Research on Control System of Permanent Magnet Synchronous Motor Based on Sliding Mode Speed Controller

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Abstract—The traditional vector control method for permanent magnet synchronous motors (PMSM) has the problems of low starting speed, overshoot, large sudden load dynamic error. A sliding mode speed controller (SMC) is designed to replace the traditional PI controller of PMSM. Firstly, the principle of sliding mode was introduced. Meanwhile, the approaching law and the selection of sliding mode surfaces were determined. Finally, the simulation results showed that the sliding mode speed controller had a faster response speed, smaller overshoot compared with the traditional controller. The robustness of the system is effectively improved. This control strategy is reliable and effective.

Keywords—PMSM; Vector control; Sliding mode control

I. INTRODUCTION

With the development of electronic technology, power electronics, new motor control theory, and digital control technology, some control strategies of AC speed regulation systems have also been developed accordingly. PMSM has the advantages of lightweight, high efficiency, no excitation loss, and so on, it is widely used in various fields of industry. Due to the intervention of external interference, the PMSM variables such as flux linkage, current, and speed, it is very difficult to control [1-3].

In recent years, a variety of control algorithms have been applied to PMSM speed regulation systems, such as fuzzy control, BP neural network control, and fractional-order control, and so on [4-5]. A fuzzy PI control method was proposed in the literature [6], compared with traditional PID control, the response time was reduced and the dynamic response was enhanced. In the literature [7], the PID control algorithm of the BP neural network was applied to PMSM, the performance of speed regulation and robustness were greatly improved. Fractional PID control was applied to PMSM in the literature [8], the system had a better dynamic response and steady-state performance than traditional integer PI control.

SMC is one of the robust and high-speed nonlinear control strategies [9], it is very suitable for the control of PMSM. The sliding mode control mainly involves the design of the approaching law and the selection of the sliding mode surface, and the sliding mode control is not affected by the parameters of the controlled object and the external disturbance. The SMC has the advantages of rapid response and no online identification, and it has been widely used in PMSM speed control systems.

An improved particle swarm algorithm was applied to the control of PMSM in the literature [10], which improved the control accuracy and response speed. The dynamic matrix model proposed in the literature [11] predicted the dynamic response of PMSM, the robustness and dynamic response of the system were enhanced, and the feasibility of the new method was verified in the PMSM oil drilling rig. In the literature [12], an active disturbance rejection control technology was proposed as a control strategy for PMSM, compared with PI control, it had better dynamic and steady-state performance, and the speed to reach a steady-state was faster and the change of the speed is small.

II. BASIC PRINCIPLES OF SLIDING MODE CONTROL

SMC is one of the control strategies of a variable structure control system. Compared with conventional control strategies, the sliding mode control is discontinuous, and has switching characteristics as time changes. Sliding mode means that the system can move up and down with small high-frequency amplitude under certain conditions, and move under the prescribed state trajectory. The sliding mode can be designed without being affected by system parameters and interference. The system in the sliding mode is relatively stable and responds quickly.

The definition of sliding mode control is as follows. Consider a nonlinear system in general

\[ \dot{x} = f(x,u,t) \]

where \( x \in \mathbb{R}^n, u \in \mathbb{R}^m \) are the system state and control quantity respectively.

Select the sliding mode surface function

\[ s(x,t), s \in \mathbb{R}^n \]

The controller function

\[ u_i(x,t) = \begin{cases} u^*(x,t), s(x,t) > 0 \\ u^*(x,t), s(x,t) < 0 \end{cases} \quad i = 1,2,...,m \]

where \( u^*(x,t) \neq u(x,t) \).

Among them:

1) Sliding mode exists.

2) Meet the accessibility condition, that is, at the moving point outside the sliding surface \( s(x,t) = 0 \), move to the sliding surface within the specified effective time, and satisfy \( s \dot{s} < 0 \).

3) Ensure the stability of sliding mode movement.

4) Satisfy the dynamic quality requirements of the control system.

Sliding mode control must satisfy the first three conditions, the control that meets these three conditions is called sliding mode control.

The motion of the sliding mode control system consists of two parts, as shown in Fig.1: Section AB is the first part, the control system moves freely outside the sliding surface, and keeps approaching the sliding surface. Section BC is the...
second part, the system moves up and down around the sliding surfaces \( (x,t)=0 \).

![Diagram of Two Motion Stages of Sliding Mode Control System](image)

Figure 1: Two Motion Stages of Sliding Mode Control System

Known from the basic principle of SMC, the normal motion must satisfy the conditions of sliding mode \( s \dot{s} < 0 \) accessibility, so it can move from an unknown initial state to the sliding mode surface within a certain time. Therefore, a variety of approaching laws can be designed to reach the steady-state. Commonly used approaching laws are as follows:

1) Isokinetic Approaching Law

\[
\dot{s} = -\varepsilon \text{sgn}(s), \varepsilon > 0
\]

2) Exponential Approaching Law

\[
\dot{s} = -\varepsilon \text{sgn}(s) - \alpha q, \varepsilon, q > 0
\]

3) Power Approaching Law

\[
\dot{s} = -\varepsilon q \text{sgn}(s), q > 0, 0.1 > \alpha > 0
\]

4) General Approaching Law

\[
\dot{s} = -\varepsilon \text{sgn}(s) - f(s)
\]

Where \( \varepsilon \) is the approach coefficient, \( q \) is the exponential approach coefficient, and \( \alpha \) is the higher-order approach coefficient.

Different approaching speeds can be obtained by adjusting the approach coefficient, \( \varepsilon \), and the larger the value, the faster the approaching speed. Meanwhile, the sensitivity of the entire sliding mode controller will be relatively high, the state of motion will produce a larger overshoot or a strong oscillation, if its value is selected too small, the response speed of sliding mode control will be affected, and affect the entire control system adversely. In the sliding mode control process, the systematic error cannot be presented in the form of quantity. So the appropriate approaching method must be selected to obtain a shorter approaching time.

To obtain a faster approaching speed and reduce the overshoot in the process of motion, the exponential approaching method was used for sliding mode control. In the general system

\[
\dot{x} = Ax + Bu
\]

where \( x \in \mathbb{R}^n \) is a state variable, \( u \in \mathbb{R}^m \) is a control variable, \( A \) and \( B \) are real matrices of appropriate dimensions.

Define the sliding mode surface function

\[
s = Cx
\]

Where \( s \in \mathbb{R}^m \) is a sliding mode surface function, \( C \in \mathbb{R}^{m \times n} \) is an appropriate vector, the desired dynamic characteristics can be obtained by \( C \).

The derivative of the sliding surface function is as follows

\[
\dot{s} = C \dot{x} = -\varepsilon \text{sgn}(s) - qs
\]

The sliding mode controller \( u \) is obtained

\[
u = (CB)^{-1}(-CAx - \varepsilon \text{sgn}(s) - qs)
\]

The sliding mode controller is brought into the system reachability function, and its correctness is verified, the system under this controller can finally reach a steady-state.

### III. PMSM Mathematical Model

The stator voltage equations of surface-mounted PMSM in the \( d-q \) synchronous rotating coordinate system are

\[
\begin{align*}
u_d &= R_i q + L_d \frac{di_d}{dt} - p\alpha m L_q i_q \\
u_q &= R_i q + L_q \frac{di_q}{dt} + p\alpha m L_d i_d + p\alpha m \psi_f
\end{align*}
\]

The equation of mechanical motion

\[
J \frac{d\omega_m}{dt} = \frac{3}{2} p \psi_f i_q - T_L
\]

where

- \( R \) — stator resistance
- \( i_d, i_q \) — \( d-q \) axis components of stator current
- \( L_d, L_q \) — stator inductance
- \( p \) — number of motor pole pairs
- \( \omega_m \) — the mechanical angular velocity of the motor
- \( \psi_f \) — permanent magnet flux linkage
- \( J \) — rotor inertia
- \( T_L \) — load torque

### IV. Design of Sliding Mode Speed Controller

The design of the sliding mode controller can be divided into two steps: designing the sliding mode surface and selecting the reaching law.

#### A. Selection of control quantity

Define the state variables of the system

\[
\begin{align*}
x_1 &= \omega_{ref} - \omega_m \\
x_2 &= \dot{x}_1
\end{align*}
\]

where

- \( \omega_{ref} \) — the reference speed of the motor
- \( \omega_m \) — actual speed value

According to (14) and (15), and obtained that

\[
\begin{align*}
\dot{x}_1 &= -\dot{\omega}_m = \frac{1}{J} \left( T_L - \frac{3p\psi_f}{2} i_q \right) \\
\dot{x}_2 &= -\dot{\omega}_m = -\frac{3p\psi_f}{2J} i_q
\end{align*}
\]

Define \( u = i_q, D = \frac{3p\psi_f}{2J} \), (16) can be expressed as

\[
\begin{bmatrix}
\dot{x}_1 \\
\dot{x}_2
\end{bmatrix} =
\begin{bmatrix}
0 & 1 \\
0 & 0
\end{bmatrix}
\begin{bmatrix}
x_1 \\
x_2
\end{bmatrix} +
\begin{bmatrix}
0 \\
- D
\end{bmatrix} u
\]

#### B. Design of the sliding surface

Select the sliding mode surface function

\[
s = c(t)x_1 + x_2
\]

where \( c > 0 \) is the parameter to be designed.
The derivative of (18) is as follows

\[
\dot{s} = c(t)x_1 + \dot{x}_1 = c(t)x_2 - Du
\]  

(19)

To ensure the system has better dynamic quality, the exponential reaching law method was adopted, and the expression of the controller can be obtained that

\[
u = \frac{1}{D}[c(t)x_2 + \varepsilon \text{sat}(s) + qs]
\]  

(20)

The reference current of the q-axis is as follows

\[
i_q^* = \frac{1}{D} \int [c(t)x_2 + \varepsilon \text{sat}(s) + qs]\,dt
\]  

(21)

The variable structure process of the controller is shown in Fig. 2.

As shown in (21), the integral term was included in the controller, so it can not only reduce the chattering but also reduce the steady-state error of the system.

According to the sliding mode approaching conditions, it is easy to verify that the system is progressively stable under the controller.

V. PMSM SPEED CONTROL SYSTEM DESIGN

A. Simulation model

The following is to verify the correctness of this method, taking Interior Permanent Magnets Synchronous Motors (IPMSM) as the research object.

The specific parameter settings of IPMSM used in the simulation model are as follows

<table>
<thead>
<tr>
<th>Table 1: Motor Parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Motor Parameters</td>
<td></td>
</tr>
<tr>
<td>Stator resistance $R_s$</td>
<td>2.875Ω</td>
</tr>
<tr>
<td>Stator $d$, $q$ axis inductance $L_d=L_q$</td>
<td>8mH</td>
</tr>
<tr>
<td>Rotor flux $\Psi_r$</td>
<td>0.175Wb</td>
</tr>
<tr>
<td>Moment of inertia $J$</td>
<td>0.003kg.m$^2$</td>
</tr>
<tr>
<td>Pole pairs $p$</td>
<td>4</td>
</tr>
<tr>
<td>Damping coefficient $B$</td>
<td>0.008N·m·s</td>
</tr>
</tbody>
</table>

The system adopts the FOC strategy with $i_d=0$ [13], the current loop adopts PI control, the speed loop adopts sliding mode control. The simulation model is built in the Matlab/Simulink. The vector control structure diagram of the system is shown in Fig. 3.

B. Analysis of simulation results

To verify the design of the sliding mode speed controller, the simulation conditions and SMC parameters are set as shown in Table 2.

<table>
<thead>
<tr>
<th>Table 2: Simulation Parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Given speed $\omega_{ref}$</td>
<td>1000r/min</td>
</tr>
<tr>
<td>Load torque $T_L$</td>
<td>0N·m</td>
</tr>
<tr>
<td>Sudden load torque $T_L$</td>
<td>10N·m</td>
</tr>
<tr>
<td>Moment of inertia $J$</td>
<td>0.003kg.m$^2$</td>
</tr>
<tr>
<td>Variable step size</td>
<td>ode23tb</td>
</tr>
<tr>
<td>Total simulation time</td>
<td>0.4s</td>
</tr>
<tr>
<td>Relative error</td>
<td>0.0001</td>
</tr>
</tbody>
</table>

The waveform diagrams of speed, torque, current are as follows

The speed comparison curve is shown in Fig. 4. Fig. 4 shows that the traditional PI control has a larger overshoot than the SMC control. When a load of 10N·m is suddenly applied in 0.2s, the SMC control can recover to the reference value of the given speed faster, and the range of deviation from the given speed value is smaller.

Fig. 5 is the amplified curve of sudden load speed, the curve shows that the designed sliding mode speed controller has better dynamic performance and anti-disturbance ability, and can meet the needs of actual motor control performance.
As shown in Fig. 6, the dotted line represents SMC control, and the solid line represents PI control. It can be seen that the torque peak value of the motor is large when it starts, and it can quickly return to no-load operation. Compared with PI control, the SMC has smaller torque fluctuations, when the load is suddenly applied at 0.2s, the torque waveform shows that the load torque can be accurately reached, and the SMC control is more agile and accurate than PI control.

![Figure 6: Torque Comparison Curve](image)

It can be seen from Fig. 7 that in a short time, the three-phase current generated by SVPWM turns into a stable value, with rapid response, a small error, and smooth transition. The motor can be well controlled.

![Figure 7: Three-phase current waveform](image)

**CONCLUSION**

This paper mainly studies the control strategy of the PMSM model, the strategy of PMSM-SMC for PMSM is proposed. Based on vector control, the operation of the motor can be precisely controlled. Firstly, analyze the basic principles of the introduced control method. Meanwhile, build a simulink simulation model for verification. The verification results show that the control method has the advantages of good control effects, rapid response, small steady-state error and robustness. Compared with the PI control, the method proposed in this article has improved speed regulation and torque ripple. The sliding surface will be further improved to obtain a better control effect to lay a good foundation for physical verification.

**References**


