The Dual-Core Sliding Mode Control Technology of Permanent Magnet Synchronous

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Abstract: Based on the structure and working principle of permanent magnet synchronous motor, a mathematical model suitable for engineering practice is established. For the system chattering problem caused by sliding mode control, a variable gain sliding mode controller is proposed to suppress chattering. Based on the MTLAB simulation platform, the permanent magnet synchronous motor servo control system model is designed and verified by simulation to verify the static and dynamic performance of the system. An experimental platform with DSP and FPGA as the core is built, and a new sliding mode control algorithm with DSP and FPGA as the core is verified. To verify the feasibility of the control strategy described in this article, the load experiment was carried out on the platform. Simulation and experimental results shown that the permanent magnet synchronous motor servo system based on dual-core sliding mode control technology has high response speed, high steady-state accuracy and robustness, and has good static and dynamic performance.

1. Introduction

Permanent magnet synchronous motor (PMSM) has a series of advantages such as high efficiency, strong load capacity, low loss and high control precision. In many fields, PMSM is used as the power source and control core[1]. The research based on PMSM motor control algorithm has also attracted more and more attention of most scholars[2]. Since the traditional PI regulator used in the classical vector control system has been unable to meet the requirements of the current high control accuracy. The sliding mode control is insensitive to parameter changes and disturbances and has strong robustness, so it has been widely used in the occasions with high control accuracy requirements[3-4]. However, the strong robustness of sliding mode control is due to the fact that it cannot be controlled continuously, so it will inevitably lead to chattering. At present, the improvement of sliding mode controller and chattering suppression have become the key research problems of sliding mode control.

The chattering suppression methods of the sliding mode controller mainly include: design approach law, quasi-sliding mode method, disturbance compensation and dynamic sliding mode control[5]. The principle of the design of the approach law is based on the chattering generated by the inertia of the system motion point near the switching surface, so that the motion speed of the system can be reasonably controlled, so as to improve the chattering. However, this method needs to judge the degree of system disturbance first, otherwise the design of the approach law cannot be carried out. The quasi-sliding mode method, which combines nonlinear and linear control, can avoid chattering caused by simple nonlinear, but its disadvantage is that the robustness of the system is reduced. By means of
parameter identification or disturbance estimation, the parameter changes and the magnitude of disturbance can be obtained to compensate the sliding mode control, and chattering can be suppressed. However, because parameter identification or observer requires a lot of operation and is greatly affected by noise, the accuracy of the result is difficult to be guaranteed. In dynamic sliding mode control, the switching function of dynamic sliding mode can introduce the discontinuity of control into the differential, which makes the control law have the continuity in time and greatly restrain the chattering. However, due to the existence of high derivatives, the system is affected by noise.

For this reason, a variable gain sliding mode control method is proposed to suppress chattering. Based on the structure and working principle of permanent magnet synchronous motor, a practical mathematical model is established, and the principle of sliding mode controller and the mechanism of chattering suppression based on variable gain sliding mode controller are deeply studied. The system simulation platform was built by using MATLAB simulation software, and the simulation research was carried out on the system. The simulation results were analyzed, and the system was verified to have good static performance and dynamic performance. The feasibility of the control strategy described in this paper is verified by the load experiment on the experimental platform.

2. Design of variable gain sliding mode controller

2.1. Working principle of sliding mode control

The essence of the sliding mode controller is non-linearity, and this non-linearity is caused by the discontinuity of the control, that is to say, its "structure" can be switched on and off over time. This transition enables the system to carry out low amplitude and high frequency motion in a preset motion path, which is called Sliding Mode Control (SMC).

Assume that the control system under normal circumstances is:

\[ \dot{x} = f(x, u, t), \quad x \in \mathbb{R}^n \]  

(1)

As shown in Figure 1, in the state space of the control system, there exists a switching surface \( S(x)=0 \), which is divided into two parts: \( S > 0 \) and \( S < 0 \).

![Fig. 1 Three kinds of points of the switch surface](image)

The points in the switching plane can be divided into three categories[3]: Class A point, known as the normal point, to which the system moves from the non-sliding mode region and enters another part of the state space through the switching plane. Class B point is called the starting point. The system moves to this point in the sliding mode region and then leaves the switching plane to the non-sliding mode region. Class C point, known as the termination point, is the point to which the system moves from the non-sliding mode region on both sides. When Class C points are all within a certain range of the switching surface, the system will tend to move towards the switching surface when it moves within this range, which is also known as the "sliding mode region". The system will carry out "sliding mode motion" within this range. That's the basic principle of a sliding mode controller.
2.2. Design of variable gain sliding mode speed controller

The sliding mode controller is insensitive to parameters and disturbances, and the control system has strong robustness. However, the strong robustness of sliding mode control is due to the fact that it cannot be controlled continuously, which will inevitably lead to chattering of the system. Ideally, the sliding mode controller is able to immediately complete the change, and the system will be carried out in continuous sliding mode, and in practical applications, often because of the space lag, time delay and inertia of the controlled object, the presence of control energy limited and not to switch from the ideal sliding mode controller structure, around the switching surface do low-rising high frequency jitter. Therefore, in order to improve the performance of the system, it is necessary to suppress chattering caused by sliding mode control.

According to sliding mode control theory, the design of sliding mode controller includes two steps: switching function design and control rate design.

Principle of integral sliding surface

The integral sliding surface can be expressed as:

\[ s(x) = c_0 \int_{-\infty}^{\tau} x \, d\tau + cx \]  

When moving in the sliding mode region, the integral sliding mode surface shall meet the following requirements:

\[ c_0 \int_{-\infty}^{\tau} x \, d\tau + c_1 x + c_2 \dot{x} + \cdots + x^{(n)} = 0 \]  

In order to make the system have global robustness, let \( t=0 \), and we can get:

\[ \int_{-\infty}^{0} x \, d\tau = -\frac{c_1 x + c_2 \dot{x} + \cdots + x^{(n)}}{c_0} \]  

The design of the integral sliding mode surface is to introduce the state product component into the conventional sliding mode surface, and through the reasonable design of the initial integral value, the control system can be located in the sliding mode region from the beginning, and the system can have the global robustness. In addition, the static error of the system can be greatly reduced by introducing integration, but the system response time becomes longer because of the existence of integration. Fig. 2a) is the trajectory diagram of traditional sliding mode motion, and Fig. 2b) is the trajectory diagram of integral sliding mode motion. Through comparison, it can be seen that the traditional sliding mode surface has two states of approaching and sliding mode, while the integral sliding mode surface is in the sliding mode state from the beginning, which has stronger robustness. The integral sliding mode surface is chosen as the sliding mode surface of the controller.

![Fig. 2 Compare of two switch surface](image)

According to \( T_e = \rho_i \psi_i i_q \), combined with Equation 1, it can be deduced that:

\[ \frac{d\omega_r}{dt} = \frac{p_e \psi_f}{J} (i_q^* - i_q) + \frac{p_e \psi_f}{J} (i_q - i_q^*) - \frac{B}{J} \omega_r - \frac{T_e}{J} \]  

Where: \( i_q^* \) is the output of the sliding mode controller, which is used as the iq reference current. The disturbance is defined as:
If the speed error $e = w_r^* - w_r$ and $w_r^*$ is set as the reference value of the speed, and the speed error is differentiated, then according to Equations 5 and 6, we can get:

$$\dot{e} = - \frac{p_a \psi_f}{J} i_q^* - a(t)$$

Through the above analysis, the system from the sliding state from the $|s|$ will increase, from that system into sliding mode condition, $|s|$ will decrease. Which can be further indicate, when switching function and $|s|$ have the same change trend, will be able to design a modified sliding mode control. According to this idea, an integral sliding mode controller with variable gain is designed.

2.3. Design of switching function and control rate

It can be seen from Equation 7 that the velocity loop of the system is a first-order differential equation. In order to ensure global robustness, the error $e$ is set as the input and $u$ is the control quantity. The integral sliding mode surface selected is

$$s = e + \int_0^t e \, d\tau$$

Where, $c = \frac{p_a \psi_f}{J} m$, and $m$ is a positive number.

When the system enters the sliding mode state, we know that $s=0$ and $\dot{s} = 0$. The setting of $m$ will determine the dynamic performance of the system.

The control quantity of equivalent control can be described as:

$$u = u_{eq} + k_f \text{sign}[s(x)]$$

Where, $u_{eq}$ is the control quantity when the system is located in the sliding mode region, and sign[] is the sign function.

Let's set $s=0$ and $\dot{s} = 0$ then we can derive $u_{eq}$. In practical engineering applications, under the action of parameter change and interference, the system may break away from the sliding mode state, so $k_f \text{sign}[s(x)]$ is added to ensure strong robustness and will not easily break away from the sliding mode state.

In this paper, equivalent control is selected to design the control law. The controller can be expressed as:

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

Where, $u_{eq}$ the equivalent part, is the control quantity of output when $\dot{s} = 0$ and $a(t)=0$. It is not difficult to derive the equivalent control:

$$u_{eq} = me$$

$u_{sw}$ is the sliding mode switching part, whose purpose is to ensure that the system error does not deviate from the switching surface in the sliding mode state, and make it move along the switching surface to the stable point, so as to enhance the robust control of the system. In order to define the functional relationship of $u_{sw}$, a simulation model of sliding mode controller was established in MATLAB software. When the sinusoidal signal is used as the input of the sliding mode controller, the output of the corresponding sliding mode controller when $u_{sw}=fex(s)$ and $u_{sw}=f\text{sign}(s)$. It can be seen that when $u_{sw}=f\text{sign}(s)$, the output signal is discontinuous and jumps at zero crossing, while when $u_{sw}=fex(s)$, the output signal is relatively flat at zero crossing and the waveform is continuous, so the resonance can be suppressed by using this function.

According to the above analysis, it can be defined as:
\[ u_{sw} = fex(s) = f \frac{1-e^{-as}}{1+e^{-as}} \] (12)

Where, \( a \) is the normal number, and the larger the value, the smaller the error. Switch gain for variables, \( f \) and \( f = k_1 + k_2 \) [s].

Therefore, it can be concluded that the designed controller is:

\[ u = i^* = me + fex(s) \] (13)

The integral sliding mode surface was selected as the sliding mode surface of the controller, and the velocity sliding mode controller was selected to replace the conventional PI controller. Block diagram of vector control structure based on sliding mode velocity controller.

3. Simulation and result analysis

In order to verify the feasibility and superiority of the proposed method, a PMSM servo system model based on sliding mode vector control was built on the Matlab simulation platform, and the performance of the motor was compared and analyzed respectively in the steady state and dynamic running state of the motor.

The parameters of the motor used in this design are: stator resistance \( R=0.66 \Omega \), \( L_d=L_q=1.62 \text{mH} \), pole logarithm \( P=4 \), moment of inertia \( J=1 \text{e}^{-3} \text{N} \cdot \text{m} \cdot \text{s}^2 \), and the magnetic flux of the main pole \( \Psi_f =0.067 \text{Wb} \). Set the simulation time as 0.5s.

The dual-core sliding mode control technology proposed in this paper is mainly to solve the system chattering problem caused by sliding mode control and to analyze the motor performance when the motor is running in steady state and dynamic state respectively. When the motor is running in steady state, the given speed is 1000r/min and the load torque is 10N*m, the motor speed and torque waveforms are obtained through the simulation platform, and the three-phase stator current waveforms are obtained. As can be seen from the figure, when the motor is in stable operation state, it can run smoothly at a given speed with almost no speed fluctuation, the output torque also reaches the load torque without torque ripple, and the three-phase stator current waveform of the motor has high sinusoidal degree and low harmonic content. It can be seen that the dual-core sliding mode control technology can suppress the system chattering caused by the sliding mode control very well, and the motor has good steady state performance.

In order to verify the dynamic performance of the proposed dual-core sliding mode control technology, the motor speed and load sudden changes were applied respectively. The motor runs stably at a speed of 500r/min and a load torque of 10N*m. When the speed changes at 0.1s, the reference speed suddenly increases from 500r/min to 1000r/min and the torque suddenly increases from 5N*m to 10N*m at 0.2s, the result is obtained. It can be seen that the speed pulsates when the speed changes abruptly, but the duration is not more than 0.02s, and the speed becomes stable quickly, which is within the allowable range. Moreover, the speed overshoot is small, less than 20% of the given speed. The motor can finally run stably at 1000r/min. When the sudden load is added, the motor speed drops briefly, and the change is less than 20r/min, which has little influence on the system. The stator current passes through the transient process of 0.01s and then enters the steady state operation. In the transient process, the amplitude of the current gradually increases, and the system reaction speed is fast. It can be seen that the dual-core sliding mode control technology makes the motor have good dynamic performance, and can well suppress the system chattering caused by sliding mode control.

In order to further illustrate the advantages and effectiveness of the dual-core sliding mode control technology proposed in this paper, the sliding mode speed controller and the traditional PI are simulated and compared under the same experimental conditions, and the speed and load mutations of the motor are applied respectively. The motor speed suddenly increased from 500r/min to 1000r/min at 0.1s and the torque suddenly increased from 5N*m to 10N*m at 0.2s. It is obvious that the sliding mode speed controller has faster response and less overrun and static errors. So using the sliding mode speed controller can improve the dynamic and static performance of the system and enhance its robustness.
4. Experiment and result analysis
By building an experimental platform based on DSP+FPGA as the core of the motor control system, the PMSM servo system based on dual-core sliding mode control technology designed in this paper is further studied. The characteristics of DSP and FPGA are fully considered in the software design. On this basis, the reasonable division of labor between DSP and FPGA is carried out to achieve the optimal performance. Table 1 shows the parameters of permanent magnet synchronous motor used.

| Name            | Value | Name               | Value |
|-----------------|-------|--------------------|-------|
| Rated power     | 1.2   | Quadrature inductance $L_q$/mH | 1.62  |
| Stator resistance $R_s$/Ω | 0.66  | Pole-pairs $P$      | 4     |
| Rated voltage   | 220   | Rated current $I_d$/A | 6     |
| Rated torque $Te$/N*m | 6     | Maximum torque/ N*m | 18    |

The two-phase stator current waveform of the motor is stable when the speed is 300r/min and 1000r/min, and the load torque is constant at 6N*m. It can be seen that when the motor is running at low speed or high speed, the current is sinusoidal and the current pulsation is very small, so the motor has a good steady-state performance. It is verified that the dual-core sliding mode control technology proposed in this paper can suppress system chattering and improve the steady state performance of the motor.

The dynamic response of phase current when the load torque increases or decreases abruptly while the motor speed is constant. Where, a) and b) are the current dynamic response and the dynamic process current waveform when the load torque suddenly increases from 1N*m to 6N*m; c) and d) are the current dynamic response and the dynamic process current waveform when the load torque decreases from 6N*m to 1N*m. It can be seen that when the load torque increases abruptly, the amplitude of the current increases during the dynamic period and enters the steady state again. In the dynamic process, the sine degree of the current is good and the effective value of the current increases from 1.02A to 5.12A. When the load torque suddenly decreases, the amplitude of the current waveform decreases during the dynamic period and can quickly enter the steady state. The dynamic process current of the load torque suddenly decreases can also maintain a good sinusoidal degree, and the effective value of the current decreases from 5.12A to 1.02A.

When the load torque is 3N*m, the change of the motor speed during the start and stop process. It can be seen that after soft start, the motor speed quickly stabilized at 2000r/min, and the fluctuation was small. In the stopping process, the motor speed is reduced from 2000r/min to 0r/min after a short dynamic process. When the load torque is 3N*m, the dynamic response of the speed when the speed is suddenly added. It can be seen that the motor starts from a stationary soft start to 1300r/min, and then the speed is suddenly increased to 2000r/min. From the waveform figure, it can be seen that the motor speed can quickly respond to the change of the reference speed, and the response speed is less than 0.2s. In addition, the speed overshoot is very small in the process of speed mutation, less than 10% of the given speed.

It can be seen that in the dynamic process of the sudden change of torque and speed of the motor load, the dual-core sliding mode control technology has a good effect on the system chattering caused by the sliding mode control, so that the motor has a good dynamic performance.

5. Conclusion
Aiming at the sliding mode vector control strategy of permanent magnet synchronous motor, this paper introduces the principle of sliding mode control, and designs the switching function and control law of variable gain sliding mode controller to suppress chattering based on the mathematical model of the
motor. The simulation and experimental results show that the motor control system is feasible both in theory and in practice, and can suppress the system chattering caused by sliding mode control, and has excellent control effect.

Reference

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