Research on Model Predictive Control Based on Sensorless Permanent Magnet Synchronous Motor

Shengwen Fan¹²³,a, Xinsen Zhang²,b, Chaonan Tong¹,c
¹University of Science and Technology Beijing, Beijing, China
²North China University of Technology, Beijing, China
³Collaborative Innovation Center of Key Power Energy-Saving Technologies, Beijing, China

ABSTRACT: For permanent magnet synchronous motor (PMSM) speed control system, aiming at the problems of slow dynamic response and large dependence on system model parameters of traditional PI control of PMSM, the model predictive current control strategy is adopted to design the predictive model. Aiming at the problems of poor reliability and high cost of traditional permanent magnet synchronous motor with mechanical sensor, the speed sensorless control technology is introduced to design the control structure, and the rotor position and speed are estimated by sliding mode observer method. Through simulation verification, the results show that the combination of the above two control methods can obviously improve the performance of the traditional permanent magnet synchronous motor control system, and has strong robustness under the conditions of motor parameters and load changes.

1. Introduction

With the high development of power electronics technology, motor system control and new permanent magnet materials in recent years, AC speed control technology has made great progress, and its dynamic and static characteristics have been completely close to or even better than DC servo system. In the field of modern AC servo control, permanent magnet synchronous motor is being favored more and more widely. And its development has reached a new height with the continuous improvement of the performance of new permanent magnet materials. Although the control technology of permanent magnet synchronous motor has made great progress with the passage of time, there are still some shortcomings in practical application. Therefore, it is of great practical value to study and improve the high-performance permanent magnet synchronous motor system.

Traditional permanent magnet synchronous motor control system with mechanical sensor reduces the anti-interference ability and reliability of motor control system due to the installation of mechanical sensor[1]. In addition, the cost of the system is increased and the complexity is increased. Therefore, in order to solve these problems, this paper studies the sensorless control technology. The application of sensorless control method can reduce the cost of permanent magnet synchronous motor and enhance the reliability and anti-interference ability of PMSM control system in actual operation.

Rotor position and speed estimation is the key of sensorless control technology, and the advantages and disadvantages of the system lie in estimation accuracy and dynamic response speed. Sensorless control of permanent magnet synchronous motor mainly includes high frequency injection method,
model reference adaptive method and sliding mode observer method. The high-frequency injection methods mentioned in reference [2] can be divided into two types: high-frequency pulse voltage injection method and high-frequency rotating voltage injection method. The detection of stator current by pulse voltage injection method is completed by injecting a certain voltage pulse into the stator winding of the motor, and then the stator inductance value and the initial position of the rotor are obtained. This method can be used for surface mounted and embedded motors; High-frequency rotating voltage injection method is divided into voltage and current high-frequency carrier, which is widely used at present, but it is only suitable for salient-pole permanent magnet synchronous motor, not for hidden-pole permanent magnet synchronous motor [2]. Model reference adaptive method is mainly to find a reference model and an adjustable model. The reference model contains known parameters, while the adjustable model contains parameters to be estimated. The output value of the adjustable model is the same as that of the reference model through regulation, so that the adjustable model can observe the state to be observed. At this time, the amount to be estimated in the adjustable model approaches the actual value. The reference model of permanent magnet synchronous motor is the motor body, the adjustable model is the current model of the motor, and the parameter to be estimated is the back electromotive force of the motor. The reference model mentioned in the literature [3] is based on the fundamental wave model of the motor, which is more dependent on the motor parameters. When the motor runs, the related parameters will be uncertain, and the position and speed estimated by the model reference adaptive method will be inaccurate, especially at low speed [3]. The sliding mode observer uses symbolic function as the structural adjustment function. Using the estimation error to adjust the structure continuously, the estimation error converges to zero in real time, which makes the system respond faster and have better performance. It has the advantages of simple algorithm and easy implementation in engineering, so this paper adopts the synovial observer algorithm.

Traditional permanent magnet synchronous motor control systems mostly adopt speed loop as the outer control loop and current loop as the inner control loop, and the design of current loop controller is mostly based on traditional PI regulation control, which has the advantages of simple structure and easy engineering implementation, but the disadvantage is that parameter setting depends on personal experience, and PI control still has some problems such as slow dynamic response and large dependence on system model parameters [5][6]. Therefore, to solve these problems, the model predictive control (MPC) method is introduced in this paper. MPC obtains the optimal solution among the control variables of the system through rolling optimization and feedback correction. Compared with vector control, it has simplified structure, no need of inner loop setting and coordinate transformation, and fast dynamic response.

Model predictive control can be divided into current predictive control (MPCC) and torque predictive control (MPTC) according to control variables. Compared with MPTC's control variables, such as electromagnetic torque and stator flux linkage, which need to design the weight coefficient in the objective function, MPCC takes the stator current of motor as the control variable, so there is no need to design the weight coefficient in the objective function. Therefore, this paper adopts the model current predictive control strategy.

2. Mathematical model of permanent magnet synchronous motor
According to the synchronous rotating coordinate system, the ideal mathematical model of permanent magnet synchronous motor can be expressed as:

\[
\begin{align*}
U_s &= R_s i_s + \frac{d\varphi_s}{dt} + j\omega\varphi_s \\
\varphi_s &= (L_d i_d + \varphi_f) + jL_q i_q \\
T_e &= \frac{3}{2} P (\varphi_s \odot i_d)
\end{align*}
\]  

(1)

In the above formula, \(U_s\) is the stator voltage; \(\varphi_s\) is stator flux linkage; \(T_e\) is electromagnetic torque; \(R_s\) is the stator resistance; \(\varphi_f\) is the permanent magnet flux linkage; \(i_s\) is the stator current; \(i_d\) and \(i_q\) are
d-axis current and q-axis current respectively; \( L_d \), \( L_q \) are d-axis inductance and q-axis inductance respectively; \( \omega \) is the rotational speed; \( P \) is the extreme logarithm.

In this paper, the surface-mounted permanent magnet synchronous motor is taken as the research object, and the inductance can be simplified as \( L_d = L_q = L \). According to formula (1), the current state space equation is obtained with the stator current as the state variable:

\[
\frac{di_s}{dt} = \frac{u_s - R_i i_s - \omega (L_i s + \varphi_f)}{L}
\]

(2)

3. Current predictive control algorithm

The current state space equation (2) is discretized by forward Euler method

\[
i_{s}^{k+1} = i_{s}^{k} + T_s * (u_{s} - R_i i_{s} - \omega L_i s - \omega \varphi_f)/L
\]

(3)

The objective function is constructed with the goal of minimizing the tracking error of the control current vector:

\[
g = |i_{s}^{*} - i_{s}^{k+1}|
\]

(4)

In which the current reference value \( i_{s}^{*} = 0 + j i_{q}^{*} \). Among them, torque current comes from PI regulator of speed outer loop, and excitation current \( i_{q}^{*} = 0 \).

Two-level voltage source inverter has seven different voltage vectors corresponding to eight switching states. The core idea of the current predictive control algorithm of permanent magnet synchronous motor is: first, according to the stator current predictive formula, predict the corresponding stator current under different voltage vectors, then calculate the corresponding objective function value, and compare it to get the voltage vector corresponding to the minimum \( g \) value as the optimal output.

4. Synovial observer algorithm

According to the mathematical model of permanent magnet synchronous motor in two-phase static coordinate system, the motor current state equation is obtained:

\[
\begin{align*}
\frac{di_A}{dt} &= -\frac{R_i}{L_s} i_A + \frac{1}{L_s} u_A - \frac{1}{L_s} e_A \\
\frac{di_B}{dt} &= -\frac{R_i}{L_s} i_B + \frac{1}{L_s} u_B - \frac{1}{L_s} e_B
\end{align*}
\]

(5)

Back electromotive force equation:

\[
\begin{align*}
e_A &= -\psi_f \omega s i n \theta \\
e_B &= \psi_f \omega c o s \theta
\end{align*}
\]

(6)

The definition of sliding mode switching function is based on the basic principle of sliding mode variable structure control, and is defined as follows:

\[
s(x) = \begin{bmatrix}
\hat{i}_A - i_A \\
\hat{i}_B - i_B
\end{bmatrix}
\]

(7)

Where \( \hat{i}_A, \hat{i}_B \) is the observed value of sliding mode observer. While \( i_A, i_B \) is the measured value, the switching surface is composed of the error between the measured value and the observed value, which is \( s(x) = 0 \). According to the sliding mode observation theory, the control strategy adopts the switching rule of constant switching \( u = k_s \text{sign}(x) \). In which \( \text{sign}(x) \) is a symbolic function. The sliding mode current observer is constructed as follows:
Among them, the current error switching signal is $Z\alpha = k_\alpha \text{sign}(\hat{i}_\alpha - i_\alpha)$ $Z\beta = k_\beta \text{sign}(\hat{i}_\beta - i_\beta)$, which is the estimated value of back EMF, and the value of switching gain of sliding mode observer must meet the requirements of sliding mode accessibility and existence.

The differential equation of estimated current of motor stator can be obtained from formulas (5) and (8):

$$\begin{align*}
\frac{di_\alpha}{dt} &= -\frac{R_s}{L_s} \hat{i}_\alpha + \frac{1}{L_s} e_\alpha - \frac{k_s}{L_s} \text{sign}(\hat{i}_\alpha) \\
\frac{di_\beta}{dt} &= -\frac{R_s}{L_s} \hat{i}_\beta + \frac{1}{L_s} e_\beta - \frac{k_s}{L_s} \text{sign}(\hat{i}_\beta)
\end{align*}$$

Sliding mode exists and is stable, that is, when $t$ tends to $\infty$, $s(x)=0$, defining Lyapunov function $V = \frac{1}{2}s^2$, according to stability theory, it should satisfy:

$$V_{\dot{s}} = \frac{1}{2} (\dot{i}_\alpha \dot{i}_\alpha + \dot{i}_\beta \dot{i}_\beta) < 0$$

That is, when $\dot{i}_\alpha \dot{i}_\alpha < 0$ and when $\dot{i}_\beta \dot{i}_\beta < 0$, the sliding mode observer slides the mode, it is deduced that:

$$\begin{align*}
\dot{i}_\alpha \dot{i}_\alpha &= \frac{\tau}{L_s} [-R_s \hat{i}_\alpha + e_\alpha - k_s \text{sign}(\hat{i}_\alpha)] \\
&= \left\{ \begin{array}{ll}
\frac{\tau}{L_s} [(e_\alpha - k_s) - R_s \hat{i}_\alpha], & \dot{i}_\alpha > 0 \\
\frac{\tau}{L_s} [(e_\alpha + k_s) - R_s \hat{i}_\alpha], & \dot{i}_\alpha < 0
\end{array} \right. \\
\dot{i}_\beta \dot{i}_\beta &= \frac{\tau}{L_s} [-R_s \hat{i}_\beta + e_\beta - k_s \text{sign}(\hat{i}_\beta)] \\
&= \left\{ \begin{array}{ll}
\frac{\tau}{L_s} [(e_\beta - k_s) - R_s \hat{i}_\beta], & \dot{i}_\beta > 0 \\
\frac{\tau}{L_s} [(e_\beta + k_s) - R_s \hat{i}_\beta], & \dot{i}_\beta < 0
\end{array} \right.
\end{align*}$$

According to formula (11), the value range is: $k_s > \max(|e_\alpha|, |e_\beta|)$

Because of the application of high-frequency switching function, the output back electromotive force is a high-frequency discontinuous signal, which leads to some distortion, so it can not be directly used to calculate the rotor position and speed. In order to filter higher harmonics to obtain continuous equivalent signals, the low-pass filter model with high cut-off frequency is introduced as follows:

$$\begin{align*}
\frac{de_\alpha}{dt} &= -\omega_c(e_\alpha - z_\alpha) \\
\frac{de_\beta}{dt} &= -\omega_c(e_\beta - z_\beta)
\end{align*}$$

According to the back emf equations (6) and (12), the rotor position can be obtained:
Because the phase delay will be caused when the first-order low-pass filter is used to filter the estimated back EMF, the rotor position angle should be compensated. The delay phase is related to the cut-off frequency of the low-pass filter and the angular frequency of the input signal, which is expressed as follows:

$$\Delta \theta = \arctan \frac{\omega}{\omega_c}$$  \hspace{1cm} (14)

Therefore, the motor rotor position is:

$$\hat{\theta} = \tilde{\theta} + \Delta \theta = -\arctan \frac{e_g}{e_b} + \arctan \frac{\omega}{\omega_c}$$  \hspace{1cm} (15)

Get the motor rotor speed according to the above formula:

$$\hat{\omega} = \sqrt{\frac{e_d^2 + e_q^2}{\psi_f}}$$  \hspace{1cm} (16)

### 5. Simulation and Results

According to the above current predictive control algorithm and sliding mode observer algorithm, the principle block diagram of predictive control based on sensorless permanent magnet synchronous motor can be obtained, and simulation experiments are carried out according to its principle.

![Predictive control block diagram based on sensorless permanent magnet synchronous motor](image)

At first, the motor is started with a reference speed of 1000 r/min and a load torque of 10 N·m. It can be seen from figs. 2 and 3 that the speed response is fast, and the motor reaches a steady state value after about 0.01 s, and the estimated rotor speed and position response curves are basically the same as the actual speed and position waveforms of the motor.
Then the given speed of the motor changes from 1000 to 1200 in 0.02s, and the simulation results are observed. It can be seen from fig. 4 that when the motor speed changes suddenly in 0.02s, the speed can quickly track the given value with small overshoot, and the dynamic response of the system is fast.

Then the given load torque changes from 10N*m to 20N*m in 0.02s, and the simulation results are observed. It can be seen from the fig. 5 that when the load of the motor changes suddenly in 0.02s, the speed fluctuates, but it can quickly restore stability, and the system has good anti-interference ability and quick response ability.
Fig 5. Speed response curve after changing load

6. Conclusion
In this paper, the current predictive control algorithm and sensorless control technology based on sliding mode observer are applied to the control system of permanent magnet synchronous motor, which not only has good steady-state performance, but also has good anti-interference ability and dynamic response ability when the motor parameters change. In this paper, the simulation model of sensorless control system of permanent magnet synchronous motor based on current prediction is established, and the simulation test is completed when the motor starts and the load torque changes.

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