Research on Sensorless Control System of PMSM Based on Adaptive Fuzzy Sliding Mode Observer

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Abstract. The vector control system of permanent magnet synchronous motor needs to use encoder and other speed measuring devices, which will increase the cost of the system and bring reliability problems. In order to solve these problems, this paper proposes a sensorless control system of PMSM Based on adaptive fuzzy sliding mode observer. Firstly, in order to suppress the chattering problem of the traditional sliding mode observer, the continuous sigmoid function is used as the switching function of the sliding mode observer to improve the stability of the system. Then, the adverse effect of the fixed sliding mode gain on the system performance is analysed. Observer Combined with the fuzzy control theory, the error function is selected as the fuzzy input, the fuzzy rules are formulated, and the fuzzy controller is designed to adjust the sliding-mode gain adaptively. Finally, the simulation model of sensorless control system of PMSM is established. The simulation results verify the feasibility of the proposed scheme.

1. Introduction
Permanent magnet synchronous motor (PMSM) is widely used in electromechanical systems because of its simple structure compared with traditional electro-excited synchronous motor, which eliminates the need for collecting ring and brush, and improves the reliability of motor operation. Meanwhile, the efficiency and power density of the motor are high [1] [2] [3]. The control system of permanent magnet synchronous motor (PMSM) usually adopts speed sensor to carry out closed-loop control. However, the high precision speed sensor is expensive, which increases the volume of the system and reduces the reliability of the system. Therefore, sensorless control of PMSM has become a research hotspot [4]. At present, there are two main methods to realize sensorless control. One is the signal injection method [5,6], which uses the salient pole effect of the motor, including rotating high-frequency signal injection method and pulse vibration high-frequency signal injection method. However, the injected high-frequency signal will cause torque fluctuation of the motor. The other method is to estimate the motor speed and rotor position by using the motor counter electromotive force[7].

Signum function is used as the switching function in the traditional sliding mode observer, but the discontinuity of the switching will cause chattering in the system, which will lead to high-frequency noise in the estimation results and affect the estimation accuracy. In order to reduce chattering and improve the estimation accuracy [8] [9], a filter is added after the switching function to filter out the clutter caused by chattering, but the addition of the filter will bring about the phase delay problem and increase the estimation error. In order to solve the problem of phase delay, a phase compensation link was added to the sensorless control system [10], but the complex structure of the system reduced the
reliability of the system. The hyperbolic sine function was introduced to reduce the chattering of the system [11], but the form of this function was complex and the system was difficult to realize.

In the sensorless system of permanent magnet synchronous motor based on traditional sliding mode observer, the sliding mode gain $k$ is usually the fixed value selected in advance and does not change during the system operation. However, the observation error of current in the actual system changes, and the fixed constant cannot adapt to all situations [12]. An improved sliding mode observer is proposed for speed adaptation of switching function and low-pass filter [13], but low-pass filter is still needed to increase the complexity of the system.

Based on the traditional sliding mode observer, an adaptive fuzzy sliding mode observer is proposed to realize sensorless control system of permanent magnet synchronous motor. First, in order to suppress the sliding mode chattering problem of traditional sliding mode observer, the continuous Sigmoid function is taken as the switching function of the sliding mode observer. At the same time, considering the sliding mode in traditional sliding mode observer gain for the chattering problem brought by the fixed value system, combined with the fuzzy control, joined the sliding mode in the sliding mode observer gain dynamic adjustment link, according to the change of the system error function, fuzzy rules and fuzzy controller is designed for dynamic sliding mode gain adjustment, so as to effectively restrain the system chattering, improve the dynamic performance and the estimation precision of the system. Finally, the simulation model of sensorless control system of permanent magnet synchronous motor is established. The simulation results verify that the adaptive fuzzy sliding mode observer can effectively suppress system chattering, improve system performance and adapt to medium-high speed control.

2. Fuzzy sliding mode adaptive observer design

Due to the sensorless control system based on the traditional sliding mode observer to realize sliding mode chattering problems, to curb the sliding mode chattering, in this paper, on the basis of traditional sliding mode observer, using a Sigmoid function as a switching function, and combines the sliding mode observer and fuzzy control, this paper proposes a fuzzy adaptive sliding mode observer, is used to implement sensorless control of permanent magnet synchronous motor.

2.1. Sliding mode observer based on Sigmoid function

The mathematical model of the permanent magnet synchronous motor in the two-phase static coordinate system includes the speed and rotor position information, so the sensorless control system is designed in the two-phase static coordinate system. The equation of the permanent magnet synchronous motor in the solid-state stationary coordinate system is as follows:

$$
\begin{align*}
\dot{i}_a &= -\frac{R_s}{L_s} i_a + \frac{1}{L_s} u_a - \frac{1}{L_s} e_a \\
\dot{i}_\beta &= -\frac{R_s}{L_s} i_\beta + \frac{1}{L_s} u_\beta - \frac{1}{L_s} e_\beta
\end{align*}
$$

(1)

Where, $i_a, i_\beta$ is the stator current in the $\alpha - \beta$ coordinate system; $u_a, u_\beta$ is the stator voltage in the $\alpha - \beta$ coordinate system; $e_a, e_\beta$ for $\alpha - \beta$ coordinates counter electromotive force, including $e_a = -\omega_r q_\varphi \sin \theta_r$, $e_\beta = \omega_r q_\varphi \cos \theta_r$, $q_\varphi$ for permanent magnet flux, $\omega_r$ and $\theta_r$ are angular velocity and position of the rotor angle respectively; $R_s$ and $L_s$ are stator resistance and inductance.

When designing the sliding mode observer, the continuous function can be chosen to replace the discontinuous switch function Sign function as the switching function. Since the continuous function has a boundary layer of a certain thickness, the system is equivalent to normal sliding mode control when it is outside the boundary layer, while the system is switched to continuous state feedback control when it is inside the boundary layer, which can effectively avoid or weaken chattering.

Based on the above analysis, the fuzzy slide-mode adaptive observer uses the continuous and strictly monotone Sigmoid function as the switching function. According to the current equation of permanent magnet synchronous motor, the sliding mode observer is:
\[ \begin{align*}
\dot{i}_a &= -\frac{R}{L} \dot{i}_a + \frac{1}{L} u_a - \frac{1}{L} kF (i_a - \bar{i}_a) \\
\dot{i}_\beta &= -\frac{R}{L} i_\beta + \frac{1}{L} u_\beta - \frac{1}{L} kF (i_\beta - \bar{i}_\beta)
\end{align*} \]  \tag{2}

Where, \( k \) is sliding-mode gain coefficient, \( F(x) \) is Sigmoid function, and its expression is as follows:
\[ \begin{bmatrix}
F(i_a - \bar{i}_a) \\
F(i_\beta - \bar{i}_\beta)
\end{bmatrix} = \begin{bmatrix}
\frac{2}{1 + e^{-\alpha x_a}} - 1 \\
\frac{2}{1 + e^{-\alpha x_\beta}} - 1
\end{bmatrix} \]  \tag{3}

Where, \( \alpha \) is the slope coefficient of Sigmoid function, which controls the boundary layer thickness of Sigmoid function, and its function image is shown in figure 1.

![Sigmoid function image](image)

**Figure 1.** Sigmoid function image

The stability of sliding mode observer is analyzed by using lyapunov stability theorem. Firstly, equation (2) is subtracted from equation (1) to obtain the error equation of current estimation as follows:
\[ \begin{align*}
\dot{\bar{i}}_a &= -\frac{R}{L} \bar{i}_a + \frac{1}{L} e_a - \frac{1}{L} kF (\bar{i}_a) \\
\dot{\bar{i}}_\beta &= -\frac{R}{L} \bar{i}_\beta + \frac{1}{L} e_\beta - \frac{1}{L} kF (\bar{i}_\beta)
\end{align*} \]  \tag{4}

Where \( \bar{i}_a = \hat{i}_a - i_a, \bar{i}_\beta = \hat{i}_\beta - i_\beta \) is the current estimation error.

The sliding-mode observer surface \( S_n \) is selected as the error value of \( \alpha - \beta \) current estimation:
\[ S_n = \begin{bmatrix} s_a & s_\beta \end{bmatrix} = \begin{bmatrix} \bar{i}_a & \bar{i}_\beta \end{bmatrix}^T \]  \tag{5}

According to the lyapunov stability theorem, when the lyapunov equation satisfies \( V < 0, V > 0 \), the system is asymptotically stable. The selected lyapunov function is as follows:
\[ V = \frac{1}{2} S_n^T S_n \]  \tag{6}

Take the derivative of equation (6), and can get
\[ \dot{V} = S_n^T \dot{S}_n = \bar{e}_a \dot{i}_a + \bar{e}_\beta \dot{i}_\beta \]  \tag{7}

By substituting equation (4) into equation (7), we can obtain
\[ \begin{align*}
\dot{V} &= -\frac{R}{L} S_n^T (\bar{T}_a^2 + \bar{T}_\beta^2) + \frac{1}{L} \bar{i}_a (e_a - kF(\bar{T}_a)) + \frac{1}{L} \bar{i}_\beta (e_\beta - kF(\bar{T}_\beta))
\end{align*} \]  \tag{8}

Since the range of Sigmoid function \( F(x) \) is \([-1, 1]\), from the stability condition \( V < 0 \), it can be deduced that sliding mode gain \( k \) should satisfy the following conditions:
In general, a larger fixed value of sliding-mode gain $k$ can be selected to satisfy the stability, but the ideal control effect cannot be achieved. When system is in sliding mode, if the absolute value of error between real and estimated values of $|s|$ large system away from the sliding mode surface, at this time should enter a larger amount of control, the system can quickly close to sliding mode surface, improve the dynamic response of the system, and as $|s|$ is lesser, near system in sliding mode surface, is in the steady state work condition, at this time, amount of control input is too big, the system will be near the sliding mode surface, namely appear sliding mode chattering phenomenon, thus to restrain the chattering, should decrease system input control.

The direction of the system input control quantity can be realized through the Sigmoid function, and the size of the control quantity depends on the size of the sliding-mode switch increment. Therefore, the sliding mode gain $k$ can be adaptive adjusted according to the variation of error value $s$.

2.2. Sliding mode gain adaptive adjustment based on fuzzy control

Because fuzzy control does not need to establish an accurate mathematical model of the controlled object in the design, the design is simple and easy to apply, so the sliding-mode observer is combined with fuzzy control to realize sliding-mode gain adaptive adjustment.

According to the above analysis, combined with the fuzzy control strategy, when $s$ is a large positive value, the sliding-mode gain $k$ should be large, and when $s$ is a small positive value, the sliding-mode gain $k$ should be small. Similarly, when $s$ is a large negative value, the sliding-mode gain $k$ should be large, and when $s$ is a small negative value, the sliding-mode gain $k$ should be small. The error $s$ is selected as the input of fuzzy control, and the scaling factor of sliding mode gain $k$ is taken as the output, denoted as $u$. The field of the input variable is defined as $[-3, 3]$, and the field of the output variable is defined as $[0.5, 1]$.

Define the fuzzy language variables of input and output variables, where the fuzzy language values of input variables are \{NB(negative large), NM(negative medium), ZE(zero), PM(middle), PB(large)\}, and output variables are \{PS(positive small), PM(middle), PB(large)\}.

According to the fuzzy subset defined by the fuzzy controller in the input/output domain, the membership function of input/output can be designed. The membership function of input/output is shown in figure 2 and figure 3.

**Figure 2.** Fuzzy input membership function

**Figure 3.** Fuzzy output membership function

The fuzzy controller is designed by using Mamdani type fuzzy logic reasoning, with a total of five fuzzy language rules. The reasoning form is as follows:

1. IF the input error $s$ is NB, THEN the output scaling factor $u$ is PB.
2. IF the input error $s$ is NM, THEN the output scaling factor $u$ is PM.
3. IF the input error $s$ is ZE, THEN the output scaling factor $u$ is PS.
4. IF input error $s$ is PM, THEN output scaling factor $u$ is PM.
5. IF the input error $s$ is PB, THEN the output scaling factor $u$ is PB.
Finally, the center of gravity method is adopted to deblur, and the transformation from fuzzy quantity to precise quantity is completed, and the sliding-mode gain scaling factor is output to realize the dynamic adjustment of sliding-mode gain k. The improved principle block diagram is shown in figure 4.

\[ \begin{bmatrix} \dot{s}_a \\ \dot{s}_\beta \end{bmatrix} = \begin{bmatrix} s_a \\ s_\beta \end{bmatrix} = [0 \ 0] \]

According to the equivalent control method, the expression of the inverse electromotive force containing the information of the rotating speed and rotor position can be obtained as follows:

\[ e_a = kF (\dot{i}_a - i_a), e_\beta = kF (\dot{i}_\beta - i_\beta) \]

By using the estimated counter electromotive force, the rotor angular velocity and position can be calculated with the following formula:

\[ \dot{\theta} = -\tan^{-1} \left( \frac{e_a}{e_\beta} \right) \]

\[ \dot{\omega} = \frac{d\dot{\theta}}{dt} \]

The sensorless control system of PMSM with fuzzy sliding-mode adaptive observer is shown in figure 5.

2.3. Speed and rotor position estimation

When the system reaches the sliding surface, the state of the system can be described as:

\[ \begin{bmatrix} \dot{s}_a \\ \dot{s}_\beta \end{bmatrix} = \begin{bmatrix} s_a \\ s_\beta \end{bmatrix} = [0 \ 0] \]

According to the equivalent control method, the expression of the inverse electromotive force containing the information of the rotating speed and rotor position can be obtained as follows:

\[ e_a = kF (\dot{i}_a - i_a), e_\beta = kF (\dot{i}_\beta - i_\beta) \]

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The sensorless control system of PMSM with fuzzy sliding-mode adaptive observer is shown in figure 5.

3. Simulation and result analysis

In order to verify the feasibility and effectiveness of the designed system, Matlab/Simulink software was used for simulation verification. The selected PMSM parameters are shown in the table 1:

| Items                  | Value          |
|------------------------|----------------|
| Input voltage (DC)     | 220v           |
| Stator resistance $R_s$| 2.875Ω         |
| Inductance $L_d, L_q$  | 8.5mH          |
| The moment of inertia $J$ | 0.001kg·m²    |
| Rotor flux $\phi_r$    | 0.175Wb        |
| number of pole-pairs   | 4              |
In order to show in this paper, the proposed adaptive fuzzy sliding mode observer control effect, the traditional sliding mode observer is compared. Motor control system using vector control strategy of $i_d = 0$, speed through the speed and current double closed-loop structure, build the sensorless control of permanent magnet synchronous motor system is shown in figure 6.

**Figure 6.** Sensorless control system of permanent magnet synchronous motor

Aiming at 1000 r/min speed starting from zero speed in simulation, the simulation results are shown in figure 7, contrast figure 7(a) and figure 7(b), the use of traditional sliding mode observer, the system of the sliding mode chattering phenomenon is obvious, as chattering system takes 0.012s to achieve stability, speed estimation error in $-10 \text{r/min} - 10 \text{r/min}$, estimation precision is poor; When the adaptive fuzzy sliding mode observer is used, the chattering suppression effect is obvious. There is no high-frequency noise in the estimated value of the motor speed, and the estimated error is 0.38r/min. The estimation accuracy is high, which only needs 0.005s to achieve stability, effectively improving the dynamic performance of the system.

(a) Motor speed estimates comparison

(b) Motor speed estimation error comparison
As for the rotor position estimation, it can be seen from the comparison of figure 7 (c) that the estimated value can also effectively track the actual value at the beginning of the operation of the improved system. By comparing the experimental results, the adaptive fuzzy sliding mode observer has higher estimation accuracy than the traditional sliding mode observer, and has obvious suppression effect on chattering.

In order to further analyze the situation of the adaptive fuzzy sliding mode observer in the full speed range, multiple experiments were carried out with the interval of 100r/min and the target speed from 100-2000r/min, and the rise time, overshoot and steady-state error of each experimental system were recorded. The data results are shown in the table 2:

Table 2. Experimental data sheet

| Target Speed | Rise Time (10-3s) | Overshoot | Steady State Error (r/min) |
|--------------|------------------|-----------|---------------------------|
| 100          | 0.469            | 71.2%     | 0.05                      |
| 200          | 0.700            | 37.1%     | 0.20                      |
| 300          | 0.934            | 23.5%     | 0.50                      |
| 400          | 1.183            | 15.58%    | 0.80                      |
| 500          | 1.447            | 11.66%    | 0.12                      |
| 600          | 1.725            | 10.7%     | 0.20                      |
| 700          | 2.013            | 7.90%     | 0.25                      |
| 800          | 2.313            | 6.30%     | 0.30                      |
| 900          | 2.621            | 5.41%     | 0.40                      |
| 1000         | 2.938            | 4.10%     | 0.50                      |
| 1100         | 3.223            | 3.45%     | 0.60                      |
| 1200         | 3.511            | 3.67%     | 0.75                      |
| 1300         | 3.929            | 2.85%     | 0.80                      |
| 1400         | 4.269            | 2.57%     | 1.00                      |
| 1500         | 4.614            | 2.13%     | 1.20                      |
| 1600         | 4.964            | 1.19%     | 1.35                      |
| 1700         | 5.314            | 1.76%     | 1.50                      |
| 1800         | 5.676            | 1.38%     | 1.70                      |
| 1900         | 6.053            | 1.21%     | 1.80                      |
| 2000         | 6.439            | 1.05%     | 2.00                      |

As can be seen from table 2, with the increase of target speed, the system rise time increased from 0.469×10-3s to 6.439×10-3s, the overshoot decreased from 71.2% to 1.05%, and the steady-state error increased from 0.05r/min to 2.00r/min. Since the experiment starts from zero speed, the time required for the system to reach the target speed will gradually increase after the set target speed increases. Therefore, although the rise time is increasing, it can still be considered that the dynamic response...
performance of the system does not change much. When starting at a low speed (100-700r/min), the system overshoot is very large and needs to be adjusted several times to achieve stability. At this point, the system will have a shock. However, when the system is running at high speed (1600-2000r/min), the rotational speed error when it reaches steady state is relatively large and the control precision is not high. However, in medium-high speed operation (800-1500r/min), the overshoot is relatively small and the steady-state error is relatively small, so the system can obtain a good control effect.

4. Conclusion

In this paper, based on the traditional sliding mode observer and aiming at the chattering problem in sensorless control system, a sensorless control system of permanent magnet synchronous motor based on fuzzy sliding mode adaptive observer is proposed, and detailed simulation verification is carried out to obtain the following conclusions:

1) using the continuous Sigmoid function as the switching function in the sliding mode observer can eliminate the low-pass filter and phase compensation link, reduce the complexity of the system, effectively suppress the chattering of the system, and improve the estimation accuracy of the speed and rotor position.

2) Analysis of the sliding mode in traditional sliding mode observer gain for the bad effect brought by the fixed value, combines fuzzy control and sliding mode observer, selection of error function as the input of the fuzzy controller, the sliding mode gain coefficient as output, fuzzy rules and fuzzy controller is designed to carry on the dynamic adjustment, the sliding mode gain can improve the static and dynamic response performance of system.

3) In the matlab/simulink to establish a permanent magnet synchronous motor based on fuzzy adaptive sliding mode observer for sensorless control system simulation model and simulation experiment, the experimental results were compared with the traditional sliding mode observer, the results show that the proposed method can effectively restrain the system chattering and improve the observation accuracy, can improve the performance of the sensorless control system. The simulation results of the sensorless control system show that the proposed adaptive fuzzy sliding mode observer has better control effect at medium and high speed.

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