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Direct Torque Control of Permanent Magnet Synchronous Motor Based on Sliding Mode Variable Structure

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Abstract

In order to solve the problem of large torque and flux ripple in the traditional direct torque control of permanent magnet synchronous motor, Super-Twisting sliding mode variable structure control strategy is adopted. Under the dl coordinate system, the torque and flux controller is designed. In the direct torque control, the problem of speed overshoot and considerable fluctuation during PI control is adopted. The synovial speed controller is designed, and the space vector pulse width modulation technology (SVPWM) is adopted to stabilize the inverter switching frequency. The simulation results demonstrate that the method can effectively reduce the torque and flux linkage and accelerate the system response.

Subject Areas

Artificial Intelligence

Keywords

Permanent Magnet Synchronous Motor, Direct Torque Control, Sliding Mode Variable Structure, Space Vector Pulse Width Modulation Technology

1. Introduction

Permanent magnet synchronous motor has the characteristics of small size, lightweight, high power factor and high efficiency, and is widely used in the field of robots and electric vehicles [1]. Direct torque control of permanent magnet synchronous motor is widely used in high performance servo applications due to its high working efficiency, small parameter dependence on the motor, strong robustness, good dynamic performance and simple structure control [2]. In the traditional direct torque control, the hysteresis controller is used to control the torque and flux linkage. The torque and flux linkage are large, the switching frequency is unstable, and the PI control is mainly used in the speed control. When the system has speed changes and load disturbances, it is impossible to achieve fast and no overshoot tracking target speed.

A lot of research has been conducted by domestic and foreign scholars on the problems existing in traditional direct torque control. Literature [3] introduces zero voltage vector and vector subdivision to improve the voltage vector switch table, which reduces the flux linkage and torque ripple to a certain extent. The literature [4] uses space vector pulse width modulation technologies to reduce the inverter. On the basis of switching frequency, many scholars combine intelligent control with traditional direct torque control. The literature [5] utilizes fuzzy control to optimize the selection of voltage space vector, but the fuzzy rules are complex and rely on experience, sliding mode variable structure. Control is applicable to the direct torque control of permanent magnet synchronous motor due to its robustness, rapid response, and insensitivity to external disturbances [6].

In this paper, the super-spiral sliding mode variable structure control is used to design the flux linkage and torque controller. The velocity controller is designed by using the sliding film control method based on the approach law. The system designed in this paper is compared with the traditional direct torque control system. It shows that the method adopted in this paper can effectively reduce the ripple of flux linkage and torque, and accelerate the speed response and anti-disturbance capability.

2. Mathematical Model of PMSM

In order to simplify the analysis, the following assumptions are often made in the mathematical modeling of permanent magnet synchronous motors:

1) Ignore the saturation of the iron core inside the motor;

2) Excluding the eddy current and hysteresis loss when the motor is running;

3) The stator winding current is a three-phase sinusoidal current, and the induced electromotive force of the stator armature winding is also a sine wave [7].

2.1. Mathematical Model of Two-Phase Stationary Coordinate System *αβ*

The stator voltage equation is:

$$\begin{cases} u_\alpha = L_s \dfrac{\mathrm{d}i_\alpha}{\mathrm{d}t} + R_s i_\alpha - \omega_r \psi_f \sin\theta_r \\ u_\beta = L_s \dfrac{\mathrm{d}i_\beta}{\mathrm{d}t} + R_s i_\beta + \omega_r \psi_f \cos\theta_r \end{cases} \tag{1}$$

where: $u_\alpha, u_\beta, i_\alpha, i_\beta$ are components of the stator voltage vector and the current vector on the α and β axes;

R_s, L_s are stator resistance and stator inductance;

ω_r is the motor angular velocity;

ψ_f is a permanent magnet flux linkage;

θ_r is the rotor position angle.

The stator flux linkage equation is [8]:

$$\begin{cases} \psi_\alpha = \int \left(u_\alpha - R_s i_\alpha \right) \mathrm{d}t \\ \psi_\beta = \int \left(u_\beta - R_s i_\beta \right) \mathrm{d}t \end{cases} \tag{2}$$

The electromagnetic torque equation is:

$$T_e = \frac{3}{2} p \left(\psi_\alpha i_\beta - \psi_\beta i_\alpha \right) \tag{3}$$

The motor motion equation is:

$$\frac{\mathrm{d}\omega_m}{\mathrm{d}t} = \frac{p}{J} \left(T_e - T_L \right) \tag{4}$$

where: p is the pole number of the motor;

J is the moment of inertia;

T_L is the load torque.

2.2. Mathematical Model under Rotating Coordinate System dq

The stator voltage equation is:

$$\begin{cases} u_d = \dfrac{\mathrm{d}\psi_d}{\mathrm{d}t} + R_s i_d - \omega_r \psi_q \\ u_q = \dfrac{\mathrm{d}\psi_q}{\mathrm{d}t} + R_s i_q + \omega_r \psi_d \end{cases} \tag{5}$$

The stator flux linkage equation is:

$$\begin{cases} \psi_d = L_d i_d + \psi_f \\ \psi_q = L_q i_q \end{cases} \tag{6}$$

The electromagnetic torque equation is [9]:

$$T_e = \frac{3}{2} p i_q \left[i_d \left(L_d - L_q \right) + \psi_f \right] \tag{7}$$

where: u_d, u_q are the components of the stator voltage on the dq axis;

i_d, i_q are the components of the stator current on the dq axis;

ψ_d, ψ_q are the components of the stator flux linkage on the dq axis;

L_d, L_q are the inductances on the dq axis;

ψ_f is the stator flux linkage.

3. PMSM Direct Torque Control Based on Sliding Mode Control

3.1. Super-Slip Sliding Mode Variable Structure Control Strategy

Sliding mode variable structure control has discontinuity, the system structure follows the switching characteristics of the time change, the system parameters are independent of the outside world, the response speed is fast, and it has good robustness. The super-spiral algorithm-based synovial controller can effectively eliminate the pulsation. The formula of the super-helical control algorithm is as follows:

$$\begin{cases} u = K_P \left| s \right|^r \operatorname{sgn}\left(s \right) + u_1 \\ \dfrac{\mathrm{d}u_1}{\mathrm{d}t} = K_I \operatorname{sgn}\left(s \right) \end{cases} \tag{8}$$

K_P and K_I are gains.

The sufficient conditions for the stability of the control system are:

$$\begin{cases} K_P \geq \dfrac{A_M}{B_m} \\ K_I \geq \dfrac{4A_M}{B_m^2} \cdot \dfrac{B_M\left(K_P + A_M \right)}{B_m\left(K_P - A_M \right)} \\ 0 \leq r \leq 0.5 \end{cases} \tag{9}$$

Among them: $B_m \leq B \leq B_M$, $A_M \geq \left| A \right|$.

And A, B meets:

$$\frac{\mathrm{d}^2 y}{\mathrm{d}t^2} = A\left(x,t \right) + B\left(x,t \right)\frac{\mathrm{d}u}{\mathrm{d}x} \tag{10}$$

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Magnetic chain controller:

$$\begin{cases} u_d = K_{P1} \left| S_\psi \right|^r \operatorname{sgn}\left(S_\psi \right) + u_{d1} \\ \dfrac{\mathrm{d}u_{d1}}{\mathrm{d}t} = K_{I1} \operatorname{sgn}\left(S_\psi \right) \end{cases} \tag{11}$$

Torque controller:

$$\begin{cases} u_q = K_{P2} \left| S_{T_e} \right|^r \operatorname{sgn}\left(S_{T_e} \right) + u_{q1} \\ \dfrac{\mathrm{d}u_{q1}}{\mathrm{d}t} = K_{I2} \operatorname{sgn}\left(S_{T_e} \right) \end{cases} \tag{12}$$

where: S_ψ is the difference between a given flux linkage and the actual flux linkage;

S_{T_e} is the difference between the given torque and the actual torque;

$K_{P1}, K_{I1}, K_{P2}, K_{I2}$ are gains.

3.2. Synovial Accessibility and Stability Analysis

According to the stator flux vector reference system, $\psi_s = \psi_d$, the stator flux linkage is derived [11]:

$$\frac{\mathrm{d}\psi_s}{\mathrm{d}t} = u_d - R_s i_d \tag{13}$$

Secondary derivation of the flux linkage:

$$\frac{\mathrm{d}^2\psi_s}{\mathrm{d}t^2} = \frac{R_s^2}{L_s} i_d - pR_s \omega i_q - \frac{R_s}{L_s} u_d + \dot{u}_d \tag{14}$$

In the above formula, R_s, L_s, i_d, p, ω are bounded values, and therefore the formula (14) satisfies the stable condition of the formula (9).

For the hidden pole permanent magnet synchronous motor, assuming that the stator flux linkage amplitude is constant, the torque is also derived:

$$\frac{\mathrm{d}T_e}{\mathrm{d}t} = \frac{3}{2} p\psi_s \frac{\mathrm{d}i_q}{\mathrm{d}t} \tag{15}$$

Continue to guide the torque:

$$\begin{aligned}\frac{\mathrm{d}^2 T_e}{\mathrm{d}t^2} = \frac{3}{2} p\psi_f \Bigg[& -\frac{p^2\psi_f}{J} i_d i_q + \frac{pB}{J} i_d \omega + \left(\frac{R_s^2}{L_s^2} - \frac{p^2\psi_f^2}{JL_s} - p^2\omega^2 \right) i_q + \frac{2pR_s}{L_s} \omega i_d \\ & - \frac{p\omega}{L_s} u_{sd} + \left(\frac{p\psi_f B}{JL_s} + \frac{p\psi_f R_s}{L_s^2} \right) \frac{p\psi_f B}{JL_s} \omega - \frac{R_s}{L_s^2} u_{sq} + \frac{p\psi_f T_L}{JL_s} + \frac{\dot{u}_{sq}}{L_s} \Bigg]\end{aligned} \tag{16}$$

It can be seen that the parameters of the second derivative of the torque are bounded values, and the analysis method is the same as the stator flux linkage, which also satisfies the stable condition of Equation (9).

3.3. Synovial Speed Controller Design

The motor motion equation is:

$$\frac{\mathrm{d}\omega_m}{\mathrm{d}t} = \frac{p}{J} \left(T_e - T_L \right) \tag{17}$$

The design switching function is:

$$s = \omega_m^* - \omega_m \tag{18}$$

where: ω_m^* is the given speed of the motor;

ω_m is the actual speed of the motor.

According to the concept of the approach law of Gao Weibing [7], the design approach law is:

$$\dot{s} = -\varepsilon |s|^\alpha \operatorname{sgn}(s) - ks \tag{19}$$

Among them: $1 > \alpha > 0, \varepsilon > 0, k > 0$.

Available from Equation (18):

$$\dot{s} = -\dot{\omega}_m = \frac{p}{J} \left(T_L - T_e \right) = -\varepsilon |s|^\alpha \operatorname{sgn}(s) - ks \tag{20}$$

Further, the slip film controller output expression is:

$$T_e = \frac{J}{p} \left[\varepsilon |s|^\alpha \operatorname{sgn}(s) + ks \right] + T_L \tag{21}$$

3.4. Synovial Accessibility and Stability Analysis

Select the Lyapunov function as:

$$V = \frac{1}{2}s^2 \tag{22}$$

Derivation of Equation (22) yields:

$$\dot{V} = \dot{s}s = s\left[-\varepsilon|s|^{\alpha}\operatorname{sgn}(s) - ks\right] = -\left(\varepsilon|s|^{\alpha+1} + ks^2\right) < 0 \tag{23}$$

This formula satisfies the stability conditions of Lyapulov, which proves the stability and accessibility of the system.

4. Simulation Analysis

In this paper, the simulation model is built by matlab/simulink. The system includes multiple subsystem modules such as flux linkage and torque estimation module, coordinate transformation module and speed adjustment module. The improved system model is shown in **Figure 1**.

The parameters of permanent magnet synchronous motor are set as follows: the stator winding resistance is $R_s = 1.2\ \Omega$, stator inductance $L_d = L_q = 0.0085\ \text{H}$, rotor flux linkage $\psi_f = 0.175\ \text{Wb}$, moment of inertia $J = 0.0008\ \text{kg}\cdot\text{m}^2$, pole logarithm $p = 4$, the system friction coefficient $B = 0$. The system simulation parameters are: given speed is $\omega_m^* = 600\ \text{rad/min}$, given flux linkage is $\psi^* = 0.3\ \text{Wb}$, load torque $T_L = 1.5\ \text{N}\cdot\text{m}$ is applied in 0.2 seconds. Simulation time is 0.4 s. The simulation results are shown in **Figures 2-7**.

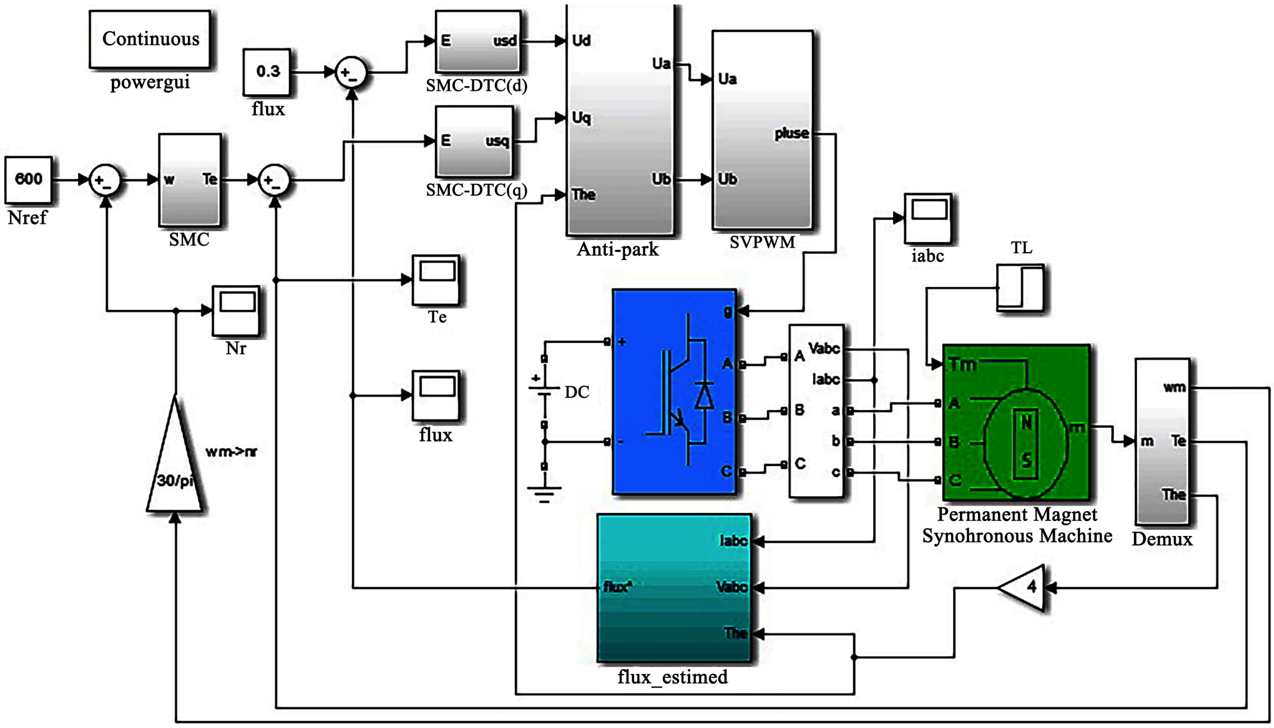

Figure 1. Improved DTC simulation model for permanent magnet synchronous motor.

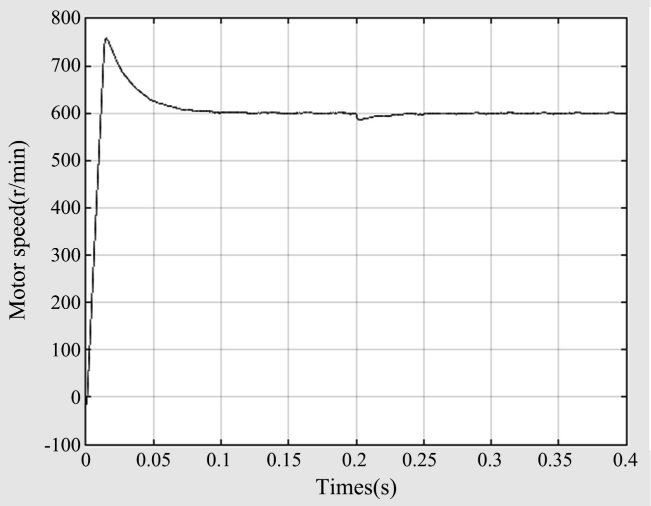

Figure 2. Traditional DTC motor speed curve.

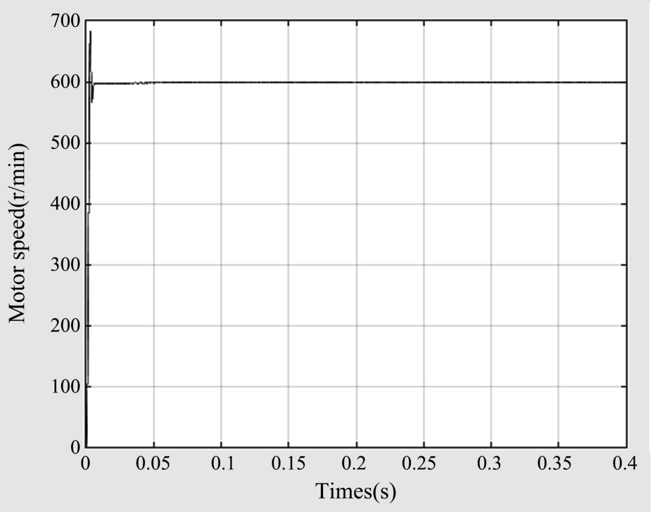

Figure 3. Improve DTC motor speed curve.

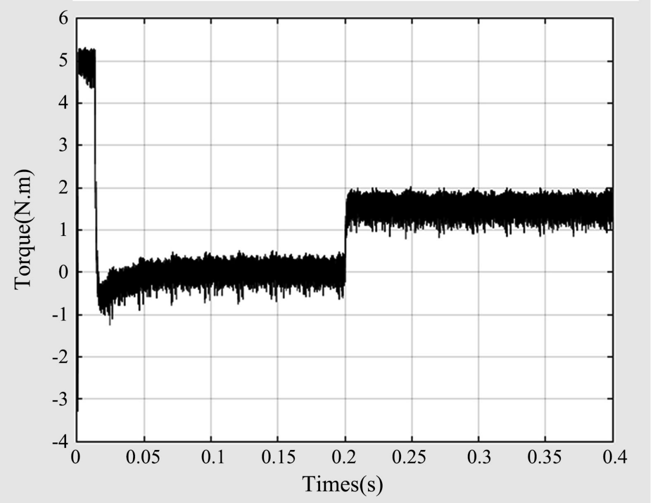

Figure 4. Electromagnetic torque curve of traditional DTC motor.

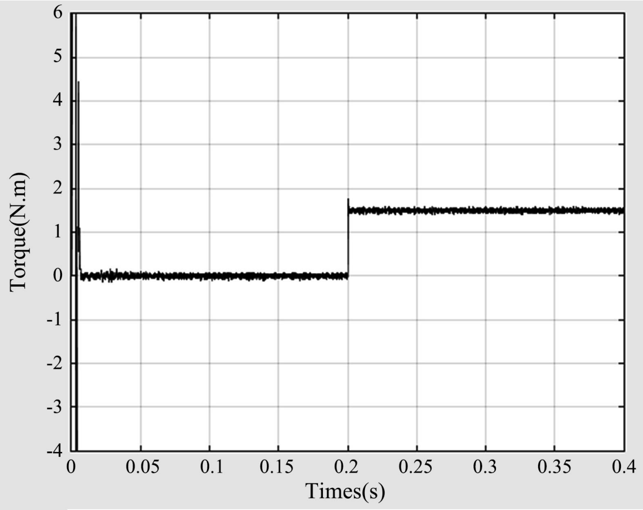

Figure 5. Improve the electromagnetic torque curve of DTC motor.

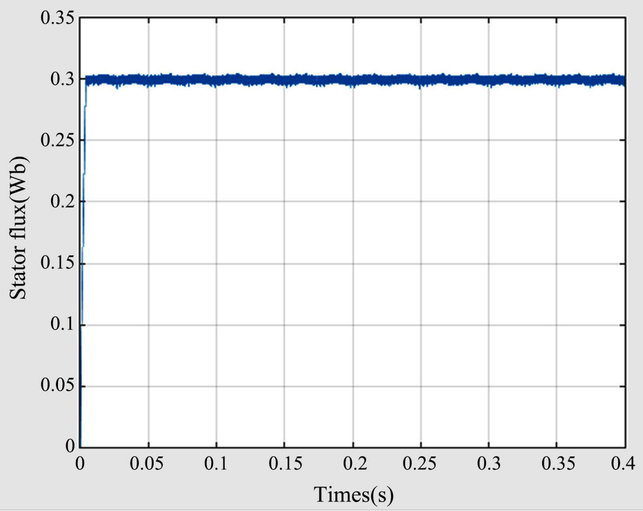

Figure 6. Traditional DTC motor electromagnetic torque curve.

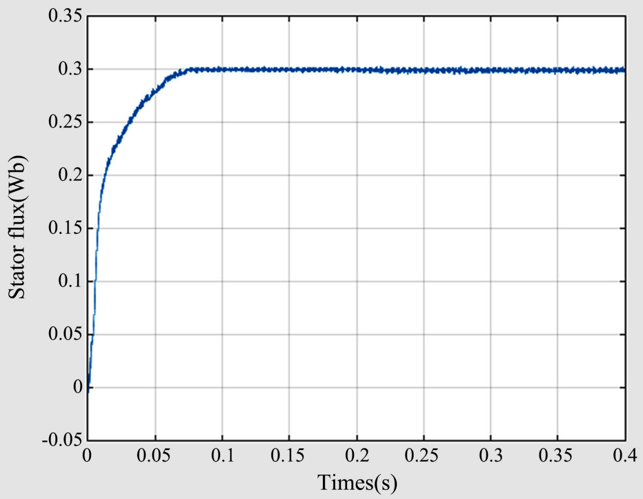

Figure 7. Traditional DTC motor electromagnetic torque curve.

It can be seen from **Figures 2-7** that when the motor speed increases from 0 to 600 r/min, compared with **Figure 2** and **Figure 3**, the conventional direct torque control has a large overshoot and the adjustment time is long, when it is within 0.2 s. When the load is applied, the rotational speed drops significantly and the steady-state performance is poor. In the improved direct torque control, the rotational speed has a small overshoot and the dynamic response is fast, and the rotational speed is substantially unchanged when the load is suddenly applied. Comparing **Figures 4-7**, in the traditional direct torque control, the torque and flux linkage are large, and in the direct torque control using the sliding mode variable structure control, the torque and flux pulsation are significantly reduced, so it can be seen The method adopted in this paper is effective, can improve the system speed regulation performance, reduce the ripple of the flux linkage and torque, and make the system have good dynamic response and anti-interference.

5. Conclusion

In this paper, based on the sliding mode theory, the flux linkage and torque controller and the sliding mode variable speed controller are designed. Compared with traditional direct torque control simulation, the method used in this paper can effectively reduce the flux linkage and torque ripple. The system has strong anti-interference and robustness.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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