Fuzzy sliding mode controller with integral sliding surface for permanent magnet synchronous motor postprint

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Abstract

In this paper, sliding mode controller with integral sliding surface is proposed to reject the system disturbances for permanent magnet synchronous motor (PMSM) speed regulation system. To reduce the chattering phenomenon, the signum function is replaced by the saturation function and fuzzy module is introduced in sliding mode controller. Simulation results show that the proposed control method can obtain satisfactory tracking performance and dynamic performance with smaller chattering.

Full Text

Preamble

Fuzzy Sliding Mode Controller with Integral Sliding Surface for Permanent Magnet Synchronous Motor

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In this paper, a sliding mode controller with integral sliding surface is proposed to reject system disturbances for permanent magnet synchronous motor (PMSM) speed regulation systems. To reduce the chattering phenomenon, the signum function is replaced by the saturation function and a fuzzy module is introduced into the sliding mode controller. Simulation results show that the proposed control method can achieve satisfactory tracking performance and dynamic performance with reduced chattering.

Keywords: Permanent Magnet Synchronous Motor (PMSM); Speed Regulation System; Fuzzy Sliding Mode Controller (FSMC); Integral Sliding Surface

1. Introduction

Permanent magnet synchronous motors (PMSM) have been widely used in many fields due to their high power density, high efficiency, low inertia, and reliable operation. The speed regulation method is critical for improving dynamic performance. The Field Orientation Control (FOC) strategy is commonly employed in speed regulation systems, and various implementations of FOC have been developed [**?**, **?**]. The FOC strategy typically includes both a speed loop and a current loop. In this paper, Current Hysteresis Band Pulse Width Modulation (CHBPWM) is introduced to control the three-phase stator current, and its structure is shown in Figure 1 [Figure 1: see original paper]. CHBPWM is the fastest strategy for current closed-loop control.

In PMSM systems, numerous disturbances and uncertainties exist, such as load disturbances, friction forces, and parameter uncertainties. Consequently, many intelligent algorithms and nonlinear control strategies have been introduced to improve system performance, including artificial neural networks (ANN) [**?**], fuzzy control [**?**], active disturbance rejection control (ADRC) [**?**], sliding mode control (SMC) [**?**], and others. SMC is widely utilized due to its invariant property against uncertain internal parameter variations and external disturbances. However, SMC exhibits a chattering phenomenon that can excite high-frequency dynamics.

In [**?**], a new exponential reaching law for sliding mode control is proposed to reduce chattering. In [**?**], a sliding mode based model predictive controller is proposed to track desired currents in finite time. In this paper, a fuzzy sliding mode controller with integral sliding surface is proposed to suppress chattering and improve reaching speed. Simulation results demonstrate that the proposed method can improve the dynamic performance and robustness characteristics of the speed servo system compared to the PI controller.

2. Model of PMSM System

Assuming that the magnetic circuit is unsaturated, hysteresis and eddy current losses are ignored, the magnetic field distribution is sinusoidal in space, and motor parameter variations are neglected, the dynamic equations for a surface-mounted PMSM in the d-q rotor reference frame can be expressed as follows:

(i) Voltage dynamic equations:

$$u_d = Ri_d + \frac{d\psi_d}{dt} - \omega_r \psi_q \tag{1}$$

$$u_q = Ri_q + \frac{d\psi_q}{dt} + \omega_r \psi_d \tag{2}$$

where u_d, u_q are the d-axis and q-axis stator voltages; i_d, i_q are the d-axis and q-axis stator currents; ψ_d, ψ_q are the d-axis and q-axis stator flux linkages; L_d, L_q are the d-axis and q-axis stator inductances; R is the stator resistance; ψ_f is the rotor flux linkage; and ω_r is the electrical angular velocity.

(ii) Flux linkage dynamic equations:

$$\psi_d = L_d i_d + \psi_f \tag{3}$$

$$\psi_q = L_q i_q \tag{4}$$

(iii) Electromagnetic torque dynamic equation:

$$T_e = 1.5 n_p [\psi_f i_q + (L_d - L_q) i_d i_q]$$

where n_p is the number of pole-pairs and T_e is the electromagnetic torque.

(iv) Mechanical dynamic equation:

$$J \frac{d\omega_m}{dt} = T_e - T_L - B\omega_m$$

where ω_m is the mechanical angular velocity ($\omega_m = \omega_r / n_p$), J is the system moment of inertia, B is the viscous friction coefficient, and T_L is the load torque.

For a surface-mounted PMSM, $L_d = L_q = L_s$. According to Eq. (1) to Eq. (4), with the d-axis reference current set to zero, we can derive the following relationship between $\dot{\omega}_r$ and i_q:

$$\dot{\omega}_r = \frac{1.5 n_p \psi_f}{J} i_q - \frac{B}{J}\omega_r - \frac{n_p}{J} T_L$$

To obtain the relationship between $\dot{\omega}_r$ and i_q^*, Eq. (5) is rewritten as:

$$\dot{\omega}_r = \frac{1.5 n_p \psi_f}{J} i_q^* - d(t)$$

where i_q^* is the q-axis reference current and $d(t)$ represents the system disturbance, defined as:

$$d(t) = \frac{1.5 n_p \psi_f}{J}(i_q^* - i_q) + \frac{B}{J}\omega_r + \frac{n_p}{J} T_L$$

3. Controller Design

3.1 Design of Sliding Surface

In [?]-[?], the sliding surface contains the derivative of the speed error. In some low-speed servo systems, the differential operation introduces high-frequency noise that may obscure the real speed error and destabilize the entire system. In this paper, the integral of the speed error is added to the sliding surface as shown in Eq. (8):

$$s = e + c\int_0^t e\, d\tau$$

where s is the sliding surface, e is the speed error defined as $e = \omega_r^* - \omega_r$ (with ω_r^* being the reference mechanical angular velocity), and c is a positive design parameter that satisfies the Hurwitz condition. Torque becomes smoother and steady-state error is reduced by adopting the integral sliding surface [?].

3.2 Design of Sliding Mode Control Law

The control law u consists of an equivalent control law u_{eq} and a switching control law u_{sw}. The equivalent control law ensures system certainty and maintains the system states on the sliding surface. The switching control law forces the system states to approach the stable point through high-frequency switching. By setting $\dot{s} = 0$ and substituting the system dynamics, we obtain u_{eq} as shown in the following equation:

$$u_{eq} = \frac{J}{1.5 n_p \psi_f} \left(\dot{\omega}_r^* + ce\right)$$

The switching control law u_{sw} is selected as:

$$u_{sw} = \frac{J}{1.5 n_p \psi_f} \eta \cdot \mathrm{sign}(s)$$

To reduce chattering, the signum function is replaced by the saturation function $\mathrm{sat}(s/\Delta)$, defined as:

$$\mathrm{sat}\left(\frac{s}{\Delta}\right) = \begin{cases} \mathrm{sign}(s) & |s| > \Delta \\ \frac{s}{\Delta} & |s| \leq \Delta \end{cases}$$

where Δ is the thickness of the boundary layer neighboring the sliding surface and is a design parameter. Therefore, the complete control law is written as:

$$u = u_{eq} + \frac{J}{1.5 n_p \psi_f} \eta \cdot \mathrm{sat}\left(\frac{s}{\Delta}\right)$$

3.3 Stability Analysis

To establish the existence condition of the sliding mode, the Lyapunov function candidate is defined as:

$$V = \frac{1}{2}s^2$$

Taking the derivative of V with respect to time:

$$\dot{V} = s\dot{s} = s\left[-\frac{1.5n_p\psi_f}{J}\eta \cdot \mathrm{sat}\left(\frac{s}{\Delta}\right) - d(t)\right] \leq -\eta|s| \leq 0$$

The Lyapunov function is less than or equal to zero, and when $\dot{V} = 0$, $s = 0$. Therefore, the control system is stable and the system states will converge toward the sliding mode surface in finite time.

3.4 Design of Fuzzy Sliding Mode Controller

Sliding mode control causes chattering phenomenon in the switching control law, which can excite high-frequency dynamics. To reduce chattering and improve control performance, a fuzzy module is introduced into the switching control law. Specifically, when the disturbance is larger, the switching control law should be larger; when the disturbance is smaller, the switching control law should be smaller. The control law is designed as:

$$u = u_{eq} + a \cdot u_{sw}$$

where a is the output of the fuzzy module. The input of the fuzzy module is the sliding surface function s. The membership functions of s and a are shown in Figure 2 [Figure 2: see original paper].

If the system states are near the sliding surface, a will become smaller. If the system states are far from the sliding surface, a will become larger. This strategy reduces chattering while ensuring that the system states reach the sliding surface. The fuzzy rules are described as:

[The fuzzy rule table would be inserted here based on the original content]

4. Simulation Results

In this section, simulations are implemented in MATLAB/Simulink to validate the feasibility and effectiveness of the proposed method. The parameters of the PMSM system are as follows: stator resistance $R_s = 2.875\,\Omega$; rotor flux linkage $\psi_f = 0.175\,\mathrm{Wb}$; d-axis and q-axis stator inductances $L_d = L_q = 8.5\,\mathrm{mH}$; number of pole-pairs $n_p = 4$; system moment of inertia $J = 0.003\,\mathrm{kg\cdot m^2}$; viscous friction coefficient $B = 0.008\,\mathrm{N\cdot m\cdot s/rad}$; load torque $T_L = 4\,\mathrm{N\cdot m}$. With these parameters, the system disturbance $d(t)$ is estimated as 1333.3. The reference mechanical angular velocity is 100 rad/s at $t = 0$ and 150 rad/s at $t = 0.2\,\mathrm{s}$. For CHBPWM, the time constant of the current filter is 0.0001 s and the width of the current hysteresis band is 0.05.

The comparative simulation results of the PI speed controller and fuzzy sliding mode speed controller are shown in Figure 3 [Figure 3: see original paper]. For the PI speed controller, the proportional gain is $K_p = 0.5$ and the integral gain is $K_i = 5$. For the fuzzy sliding mode controller, the design parameters are $c = 50$,

$\eta = 50$, and the boundary layer thickness $\Delta = 0.5$. The results indicate that dynamic performance is improved with the fuzzy sliding mode speed controller.

To reduce chattering, the signum function is replaced by the saturation function and a fuzzy module is introduced into the sliding mode controller. The control outputs of SMC, SMC with saturation function, and FSMC with saturation function are shown in Figure 4 [Figure 4: see original paper]. The results demonstrate that the proposed method produces the smallest chattering in the control output.

5. Conclusion

This paper has proposed a sliding mode controller with integral sliding surface to enhance the robustness of the PMSM speed regulation system. To suppress chattering, the signum function is replaced by the saturation function and a fuzzy module is introduced into the sliding mode controller. Comparative simulation results have validated the effectiveness of the proposed method.

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