

Postprint: Improved Sliding-Mode Model Reference Adaptive Sensorless Control for PMSM

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Abstract

To address the sensitivity of the MRAS (Model Reference Adaptive System) observer to parameter variations and external disturbances in PMSM (Permanent Magnet Synchronous Motor), a soft-switching sliding mode model reference adaptive observer is designed for PMSM sensorless control. This observer integrates sliding mode control with MRAS and constructs a sinusoidal saturation function with variable boundary layer to suppress system chattering induced by sliding mode control and enhance system robustness. Additionally, a sigmoid function is introduced to improve the stability of the sliding mode soft-switching speed controller. Experimental simulation results demonstrate that the soft-switching sliding mode model reference adaptive control not only achieves fast convergence within the boundary layer and attenuates chattering, but also exhibits strong tracking capability.

Full Text

Preamble

Sensorless Control of PMSM Based on Improved Sliding-Mode Model Reference Adaptive System

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Abstract: Due to the disadvantage that Model Reference Adaptive System (MRAS) observers are sensitive to parameter variations of Permanent Magnet Synchronous Motors (PMSM) and external disturbances, this paper proposes a soft-switching sliding-mode model reference adaptive observer for PMSM sensorless control. The observer combines sliding-mode control with MRAS and constructs a variable-boundary-layer sinusoidal saturation function to suppress

system chattering caused by sliding-mode control and enhance robustness. Simultaneously, a sigmoid function is introduced to improve the stability of the sliding-mode soft-switching speed controller. Experimental and simulation results demonstrate that the soft-switching sliding-mode model reference adaptive control not only achieves rapid convergence within the boundary layer and weakens chattering but also exhibits strong tracking capability.

Keywords: Permanent Magnet Synchronous Motor; Sliding-mode soft switch; Sliding-mode model reference adaptive system; Sinusoidal saturation function

Method

Sensorless Control of PMSM Based on Improved Sliding-Mode Model Reference Adaptive System

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Abstract: Due to the disadvantage that Model Reference Adaptive Observer (MARS) is sensitive to parameter variations of PMSM (Permanent Magnet Synchronous Motor) and external disturbances, this paper developed a soft-switched sliding mode model reference adaptive observer for PMSM sensorless control. The observer combined the sliding mode control with MRAS. Constructing a variable sinusoidal saturation function was to enhance the robustness of the system and effectively reduce the chattering phenomenon. At the same time, introducing the sigmoid function was to improve the stability of the sliding mode soft switching speed controller. The simulation results show that the soft-switching sliding mode model reference adaptive control can achieve convergence faster, reduce the chattering phenomenon and improve the tracking performance.

Key words: PMSM; sliding mode soft switch; sliding-mode MRAS; saturation function

0 Introduction

Permanent Magnet Synchronous Motors (PMSM) offer numerous advantages including compact size, light weight, reliable operation, excellent speed regulation performance, and high power density, making them widely adopted in industrial robotics, wind power generation, aerospace, and various other fields [1-3]. High-performance control of PMSM depends on accurate rotor position information; however, conventional mechanical position sensors such as photoelectric encoders or resolvers are costly and exhibit poor anti-interference capability, significantly limiting the development and application of PMSM. Sensorless control technology can eliminate mechanical position sensors, simplify wiring between

the frequency converter and motor, reduce system volume, and improve reliability, thus becoming a research hotspot in motor control [4-5].

Sensorless control methods for PMSM can be categorized into low-speed methods based on high-frequency signal injection and medium-to-high-speed methods based on back-EMF and flux linkage estimation. The high-frequency injection method exploits motor structural saliency or saturation saliency characteristics by injecting rotating or pulsating high-frequency signals to obtain rotor position information during standstill and low-speed operation. Observer methods represent a widely used medium-to-high-speed estimation approach that establishes back-EMF or flux linkage observers to derive rotor position and speed information, including Extended Kalman Filter methods [6], Model Reference Adaptive System (MRAS) methods [7-9], sliding-mode observer methods [10-11], disturbance observer methods [12-13], and nonlinear observer methods [14].

Domestic and international scholars have conducted extensive research on sensorless control technology, yielding numerous achievements. Literature [7] demonstrates that traditional MRAS control is highly sensitive to internal motor parameter variations and exhibits poor robustness. Literature [8] incorporates variable structure control into model reference adaptation, significantly improving system robustness but simultaneously increasing system chattering. Literature [9] replaces the switching function in variable structure control with a hyperbolic tangent saturation function, which reduces system chattering but suffers from long algorithm computation time, making it unsuitable for engineering applications. This paper designs a soft-switching sliding-mode model reference adaptive observer that combines sliding-mode control with MRAS to improve speed estimation accuracy and enhance system robustness. A variable-boundary-layer sinusoidal saturation function is constructed to replace the switching function, suppressing system chattering caused by sliding-mode control. Additionally, a sigmoid function is introduced to enhance the stability of the sliding-mode soft-switching speed controller. Comparative measurements of position and speed tracking errors were conducted against sliding-mode MRAS and MRAS control. Simulation results demonstrate that the proposed method not only significantly suppresses chattering caused by sliding-mode control and enhances system robustness but also achieves high tracking accuracy with simple algorithm computation, making it suitable for engineering applications.

1 PMSM Mathematical Model

The mathematical model of a three-phase surface-mounted PMSM in the synchronous rotating d-q coordinate system is as follows:

$$\begin{cases} u_d = Ri_d + L \frac{di_d}{dt} - \omega_e Li_q \\ u_q = Ri_q + L \frac{di_q}{dt} + \omega_e (Li_d + \psi_f) \end{cases}$$

where u_d, u_q are the d- and q-axis voltages; i_d, i_q are the d- and q-axis currents; L_d, L_q are the d- and q-axis inductances ($L_d = L_q = L$); R is the stator resistance; ω_e is the electrical angular speed; and ψ_f is the rotor permanent magnet flux linkage.

The mechanical motion equation is:

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

where T_L is the load torque; T_e is the electromagnetic torque; ω_m is the mechanical angular speed of the motor; J is the moment of inertia; and B is the damping coefficient.

2.1 MRAS Observer

Model reference adaptive observers are highly sensitive to parameter variations in the reference model and system disturbances. To address this, this paper introduces sliding-mode control into model reference adaptation to enhance system robustness. Equation (1) can be rewritten as:

Reference Model:

$$\frac{d}{dt} \begin{bmatrix} i_d \\ i_q \end{bmatrix} = \begin{bmatrix} -\frac{R}{L} & \omega_e \\ -\omega_e & -\frac{R}{L} \end{bmatrix} \begin{bmatrix} i_d \\ i_q \end{bmatrix} + \begin{bmatrix} \frac{1}{L} & 0 \\ 0 & \frac{1}{L} \end{bmatrix} \begin{bmatrix} u_d \\ u_q \end{bmatrix} + \begin{bmatrix} 0 \\ -\frac{\omega_e \psi_f}{L} \end{bmatrix}$$

Adjustable Model:

$$\frac{d}{dt} \begin{bmatrix} \hat{i}_d \\ \hat{i}_q \end{bmatrix} = \begin{bmatrix} -\frac{R}{L} & \hat{\omega}_e \\ -\hat{\omega}_e & -\frac{R}{L} \end{bmatrix} \begin{bmatrix} \hat{i}_d \\ \hat{i}_q \end{bmatrix} + \begin{bmatrix} \frac{1}{L} & 0 \\ 0 & \frac{1}{L} \end{bmatrix} \begin{bmatrix} u_d \\ u_q \end{bmatrix} + \begin{bmatrix} 0 \\ -\frac{\hat{\omega}_e \psi_f}{L} \end{bmatrix}$$

where $\hat{i}_d, \hat{i}_q, \hat{\omega}_e$ are the estimated values of i_d, i_q, ω_e .

Error Equation: Defining the error as $e = i' - \hat{i}'$, subtracting the adjustable model from the reference model yields:

$$\frac{de}{dt} = Ae + C\hat{\omega}_e$$

where $e = \begin{bmatrix} e_d \\ e_q \end{bmatrix}$ and $C = \begin{bmatrix} 0 & -\omega_e \\ 0 & \omega_e \end{bmatrix}$.

To improve speed estimation accuracy, a proportional-integral based MRAS is adopted. The following Lyapunov energy function is constructed:

$$V = \frac{1}{2}(e_d^2 + e_q^2) + \frac{1}{2k_\omega}(\hat{\omega}_e - \omega_e)^2$$

where k_ω is a positive constant. The speed adaptation law is:

$$\hat{\omega}_e = k_p(e_d \hat{i}_q - e_q \hat{i}_d) + k_i \int (e_d \hat{i}_q - e_q \hat{i}_d) dt$$

where k_p and k_i are positive gains.

2.3 Improved Sliding-Mode MRAS Observer Design

To suppress chattering caused by sliding-mode control, the concept of a “boundary layer” is introduced, employing linear elementary saturation functions, nonlinear terminal sliding-mode saturation functions, or nonlinear hyperbolic tangent saturation functions to replace traditional switching functions. According to literature [15], with the same boundary layer thickness, elementary and terminal sliding-mode ($a = 5/7$) saturation functions have relatively long equivalent convergence times. While the hyperbolic tangent saturation function significantly reduces equivalent convergence time, its algorithm is computationally intensive and unsuitable for engineering applications. This paper designs a sinusoidal saturation function with short equivalent convergence time and simple computation.

Assuming 0.0001 is negligible compared to 1, the sinusoidal saturation function is:

$$F(s) = \begin{cases} \text{sign}(s), & |s| > \varepsilon \\ \frac{2}{\pi} \sin\left(\frac{\pi s}{2\varepsilon}\right), & |s| \leq \varepsilon \end{cases}$$

where ε is the boundary layer thickness. When ε is sufficiently large, the function becomes a traditional switching function. Increasing ε can reduce chattering caused by sliding-mode control, but excessively large values will degrade system robustness and slow convergence.

The sinusoidal saturation function curve is shown in [Figure 1: see original paper]. When $\varepsilon = 0$, the saturation function becomes a traditional switching function. By appropriately increasing ε , chattering caused by sliding-mode control can be reduced, but if ε is too large, system robustness will be compromised and convergence speed reduced. Therefore, boundary layer thickness should be minimized while suppressing chattering.

Based on sliding-mode variable structure theory, the speed obtained from the speed adaptation law is selected as the sliding-mode surface. The traditional sliding-mode MRAS observer is:

$$\hat{\omega}_e = \lambda \cdot \text{sign}(s)$$

where $\lambda > 0$ and $s = e_d \hat{i}_q - e_q \hat{i}_d$.

The improved (soft-switching) sliding-mode MRAS observer is:

$$\hat{\omega}_e = \lambda \cdot F(s)$$

where $F(s)$ is the sinusoidal saturation function defined above.

To ensure observer stability, the following Lyapunov function is constructed:

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

Taking the derivative of V yields:

$$\dot{V} = S\dot{S} = S(g_1 + g_2 \hat{\omega}_e)$$

where g_1 and g_2 are system parameters. To ensure $\dot{V} \leq 0$, the following condition must be satisfied:

$$\lambda \geq \frac{|g_1|}{|g_2|}$$

Thus, the (soft-switching) sliding-mode model reference adaptive observer is globally asymptotically stable. When the observer reaches the sliding surface ($S = 0$), the equivalent speed converges to the actual speed, and the system is stable. The position observation value is:

$$\hat{\theta}_e = \int \hat{\omega}_e dt$$

The system structure diagram of the improved sliding-mode MRAS control is shown in [Figure 2: see original paper].

3 Sliding-Mode Soft-Switching Speed Controller Design

Defining the speed tracking error as $E(t) = \omega_r^* - \hat{\omega}_r$ (where $\hat{\omega}_r$ is the estimated speed and ω_r^* is the reference speed), the integral of the error is selected as the sliding surface:

$$S(t) = E(t) + k_E \int_0^t E(\tau) d\tau$$

where k_E is a positive constant. Substituting the error definition yields:

$$\dot{S}(t) = \dot{E}(t) + k_E E(t)$$

The sign function causes inherent chattering near the sliding surface, making the estimated value oscillate around the actual value and directly affecting estimation accuracy. This paper constructs a variable-boundary-layer sinusoidal saturation function to replace the sign function for chattering suppression.

When motor parameters change or external disturbances occur, the system state deviates from the sliding surface. Typically, switching compensation u_{eq} is added to suppress this deviation, but it also aggravates chattering [16-20]. Therefore, this paper employs a sigmoid function to replace the sign function, which not only suppresses state deviation but also significantly reduces system chattering.

The sigmoid function is defined as:

$$\text{sigmoid}(x) = \frac{2}{1 + e^{-mx}} - 1$$

where $m > 0$ and $b > 0$ are design parameters. The soft-switching control law is:

$$u = u_{eq} + u_{sw}$$

where $u_{sw} = \lambda \cdot \text{sigmoid}(S)$.

To ensure observer stability, the following Lyapunov function is constructed:

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

Taking the derivative and substituting the control law yields:

$$\dot{V} = S\dot{S} = S(-\lambda \cdot \text{sigmoid}(S) + \Delta) \leq 0$$

where Δ represents system uncertainties. The condition $\lambda \geq |\Delta|$ ensures stability.

4 Simulation Results

A simulation system was built in MATLAB/Simulink with the structure shown in [Figure 2: see original paper]. The PMSM parameters used in the system are: stator resistance (R) = 2.875 Ω ; d- and q-axis stator inductances (L_d, L_q) = 8.5 mH; number of pole pairs (n_p) = 4; flux linkage (ψ_f) = 0.175 Wb; moment of inertia (J) = 6.24 $\times 10^{-4}$ kg \cdot m²; damping coefficient (B) = 0 N \cdot m \cdot s; DC bus voltage (V_{dc}) = 311 V.

The PI parameters on the d-axis are: $K_{pd}^* = 380$, $K_{id}^* = 1700$.

The PI parameters on the q-axis are: $K_{pq}^* = 1900$, $K_{iq}^* = 1700$.

The PI parameters in the MRAS observer are: $K_{p1} = 1.1$, $K_{i1} = 1.8$.

In equation (13), $\lambda = 420$.

To verify the robustness of the designed system, comparative simulations were conducted for MRAS control, sliding-mode MRAS control, and improved sliding-mode MRAS control under external load variations and internal motor parameter changes.

4.1 Variable Load Analysis

The reference speed (ω_r^*) is set to 1000 r/min with no-load startup. At $t = 0.2$ s, the load torque (T_L) changes from 0 N \cdot m to 0.6 N \cdot m. The torque response curves for MRAS control, sliding-mode MRAS control, and improved sliding-mode MRAS control are shown in [Figure 3: see original paper], speed response curves in [Figure 4: see original paper], position response curves in [Figure 5: see original paper], and tracking errors in [Figure 6: see original paper].

As shown in [Figure 3: see original paper], under load 突变, the electromagnetic torque generated by MRAS control requires 5 ms to converge, while sliding-mode MRAS produces severe torque chattering with slow convergence. In contrast, improved sliding-mode MRAS achieves rapid convergence to the set value.

From [Figure 4: see original paper] through [Figure 6: see original paper], when load suddenly increases, the actual speed of MRAS control deviates from the reference speed by 250 r/min, with an observation speed tracking error of 100 r/min, stabilizing after approximately 18 ms. At steady state, the speed tracking error is 8 r/min and position tracking error is 0.1 rad. Sliding-mode MRAS exhibits large speed fluctuations, obvious chattering, and severe deviation from the reference speed, causing the observed speed to lose accurate tracking capability. Improved sliding-mode MRAS significantly weakens chattering caused by sliding-mode variable structure, limiting the observed speed tracking error to within 100 r/min and achieving steady state in only 10 ms. At steady state, the speed tracking error is controlled within 6 r/min and position tracking error is 0.02 rad.

Simulation results demonstrate that under load 突变, improved sliding-mode

MRAS control not only effectively suppresses chattering caused by sliding-mode control but also exhibits strong tracking capability and robustness.

4.2 Variable Parameter Analysis

The reference speed (ω_r^*) remains at 1000 r/min with constant load torque of $0 \text{ N} \cdot \text{m}$. Assuming inductance remains unchanged, the motor stator resistance changes from R to $2R$. The tracking error curves for MRAS control, sliding-mode MRAS control, and improved sliding-mode MRAS control are shown in [Figure 7: see original paper]. If the motor stator resistance remains unchanged while inductance changes from L to $2L$, the tracking error curves are shown in [Figure 8: see original paper].

As shown in [Figure 7: see original paper], when stator resistance changes from R to $2R$, MRAS control exhibits a speed tracking error of 300 r/min and position tracking error of 0.23 rad, stabilizing after approximately 16 ms. At steady state, the speed tracking error is 8 r/min. Sliding-mode MRAS control shows extremely large startup overshoot, reaching 2000 r/min, stabilizing after about 25 ms with a steady-state deviation of approximately 100 r/min. Improved sliding-mode MRAS accurately tracks the actual rotor speed with tracking error limited to within 5 r/min and position error nearly 0 rad.

As shown in [Figure 8: see original paper], when motor inductance changes from L to $2L$, MRAS control requires 0.05 s to reach steady state with small tracking errors. Sliding-mode MRAS control exhibits large startup overshoot, severe speed fluctuations, and reaches steady state after 0.07 s with speed tracking error of 200 r/min and position tracking error of 0.05 rad. Improved sliding-mode MRAS control experiences only a brief small deviation before quickly stabilizing, with steady-state speed tracking error controlled within 3 r/min and position tracking error of 0 rad.

Therefore, when internal motor parameters vary, the improved sliding-mode MRAS observer can still track the actual rotor values rapidly and accurately, demonstrating strong system robustness.

5 Conclusion

This paper designs an improved sliding-mode model reference adaptive observer that combines sliding-mode control with MRAS to enhance system tracking accuracy and anti-interference capability. By employing a variable-boundary-layer sinusoidal saturation function to replace the switching function, chattering is significantly reduced. The introduction of a sigmoid function further improves system stability. Comparative simulations under load disturbance and parameter variations demonstrate that the improved sliding-mode MRAS control ex-

hibits strong external disturbance rejection, low sensitivity to internal motor parameter changes, high tracking accuracy, and obvious chattering reduction.

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