta) + K_0 \cdot \text{fal}(\varepsilon_{02}, \alpha_{02}, \delta)
\end{align*}
\]

Total control quantity after disturbance compensation\(^{[1-2]}\):

\[u = u_0 - z_2 / b_0\]

3. Identification of rotor displacement angle and rotation speed in two-phase static coordinate system

The voltage equation of SMSM in two-phase stationary coordinate system is\(^{[7]}\):

\[
\begin{align*}
\frac{di_\alpha}{dt} &= -\frac{R_i}{L} i_\alpha + \frac{u_\alpha}{L} - \frac{e_\alpha}{L} \\
\frac{di_\beta}{dt} &= -\frac{R_i}{L} i_\beta + \frac{u_\beta}{L} - \frac{e_\beta}{L}
\end{align*}
\]

The expression of the back EMF is as follows\(^{[7]}\):

\[
\begin{align*}
e_\alpha &= -\psi_f \omega \sin \theta \\
e_\beta &= \psi_f \omega \cos \theta
\end{align*}
\]
Where \( \omega \) is the electrical angular velocity of the rotor, \( \psi_f \) is the rotor flux, and \( \theta \) is the rotor displacement angle. As long as the back EMF \( e_\alpha \) and \( e_\beta \) is observed, the estimated values of rotor displacement angle and rotor electric angular velocity can be calculated as follows:

\[
\begin{align*}
\dot{\theta} &= -\arctan(\frac{e_\alpha}{e_\beta}) \\
\dot{\omega} &= \frac{\sqrt{(e_\alpha')^2 + (e_\beta')^2}}{\psi_f}
\end{align*}
\]

According to formula (2), an extended state observer of back EMF can be constructed as follows:

\[
\begin{align*}
\epsilon_\alpha &= i_\alpha - \hat{i}_\alpha \\
\frac{di_\alpha}{dt} &= -\frac{R}{L} i_\alpha + u_\alpha + Q_\alpha - \beta_{\alpha1} f_{\alpha}(\alpha_{11}, \delta) \\
\frac{dQ_\alpha}{dt} &= -\beta_{\alpha2} f_{\alpha}(\alpha_{12}, \delta)
\end{align*}
\]

\[
\begin{align*}
\epsilon_\beta &= i_\beta - \hat{i}_\beta \\
\frac{di_\beta}{dt} &= -\frac{R}{L} i_\beta + u_\beta + Q_\beta - \beta_{\beta1} f_{\beta}(\beta_{21}, \delta) \\
\frac{dQ_\beta}{dt} &= -\beta_{\beta2} f_{\beta}(\beta_{22}, \delta)
\end{align*}
\]

Control quantity after compensation:

\[
\begin{align*}
u_\alpha &= u_{\alpha0} - LQ_\alpha \\
u_\beta &= u_{\beta0} - LQ_\beta
\end{align*}
\]

Observation value of back EMF:

\[
\begin{align*}
\dot{e}_\alpha &= -LQ_\alpha \\
\dot{e}_\beta &= -LQ_\beta
\end{align*}
\]

According to formula (8), the estimated value \( \omega^* \) of rotor electric angular velocity and rotor displacement angle \( \theta^* \) can be calculated.

4. Construction of PMSM double closed loop control system based on auto disturbance rejection technology

In order to achieve good dynamic and static performance of PMSM control system, a double closed-loop control system of speed and current should be built. Since ADRC has better anti-interference performance than PI control, ADRC is used to replace PI control in this paper.

4.1. Construction of speed loop

TD is used to filter the given speed signal \( \omega^* \), and the target signal \( \alpha_t \) and its derivative \( \alpha_t^* \) are obtained. The equation is as follows:
\[
\begin{align*}
    &e_0 = \omega^* - \omega_1 \\
    &\frac{d\omega_1}{dt} = -\beta_0 \cdot f_{al}(e_0, \alpha_0, \delta)
\end{align*}
\] (14)

Motion equation of motor rotor:
\[
\frac{d\omega}{dt} = \frac{P_n}{J} (T_e - T_L) - \frac{B}{J} \omega
\] (15)

The resulting speed loop ESO is:
\[
\begin{align*}
    e_1 &= \omega_1 - \omega_0 \\
    \frac{d\omega_1}{dt} &= -\beta_{el} \cdot f_{al}(e_1, \alpha_{el}, \delta) + T + \frac{P_n}{J} T_e - \frac{B}{J} \omega_1 \\
    \frac{dT}{dt} &= -\beta_{el2} \cdot f_{al}(e_1, \alpha_{el2}, \delta)
\end{align*}
\] (16)

In equation (16), \(\omega_0\) is the estimated value of the speed loop ESO, which is only used to build the speed loop ESO, while \(\omega^\prime\) is the estimated value of the electrical angular velocity of the rotor in the two-phase static coordinate system mentioned above.

Compensation value of electromagnetic torque:
\[
T_e = \frac{J}{P_n} T
\] (17)

The output of speed ring is the given value of electromagnetic torque:
\[
T_e = T_{e0} + T_e^\prime
\] (18)

\(T_{e0}\) from NLESF:
\[
\begin{align*}
    &e_1 = \omega_1 - \omega_0, e_2 = \omega_2 - \omega_2^\prime \\
    &T_{e0} = K_{e1} f_{al}(e_1, \alpha_{el}, \delta) + K_{e2} f_{al}(e_2, \alpha_{el2}, \delta)
\end{align*}
\] (19)

The given value of electromagnetic torque obtained by speed loop is the given value of current loop.

4.2. Construction of current loop

Using id = 0 control mode, according to the rotor displacement angle identified in the two-phase static coordinate system, coordinate transformation is carried out, and the current given values \(i_{\alpha}^*\) and \(i_{\beta}^*\) in the two-phase static coordinate system are obtained. According to equation (11), the output of current loop can be obtained, that is, the compensation formula of voltage given values \(u_{\alpha}^*\) and \(u_{\beta}^*\):
\[
\begin{align*}
    &u_{\alpha}^* = u_{\alpha0} - LQ_{\alpha} \\
    &u_{\beta}^* = u_{\beta0} - LQ_{\beta}
\end{align*}
\] (20)

\(u_{\alpha0}\) and \(u_{\beta0}\) can be calculated in this way:
\[
\begin{align*}
    &e_\alpha = i_\alpha - i_\alpha^*, e_\beta = i_\beta - i_\beta^* \\
    &u_{\alpha0} = K_{\alpha} f_{al}(e_\alpha, \alpha, \delta) \\
    &u_{\beta0} = K_{\beta} f_{al}(e_\beta, \alpha, \delta)
\end{align*}
\] (21)

\(u_{\alpha}^*\) and \(u_{\beta}^*\) for subsequent vector control operation.

4.3. Structure chart of double closed loop sensorless control system based on ADRC
In the two-phase static coordinate system, the current expansion state observer is used to identify the rotor speed and displacement angle, and ADRC is used to replace pi to realize the double closed-loop control of speed and current. The structure diagram of double closed-loop control system is shown in Figure 2.

5. Simulation results and analysis

In order to verify the feasibility of the proposed method, the system model is built in Matlab / Simulink environment, and the simulation experiment is carried out.

The pole pairs of the motor is 2, the supply voltage of the DC side is 200V, the inductance of the phase winding is 0.5mH and the flux of the permanent magnet is 0.36 Wb.

Fig. 3 shows the angular velocity response when 2 N\cdot m loads are suddenly applied at 0.02s.

Figure 4 shows the real value and estimate d value of the rotor displacement angle when the given angular velocity is 200 rad / s. The estimated value of rotor displacement angle has high accuracy.
6. Conclusion
In this paper, the speed sensorless control system of SMSM is constructed in two-phase static coordinate system, and the PI controller is replaced by auto disturbance rejection control for speed and current closed-loop control. The simulation results show that the method is feasible and the control system is stable.

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References
[1] HAN Jingqing. From PID to active disturbance rejection control, IEEE transactions on Industrial Electronics, 2009, (3): 900-906.
[2] HAN Jingqing. Active Disturbance Rejection Control Technique: the Technique for Estimating and Compensating the Uncertainties. Beijing, 2008.
[3] GAO Zhiqiang. On the foundation of active disturbance rejection control, Control Theory & Applications, 2013, 33(12): 1498-1510.
[4] WEN Jianping, CAO Binggang. Active Disturbances Rejection Control Speed Control System for Sensorless IPMSM, Proceedings of the CSEE, 2009, 29(30):58-62.
[5] Sun Kai, Xu Zhenlin, Zou Jiayong. A novel approach to positionsensorless vector control of PMSM based on active-disturbancerejection controller, Proceedings of the CSEE, 2007, 27(3): 18-22.
[6] TENG Qingfang, LI Guofei, ZHU Jian-guo, GUO You-guang. Sensorless active disturbance rejection model predictive torque control using extended state observer for permanent magnet synchronous motors fed by three-phase four-switch inverter, Control Theory & Applications, 2016, 33(5):676-684.
[7] TANG Renyuan. Theory and Design of Modern Permanent Magnet Synchronous Motor. Beijing: Machinery Industry Press, 1997:244-252.