Sensorless control of permanent magnet synchronous motor based on adaptive sliding mode observer and sliding mode gain design

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Abstract. Aiming at the chattering problem in the traditional sliding mode observer of permanent magnet synchronous motor, an improved sliding mode observer is designed. The Kalman observer is designed, the phase-locked loop (PLL) control algorithm is introduced, and the problem of phase delay and precision reduction caused by ordinary filter is solved. The simulation results show that the improved sliding mode observer can accurately estimate the rotation speed and reduce the chattering phenomenon in the process of rotor position estimation.

1. Introduction
In this paper, an improved adaptive sliding mode observer is designed, hyperbolic sine function is introduced, and boundary variable function is used as switching function, through this strategy, chattering problem of the system is reduced, and it is demonstrated and analyzed according to Lyapunov stability theory. In this paper, a control system is added to optimize the gain. In order to avoid the phase delay caused by the low pass filter, a Kalman observer is designed to obtain the counter potential and estimate the velocity and position of the rotor. The phase locked loop is improved to ensure the dynamic performance of the system. Finally, Matlab is used to verify the above contents, proving that the method proposed in this paper has good robustness.

2. Methods

2.1. Adaptive sliding mode observer
The expression of stator current state in $\alpha\beta$ coordinate system is:

$$\frac{d}{dt} \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = - \begin{bmatrix} R_s/L & 0 \\ 0 & R_s/L \end{bmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} + \frac{1}{L} \begin{bmatrix} u_\alpha \\ u_\beta \end{bmatrix} - \frac{1}{L} \begin{bmatrix} e_\alpha \\ e_\beta \end{bmatrix}$$

(1)

The torque of the motor is controlled by adjusting the magnitude of the control electronic current $i_d$ by adopting a control method with a given $i_d = 0$. The back EMF equation is:

$$\begin{cases} e_\alpha = -\psi_\alpha \omega \sin \theta_c = -k_c \sin \theta_c \\ e_\beta = \psi_\beta \omega \cos \theta_c = k_c \cos \theta_c \end{cases}$$

(2)

The extended back EMF equation is $k_e$. Constructing Sliding Mode Observer:
\[
\frac{d}{dt} \begin{bmatrix} \dot{i}_a \\ \dot{i}_\beta \end{bmatrix} = -\begin{bmatrix} \frac{R_s}{L} & 0 \\ 0 & \frac{R_s}{L} \end{bmatrix} \begin{bmatrix} i_a \\ i_\beta \end{bmatrix} + \begin{bmatrix} 1/L & 0 \\ 0 & 1/L \end{bmatrix} \begin{bmatrix} u_a \\ u_\beta \end{bmatrix} + \begin{bmatrix} 1/L \\ \dot{e}_a \end{bmatrix} + \begin{bmatrix} 1/L \\ \dot{e}_\beta \end{bmatrix}
\]  
(3)

In this formula, \( \dot{i}_a \) and \( \dot{i}_\beta \) is observation value of stator current; \( \dot{e}_a \) and \( \dot{e}_\beta \) observation of back potential. According to the state expression of stator current error, a linear sliding surface function is designed and selected:

\[
S = \begin{bmatrix} S_a \\ S_\beta \end{bmatrix} = \begin{bmatrix} i_{sa} \\ i_{s\beta} \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \end{bmatrix}
\]  
(4)

The traditional sliding mode observer generally takes the switching function as the switching function of the control system, but due to the discontinuity of \( \text{sgn}(x) \), the system will generate chattering:

\[
F(x) = \begin{cases} 
  s_1(x) & |S| \geq \delta \\
  s_2(\alpha x) & |S| < \delta 
\end{cases}
\]  
(5)

In this formula, \( a = 2\pi \delta \), \( \delta \) is boundary thickness.

\[
s_1(x) = \text{sgn}(x)
\]  
(6)

\[
s_2(\alpha x) = \tanh(\alpha x) = \frac{\sinh \alpha x}{\cosh \alpha x} = \frac{e^{\alpha x} - e^{-\alpha x}}{e^{\alpha x} + e^{-\alpha x}}
\]  
(7)

When \( a = 1 \), the expression of the current error switching signal is:

\[
\dot{e}_a = k_w F(S_a) \\
\dot{e}_\beta = k_w F(S_\beta)
\]  
(8)

\( k_w \) is sliding mode gain and is dynamically adjusted according to the change of the control system. The state expression with stator current error as the state variable is:

\[
\frac{d}{dt} \begin{bmatrix} i_{sa} \\ i_{s\beta} \end{bmatrix} = -\begin{bmatrix} \frac{R_s}{L} & 0 \\ 0 & \frac{R_s}{L} \end{bmatrix} \begin{bmatrix} i_{sa} \\ i_{s\beta} \end{bmatrix} + \begin{bmatrix} 1/L & 0 \\ 0 & 1/L \end{bmatrix} \begin{bmatrix} e_a - k_w F(S_a) \\ e_\beta - k_w F(S_\beta) \end{bmatrix}
\]  
(9)

In order to prove the stability of the system according to the idea of equivalent control, Lyapunov function is defined as:

\[
\dot{V} = V = 1/2 S^T \dot{S}
\]  
(10)

\[
\dot{V} = \dot{S}^T \dot{S} \leq 0
\]  
(11)

The stability condition can be expressed as

\[
\dot{V} = S^T \dot{S} = S_a \dot{S}_a + S_\beta \dot{S}_\beta = 1/L (\dot{i}_a - i_a) [e_a - k_w F(\dot{i}_a - i_a)] \\
+ 1/L (\dot{i}_\beta - i_\beta) [e_\beta - k_w F(\dot{i}_\beta - i_\beta)] - R_s/ L (\dot{i}_a - i_a)^2 + (\dot{i}_\beta - i_\beta)^2
\]  
(12)

In this formula, \(-R_s/ L (\dot{i}_a - i_a)^2 + (\dot{i}_\beta - i_\beta)^2 \leq 0 \) is established in perpetuity, and \(-1 < \text{tanh}(x) < 1 \), therefore \( k_w \) must meet the conditions.

\[
k_w > \max (|e_a|, |e_\beta|)
\]  
(13)

2.2. Design of Sliding Mode Gain

In this paper, fuzzy rules are used to effectively control the system which can not establish an accurate model, and the sliding mode gain is designed to ensure the optimal gain value is selected. \( S \) and \( \dot{S} \) is selected as the input of the fuzzy controller, and the defined interval is \([-1, 1]\); Sliding mode gain \( k_w \) is the output, which quantifies the input and output of the controller and defines the interval as \([-1, 1]\). The control rules of the fuzzy controller are shown in table 1. \( S \) and \( \dot{S} \) is selected as the input of the fuzzy controller, and the defined interval is \([-1, 1]\); Sliding mode gain \( k_w \) is the output, which quantifies the input and output of the controller and defines the interval as \([-1, 1]\).
Table 1. Control Rules

| S | NB | NM | ZE | PM | BM |
|---|----|----|----|----|----|
| S | NB | NB | NB | NM | NS | ZE |
| NM | NB | NM | NS | ZE | PS |    |
| ZE | NM | NS | ZE | PS | PM |    |
| PB | NS | ZE | PS | PM | PB |    |
| PS | ZE | PS | PM | PB | PB |    |

Fig 1. Input the membership function

Fig 2. Output the membership function

The membership functions of input and output are shown in Figures 1 and 2. Fuzzy languages defining input variables are \{NB (negative large), NM (negative medium), ZE (zero), PM (middle), PB Zhengda\}; The fuzzy language values of the output variables are \{NB (negative large), NM (negative medium), NS (negative small), ZE (zero), PS (positive small), PM (median), PB (Zhengda)\}.

2.3. Rotor Position Estimation Based on Kalman Filter Back EMF Observer

The rotor position information of PMSM is only related to the back electromotive force, which contains the rotor position and rotation speed information. In order to obtain the rotor position information from it, the arctangent function is generally used, that is:

$$\theta_e = -\arctan(\hat{\theta}/\hat{\omega})$$  \hspace{1cm} (14)

The rotor speed information can be estimated by equation (14):

$$\hat{n} = \sqrt{(\hat{\omega})^2 + (\hat{\omega})^2} / k_e$$  \hspace{1cm} (15)

The back electromotive force observer constructed according to equation (15) is as follows

$$\dot{\hat{e}} = -\hat{\omega} \hat{e} - L(\hat{e} - e)$$  \hspace{1cm} (16)

The error equation of back electromotive force is obtained as follows

$$\ddot{\hat{e}} = -\hat{\omega} \dot{\hat{e}} - \hat{\omega} \hat{e} - L(\hat{e} - e)$$  \hspace{1cm} (17)

In order to prove the stability of the system, Lyapunov function is defined as:

$$V = 1/2(\hat{e}_a)^2 + (\hat{e}_b)^2 + (\hat{\omega})^2$$  \hspace{1cm} (18)

$$\dot{V} = \hat{e}_a \hat{\dot{e}}_a + \hat{e}_b \hat{\dot{e}}_b + \hat{\omega} \hat{\dot{\omega}} - l((\hat{e}_a)^2 + (\hat{e}_b)^2) < 0$$  \hspace{1cm} (19)

Judging from equation (19), the back electromotive force observer is stable. Through the above method, the phase compensation link can be omitted.
2.4. Design of Improved Phase Locked Loop
There is high frequency chattering in the calculation of rotor position angle. In order to solve this problem, an improved two-phase orthogonal phase locked loop (PLL) is used to obtain the rotation speed of the motor. According to the mathematical model of permanent magnet synchronous motor, it can be obtained
\[
e_{
s_\theta} = e_{\rho} \sin \theta_v
\]  
(20)

The actual rotor position angle is traced by that rotor position angle obtained by integrating the observed back EMF and the rotation speed estimated by the phase locked loop.

The difference in back electromotive force is
\[
\Delta E = -e_{\ns_\theta} \cos \theta_v - e_{\rho} \sin \theta_v
\]  
(21)

If the position estimation error is accord with \(|\theta_v - \hat{\theta}_v| < \pi / 6\), it can thought of
\[
sin(\theta_v - \hat{\theta}_v) = \theta_v - \hat{\theta}_v = \Delta \theta_v
\]  
(22)

In combination with the trigonometric function transformation formula, equation (22) is normalized
\[
\Delta E = k_n \sin \theta_v \cos \theta_v - k_n \cos \theta_v \sin \theta_v = k_n \sin(\theta_v - \hat{\theta}_v) = k_n \Delta \theta_v
\]  
(23)

In this paper, the phase-locked loop is improved, the amplitude of back electromotive force is added, the open-loop gain is fixed, and after the above equivalent treatment, the improved phase-locked loop schematic diagram is shown in fig. 3.

![Improved phase-locked loop schematic diagram](image)

3. Results and Discussion
In this paper, the Matlab simulation software is used to verify, and the parameters of permanent magnet synchronous motor are selected as shown in Table 2.

| Parameter                      | Numerical |
|--------------------------------|-----------|
| Phase voltage /V               | 220       |
| Phase resistance /Ω            | 2.875     |
| Direct cross-axis inductance / mH | 8.35     |
| moment of inertia / kg · m²    | 0.000 8kg · m² |
| Rotor flux linkage / Wb        | 0.175     |
| number of pole-pairs          | 4         |

Figs. 4 to 5 show the comparison of simulation results between the traditional sliding mode observer and the improved sliding mode observer designed in this paper. It can be seen from fig. 5 (a) (b) that the chattering of the rotor position and speed of the motor are effectively suppressed and the observation accuracy is improved. The improved observer can effectively track the actual value of rotor information.

The rotational speed of the motor in figs. 6 and 7 is given by a step signal, and the accuracy of the system in different rotational speed ranges can be judged by measuring the dynamic performance of the system through sudden addition of rotational speed. By comparing the two graphs, it can be seen that the traditional sliding mode observer has obvious chattering when running in low speed and high speed. The improved observer in this paper can effectively suppress chattering in both low-speed and
high-speed sections, with more stable speed waveform and high observer accuracy.

Fig 4(a). The actual and observed values of rotor position of traditional sliding mode observer

Fig 4(b). The actual and estimated rotational speed of traditional sliding mode observer

Fig 4(c). Rotor position error of traditional sliding mode observer

Fig 5(a). Actual and estimated values of the improved observer rotor position

Fig 5(b). The actual and estimated values of the observer speed are improved

Fig 5(c). The rotor position error of the improved observer is improved

Fig 6. Traditional sliding mode observer speed Waveform

Fig 7. Adaptive fuzzy sliding mode observer speed
4. Conclusions

In this paper, an improved adaptive sliding mode observer is designed for surface-mounted permanent magnet synchronous motor. The hyperbolic sine function is introduced, the boundary variable function is taken as the switching function, and a fuzzy control system is added to optimally select the gain. An Kalman observer is designed to obtain the back EMF and estimate the rotor speed and position information. The phase-locked loop is improved to fix its open-loop gain and ensure the dynamic performance of the system. The simulation results show that the proposed method has good performance.

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