Research on Improved Static Compensation Flux Error MARS Observer Based on SMC

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Abstract: Aiming at the integral drift and saturation problems of the traditional voltage model flux observer, an improved rotor flux observation scheme is proposed. A programmable low-pass filter is used to replace the pure integrator, and the flux error before the filter is corrected. The sliding mode speed controller is used to replace the traditional PI speed controller. The proposed observer can reduce the speed response overshoot of the system at medium and high speed range, reduce the steady-state time, and improve the load capacity and robustness of the system. The simulation results show the effectiveness of the algorithm.

1. Introduction
Induction motors are widely used in practice because of their simple structure, robustness, and low cost. The induction motor speed control system based on vector control strategy can achieve the same performance as the DC speed control system. With the higher requirements of industrial production on system volume, cost, reliability, etc., the speed sensorless control technology of induction motors has gradually become the focus of academic research.

At present, the speed sensorless induction motor is mainly divided into V/F control, vector control and DTC control. Vector control has been widely used due to its good dynamic energy. The speed observation method based on the motor model in vector control includes the open-loop model method and the closed-loop model method. In the open-loop model method, the obvious defect of the current model is that the estimation result depends heavily on the rotor time constant Tr. When Tr has a deviation, it will directly lead to inaccurate field orientation. The voltage model does not need to use speed information, and has little dependence on the motor rotor parameters. However, the voltage model depends on the stator parameters. Especially at low speeds, the motor stator voltage value is small, which is sensitive to the electronic stator resistance parameters. Moreover, due to the use of pure integrators, there are temperature drift and integral saturation problems, which affect the observation of the flux linkage. The closed-loop model method introduces state variables as feedback items to improve the stability and robustness of the system. Model reference adaptive method [1] has strong anti-interference ability, but parameter identification and correction are often needed in the system to improve robustness. The sliding mode observer has a simple structure, is easy to implement, and has strong robustness, but there is a serious chattering phenomenon, and its application range is limited [2]. The extended Kalman filter has high observation accuracy, fast convergence speed, and strong anti-interference ability, but the calculation is more complicated, and it is not widely used in actual industrial production [3]. The full-order observer uses the induction motor model as a reference model, designs an
adjustable model according to the induction motor model, and uses the output state difference between the models as a feedback signal to observe the motor speed [4]. The full-order observer has the characteristics of strong anti-noise interference ability and has been widely used. At present, the possibility of unstable regions in low-speed conditions is a key issue to be solved by this method.

The traditional voltage model is simple, and the speed estimation accuracy is not high. In order to improve the accuracy of the voltage model to estimate the speed, an improved MRAS observer based on the series filter of the static compensation voltage model is designed. In order to improve the high-speed dynamic performance and steady-state performance of the MRAS observer, a sliding mode speed controller [5] was designed to replace the traditional PI speed controller. The effectiveness of this method can be seen through the simulation of speed following, sudden change of speed and load capacity through the built model.

2. Asynchronous motor model

According to the inverse Γ-type steady-state equivalent circuit as shown in Figure 1, the mathematical model under the two-phase stationary coordinate system can be established as shown in equations (1) and (2):

\[
L_s \frac{di_s^*}{dt} = v_s^* - R_s i_s^* - \frac{d\psi_r^*}{dt}
\]

\[
\frac{d\psi_r^*}{dt} = R_s i_s^* - (a - j\omega_r)\psi_r^*
\]

\(a\) is the rotor time constant; \(v_s^*\) is the stator voltage; \(i_s^*\) is the stator current; \(R_s\) is the stator resistance; \(\psi_r^*\) is the rotor flux; \(\omega_r\) is the rotor speed. \(R_s = \left( L_m / L_r \right)^2 R_s\) is the rotor resistance; \(L_M = L_m^2 / L_r\) is the mutual inductance and \(L_s = L_s - L_M\) is total leakage inductance.

\[\text{Figure 1 inverse } \tau \text{ steady-state equivalent circuit.} \]

\[\text{Figure 2 vector control block diagram.}\]

Transform (1) and (2) into a synchronous d-q coordinate system (where the space vector is not superscripted, and the following equation is obtained:

\[
L_d \frac{di_s}{dt} = v_s - (R_s + j\omega_L) i_s - j\omega_L \omega_r i_s - \frac{d\psi_r}{dt}
\]

\[
\frac{d\psi_r}{dt} = R_s i_s - \left[ a + j(\omega_r - \omega_s) \right] \psi_r
\]

The electromagnetic torque and motion equation of the asynchronous motor are:

\[T_e = \frac{3n_p}{2} \text{Im}(\psi_r i_s^*)\]
In formulas (4), (5), (6), $\omega_1$ is the synchronous angular velocity; $n_p$ is the number of pole pairs of the motor; $\psi_R^*$ is the conjugate of the rotor flux linkage; $J$ is the moment of inertia; $T_L$ is the load torque.

3. Low-pass filter voltage model flux linkage error MRAS observer design

3.1. Voltage model

For the traditional voltage model, the actual value of the motor parameters is replaced by the model estimated value parameters, and the realizing formula of direct magnetic field orientation can be obtained. We take $\hat{E} = d\hat{\psi}_R^* / dt$, then

$$\hat{E} = v_s - \hat{R}_d i_d - \hat{L}_d i_s / dt$$

The flux linkage estimation in Cartesian coordinate system can be obtained $\hat{\psi}_R^* = \hat{\psi}_a + j\hat{\psi}_b$.

It is assumed that the current response time established by the current control loop is much shorter than the response time of the magnetic flux., i.e. $di_s / dt = 0$.

Transform (7), with $\hat{E} = e^{j\theta}\hat{E}_d, \hat{\psi}_R^* = e^{j\theta}\hat{\psi}_R$, into the synchronous coordinate system. According to the previous analysis hypothesis of the article, we can get equations (8) and (9).

$$\frac{d\hat{\psi}_R^*}{dt} + j\frac{d\hat{\theta}}{dt}\hat{\psi}_R = \hat{E}$$

$$\hat{E} = v_s - (\hat{R}_d + j\omega L_d)i_s$$

Expand (7) and (8) to get:

$$\frac{d\hat{\psi}_R^*}{dt} = \hat{E}_d$$

$$\frac{d\hat{\theta}}{dt} = \omega_1 = \frac{\hat{E}_q}{\hat{\psi}_R}$$

where $\hat{E}_d = v_d - \hat{R}_d i_d + \omega L_d i_q, \hat{E}_q = v_q - \hat{R}_d i_q + \omega L_d i_d, i_s = i_s + j i_q, \hat{E} = \hat{E}_d + j\hat{E}_q$.

The estimated value of the rotor flux linkage can be obtained by integrating the back electromotive force, but this method of directly using a pure integrator cannot ensure that the motor remains stable in all operating ranges. In the low speed area, the observed flux linkage value is compared with the true value. The error is large.

3.2. Programmable low-pass filter flux observation

In order to ensure the accuracy of the rotor flux estimation, the method of adding a low-pass filter was chosen to replace the pure integral link. The back EMF before compensation is $\hat{E}$, and the back EMF after compensation is $\hat{E}'$.

$$\hat{\psi}_R = \hat{E} / s = \hat{E}' / (s + \omega_c)$$

Where $\omega_c$ is the cut-off frequency of the low-pass filter. Substitute $\omega_c = \lambda |\omega|$ and $s = j\omega$ into equation (11) to get the compensated back EMF:

$$\hat{E}_{ra} = \hat{E}_{ra} + \lambda \hat{E}_{r\beta} \text{sign}(\omega)$$

$$\hat{E}_{r\beta} = \hat{E}_{r\beta} + \lambda \hat{E}_{ra} \text{sign}(\omega)$$

Equations (12) and (13) are the back EMF after compensation. The synchronous angular frequency of the motor can be expressed by the following formula:
4. Design of sliding mode speed controller

The fundamental difference between sliding mode variable structure control and conventional control methods lies in the discontinuity of control, that is, a switching characteristic that makes the "structure" of the system change at any time, so that the system can perform small amplitude and high frequency move up and down along a specified state track under certain conditions. This sliding mode can be designed and has nothing to do with system parameters and disturbances. So that the system has good robustness. In this paper, the sliding mode control theory is used in the design of the flux linkage observer. A new type of rotor flux linkage error MARS observer is proposed. The observer has a simple structure and is easy to implement. Using it in the speed sensorless control system of induction motors improves the robustness and observation accuracy of the flux linkage and speed, effectively reduces torque ripple, expands the speed regulation range, and improves the speed regulation performance.

We define the error \( e_\omega \) between the given speed and the estimated speed. In the traditional PI current regulator,

\[
i_{qk} = K_1 e_\omega + K_2 \int e_\omega
\]

Define the sliding mode surface function: \( z_\omega = \omega'_\omega - \omega_\omega \), then the sliding mode PI current regulator

\[
i_{qk} = K_1 e_\omega + K_2 \int e_\omega + K_3 \text{sign}(e_\omega)
\]

Use the Lyapunov stability theorem to verify whether the sliding mode controller is stable, and define the Lyapunov function \( V \) as follows:

\[
V = z^2_\omega
\]

Derivation of \( V \) can be obtained:

\[
\frac{dV}{dt} = -\frac{3n^2_p L_m}{JL_r} \psi_r z^2_\omega - \frac{3n^2_p L_m}{JL_r} \psi_r K_2 z\omega_\omega \text{sgn}(z_\omega) + 2\left( \frac{d\omega'_\omega}{dt} + \frac{n_p}{J} T_L \right) z_\omega
\]

As long as the design is reasonable, the Lyapunov stability theorem can be satisfied, the system is gradually stable, and the estimated speed is consistent with the given speed.

5. System simulation and result analysis

Build a model in MATLAB/Simulink environment to simulate and verify the designed sliding mode speed controller. The simulation model uses vector control based on rotor field orientation, the "speed loop" uses a sliding mode PI controller, and the current loop uses a traditional PI controller. The vector control block diagram of the asynchronous motor without speed sensor is shown in Figure 2. The rated power of the motor is 2.2KW, rated voltage is 380V, rated frequency is 50Hz, rated speed is 1430r/min, stator resistance is 2.804Ω, rotor resistance is 2.178Ω, stator inductance is 0.3303H, rotor inductance is 0.3303H, excitation The mutual inductance is 0.3197H, the number of pole pairs is 4, the moment of inertia is 0.03 kg*m^2, and the rated torque is 14.7N·m. In the simulation, the m file is used to build the system, and the whole system is discretized. When discretizing, each variable is standardized. The reference values of voltage, current, and speed are 310V, 6.9A, and 1500r/min, respectively.

Figure 3 and Figure 4 respectively show the dynamic response of the system speed response of the normal PI and sliding mode PI control of the motor with a rated load and a speed of 0.8 pu (1200r/min).
Figure 3 estimated speed of traditional PI control.  Figure 4 estimated speed of SMC PI control.

It can be seen from Figure 3 and Figure 4 that the speed overshoot of the traditional PI control is 23.1%, and the speed overshoot of the sliding mode PI control is 18.4%, and the overshoot is reduced. The time for the latter to enter the steady state value is 1.41s, the time for the former is 1.64s, and there is a certain amount of overshoot. When the rated load is suddenly applied at 2s, the speed drop of sliding mode PI control is smaller than that of traditional PI control, and it returns to the steady state value at 2.26s. The time is shorter than that of traditional PI control, and it has a strong load capacity.

The given speed is 750r/min, that is, 0.5pu, and the pre-excitation setting is performed 1s before. After 1s, the motor starts without load, and the load torque is 7.35N·m at 2s. The dynamic response of system speed based on traditional PI and sliding mode PI control is shown in Figure 5 and Figure 6.

Figure 5 estimated speed of traditional PI control.  Figure 6 estimated speed of SMC PI control.

It can be seen from Figure 5 and Figure 6 that the speed overshoot of the traditional PI control is 32%, and the speed overshoot of the sliding mode PI control is 26%, and the overshoot is reduced. The time for the latter to enter the steady state value is 1.3s, and the time for the former is 1.5s, and there is a certain amount of overshoot. When half load is suddenly added at 2s, the speed drop of sliding mode PI control is smaller than that of traditional PI control, and it returns to the steady state value at 2.24s. The time is shorter than that of traditional PI control, and it has a strong load capacity.

Figure 7 and Figure 8 show the speed response of the motor from forward rotation to reverse rotation under half load (7.35N·M). Pre-excitation setting is performed 1 second before. The motor starts without load after 1 second, and adds half load at 2 seconds. At 3 seconds, the motor is switched from forward rotation to reverse rotation, and the given speed is switched from 1200r/min to -750r/min.
It can be seen from Figure 7 and Figure 8 that the speed response before 3s, the sliding mode PI control is less than the traditional PI control whether it is overshoot or the time to enter the steady state value. After 3s, the rotation speed is switched between forward and reverse. The time for sliding mode PI control to enter -0.5pu is 3.4s, and the time for traditional PI control to enter -0.5pu is 3.6s, indicating that this method has good adaptive ability.

6. Conclusion

Aiming at the shortcomings of the traditional voltage model with low-pass filter to identify the speed accuracy, poor dynamic performance at medium and high speeds, and long steady-state time, this paper proposes a flux linkage of an asynchronous motor based on sliding mode control and a low-pass filter. Observer. This method replaces the pure integration link with a programmable low-pass filter whose cut-off frequency is adjusted with the synchronization angle frequency, and adopts an algorithm that compensates first and then low-pass filter. And the use of sliding mode PI in the speed regulator instead of traditional PI can reduce the overshoot of the speed response at medium and high speeds, reduce the steady-state time, and improve the accuracy of speed identification. The simulation results show that the designed flux observer based on sliding mode control of asynchronous motor and low-pass filter has good steady-state performance and dynamic performance.

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