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Synchronous Control of Two Motors Based on Improved Sliding Mode Control

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Abstract: With the technological development of the society, permanent magnet synchronous motors are used more and more widely, especially in the two-motor synchronous system. Aiming at the problems of response performance and anti-interference ability of the dual motor synchronous system, this paper proposes an improved sliding mode speed control controller. First, its mathematical model is established by analyzing the mechanical principle and working principle of the permanent magnet synchronous motor. On the basis of the traditional sliding mode controller, the sliding mode surface and convergence rate are improved to obtain the improved sliding mode controller, and the simulation model of the improved sliding mode controller is built. MATLAB/Simulink is used to build a dual motor synchronous system model for verification, and the experimental results show that the improved sliding mode speed controller has no overshooting, fast response speed, and strong anti-jamming ability, and its response performance and anti-jamming ability are better than that of the traditional sliding mode speed controller.

Keywords: Dual motor; improved sliding mold; speed control.

1. Introduction

AC speed control systems play a crucial role in modern industry and transportation, especially in the context of the rapid development of motor drive technology. As the global concern for energy efficiency and environmental protection intensifies, AC motors, with their advantages of high efficiency, low noise, and simple maintenance, have gradually replaced the traditional DC motors as the mainstream drive solution[1,2].

Permanent magnet synchronous motors are widely used in AC speed control systems due to their simple structure, fast response speed and high power density. Proportional-integral control technology is widely used in dual-motor synchronous systems because of its simple structure and easy digital implementation. However, traditional sliding mode controllers are often difficult to meet the requirements of high-precision control in the face of system uncertainties and external disturbances.

In recent years, in order to solve the shortcomings of the traditional sliding mode control in the field of high-performance control of permanent magnet synchronous motor, many scholars have combined various control strategies, such as fuzzy control, self-resistant control, sliding mode control, and model predictive control, in order to enhance the anti-interference ability and dynamic performance of the PMSM speed control system[3–5]. In particular, the successful application of sliding mode control in the motor speed control system significantly enhances the robustness of the system and improves the response speed[6,7]. In order to achieve overshoot-free, fast response and enhanced robustness, researchers have proposed a novel convergence-rate sliding-mode control method, which outperforms the traditional convergence-rate control[8]. In the literature [9], the researcher designed the sliding mode control with optimal integral performance and optimal switching function using dynamic error as the performance index, thus improving the speed response and robustness of the system. Literature [10] , on the other hand, combines a fast twisting algorithm with a perturbation observer for composite control, which effectively suppresses the jitter vibration phenomenon in the sliding mode control. Literature [11] designed a speed controller with an integral sliding mode variable structure and combined it with a load torque observer, which significantly improves the speed control performance of the system. Literature [12] compensated the reference voltage variations caused by motor parameter perturbations by improving the sliding mode exponential convergence law in combination with a disturbance observer, thus enhancing the parameter robustness of the system. Literature [13] introduced an enhanced adaptive sliding mode controller in the speed loop of the speed control system, and although the speed control performance was comprehensively improved, there were some difficulties in implementation. Literature [14] used a self-imposed control structure combined with sliding mode control to optimize the designed extended state observer and nonlinear error feedback control law. Literature [15] designed a full-order sliding mode observer, omitted the low-pass filter, and selected the sigmoid function as the switching function to suppress the system's jitter, and introduced the fuzzy control to improve the robustness of the system. In order to solve the problems such as parameter variation, literature [16] improved the observer for stator resistance, which improves the system accuracy and attenuates the jitter. To address the problems of low accuracy of speed estimation and large jitter, literature [17] adopts a sliding mode observer and designs a new switching function, which effectively eliminates the high-frequency harmonics.

Based on the above research, improving the dynamic response of the speed control system and suppressing jitter has become an important research direction in the field of permanent magnet synchronous motors. This paper focuses on the sliding mode control speed governing system for a two-motor synchronous system. In order to verify the characteristics and advantages of sliding mode control. In this paper, simulation verification is carried out through the dual motor synchronous system. Firstly, its mathematical model is established through the permanent magnet synchronous motor, and the relationship between the electromagnetic torque and speed of the motor is established according to its mathematical model, on the basis of the traditional sliding mode controller, the sliding mode surface and convergence rate are improved to obtain the improved sliding mode controller, and the simulation analysis is carried out by constructing the simulation model of the improved sliding mode controller.

2. Mathematical Model of Permanent Magnet Synchronous Motor

The mathematical model of permanent magnet synchronous motor is established under the condition of neglecting the change of motor parameters and external disturbances, and the voltage equation can be obtained as follows:

$$\begin{cases} u_\mathrm{d} = Ri_\mathrm{d} + L_\mathrm{d}\dfrac{\mathrm{d}i_\mathrm{d}}{\mathrm{d}t} - \mathrm{p}\omega_\mathrm{m} L_\mathrm{q} i_\mathrm{q} \\ u_\mathrm{q} = Ri_\mathrm{q} + L_\mathrm{q}\dfrac{\mathrm{d}i_\mathrm{q}}{\mathrm{d}t} + \mathrm{p}\omega_\mathrm{m} L_\mathrm{d} i_\mathrm{d} + \mathrm{p}\omega_\mathrm{m}\psi_\mathrm{f} \end{cases} \tag{1}$$

Where: u_d, i_d, L_d are the voltage, current, and inductance on the d-axis; u_q, i_q, L_q are the voltage, current, and inductance on the q-axis; R is the stator winding resistance;ω_m is the electrical angular velocity; ψ_f is the magnetic chain; p is the number of pole pairs.

Also since the surface type permanent magnet synchronous motor has L_d=L_q and T_e is the target torque, the torque equation is as follows:

$$T_\mathrm{e} = \frac{3}{2} p\psi_f i_q \tag{2}$$

which is under the PMSM equation of motion:

$$\frac{\mathrm{d}\omega_m}{\mathrm{d}t} = \frac{3p\psi_f}{2J} i_\mathrm{q} - \frac{T_\mathrm{L}}{J} \tag{3}$$

Where: J is the moment of inertia; T_L is the load torque.

3. Improved Design of Sliding Mode Controller

3.1. Design of sliding mold surface

Define the state variables of the PMSM system:

$$\begin{cases} x_1 = \omega_{ref} - \omega_m \\ x_2 = \dot{x}_1 \end{cases} \tag{4}$$

Where, ω_{ref} is the reference speed of the motor, ω_m is the actual speed value. According to equation equation (3), (4) can be obtained:

$$\begin{cases} x_1 = -\dot{\omega}_m = \dfrac{1}{J}(-T_L + \dfrac{3p\psi_f}{2} i_\mathrm{q}) \\ x_2 = -\ddot{\omega}_m = -\dfrac{3p\psi_f}{2J} i_\mathrm{q} \end{cases} \tag{5}$$

Define u , D.

$$\begin{cases} u = \dot{i}_q \\ D = \dfrac{3p\psi_f}{2J} \end{cases} \tag{6}$$

Then Eq. (5) is transformed into:

$$\begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} + \begin{bmatrix} 0 \\ -D \end{bmatrix} u \tag{7}$$

Design the system with a sliding mold surface of:

$$s = c(t)x_1 + x_2 \tag{8}$$

Assuming that the system is initially on the sliding mold surface, it can be obtained:

$$s = 0 \tag{9}$$

The following integral performance index J for $c(t)$ is minimized by design.

$$J = \int_{t_0=0}^{t_f=T} (x_1^2(t) + x_2^2(t))dt \tag{10}$$

T is the terminal time to reach the slip mold surface, solving equation (10) yields.

$$\begin{cases} x_1^2(t) = \alpha^2 e^{-2\int_0^t c(t)dt} \\ x_2^2(t) = -\alpha^2 c^2(t) e^{-2\int_0^t c(t)dt} \end{cases} \tag{11}$$

α is the initial condition parameter of the system. Let c_m,c_p be the initial and final values of $c(t)$ change curve. Combining equations (11)(12) gives:

$$\begin{aligned} J &= \int_{t_0=0}^{t_f=T} (\alpha^2 e^{-2\int_0^t c(t)dt} + \alpha^2 c^2(t) e^{-2\int_0^t c(t)dt})dt \\ &\int_{t_0=0}^{t_f=T} (1 + c^2(t)) e^{-2\int_0^t c(t)dt} dt \end{aligned} \tag{12}$$

To simplify this integral, redefine $c(t)$ and $v(t)$:

$$c(t) = \dot{v}(t) = \frac{d}{dt}(\int_0^t c(\tau)d\tau) + c \tag{13}$$

Rewrite the objective function J:

$$J = \int_{t_0=0}^{t_f=T} (1 + \dot{v}^2(t)) e^{-2(v(t)+c)} dt \tag{14}$$

Introduce the function g:

$$g = (1 + \dot{v}^2(t)) e^{-2(v(t)+c)} \tag{15}$$

According to the Lagrange equation we get.

$$\frac{\partial g}{\partial v}-\frac{d}{dt}(\frac{\partial g}{\partial \dot{v}})=0 \tag{16}$$

Calculate the derivatives and get:

$$\begin{aligned}&\frac{\partial g}{\partial \dot{v}}=2\dot{v}^2(t)e^{-2(v(t)+c)}\\&\frac{d}{dt}(\frac{\partial g}{\partial \dot{v}})=\frac{d}{dt}(2\dot{v}^2(t)e^{-2(v(t)+c)})\end{aligned} \tag{17}$$

Solving the differential equation yields.

$$\ddot{v}(t)=\dot{v}^2(t)-1 \tag{18}$$

obtained by separating the variables and integrals:

$$c(t)=\frac{f+e^{2t}}{f-e^{2t}} \tag{19}$$

Substitute the initial value c_m and solve for the coefficient f.

$$f=\frac{c_m+1}{c_m-1} \tag{20}$$

Substitute the final value c_p to find the moment T of arrival at the final value.

$$T=\frac{1}{2}\ln f\frac{(c_m+1)}{(c_m-1)} \tag{21}$$

3.2. Design of sliding mode convergence rate

Derivation for the sliding mold surface yields.

$$\dot{s}=c(t)\dot{x}_1+\dot{x}_2=c(t)x_2-Du \tag{22}$$

In order to ensure the good dynamic quality of the PMSM motor, the sign function is chosen to replace the exponential convergence rate. The sign function is designed as.

$$\mathrm{sgn}(s)=\begin{cases}1 & s>0\\0 & s=0\\-1 & s<0\end{cases} \tag{23}$$

Find the expression for the controller:

$$u=\frac{1}{D}[c(t)x_2+\varepsilon\,\mathrm{sgn}(s)+qs] \tag{24}$$

From this, the q-axis reference current is found to be.

$$i_q^*=\frac{1}{D}\int_0^t[c(t)x_2+\varepsilon\,\mathrm{sgn}(s)+qs]d\tau \tag{25}$$

The block diagram of the improved sliding mode controller structure is shown in Fig. 1.

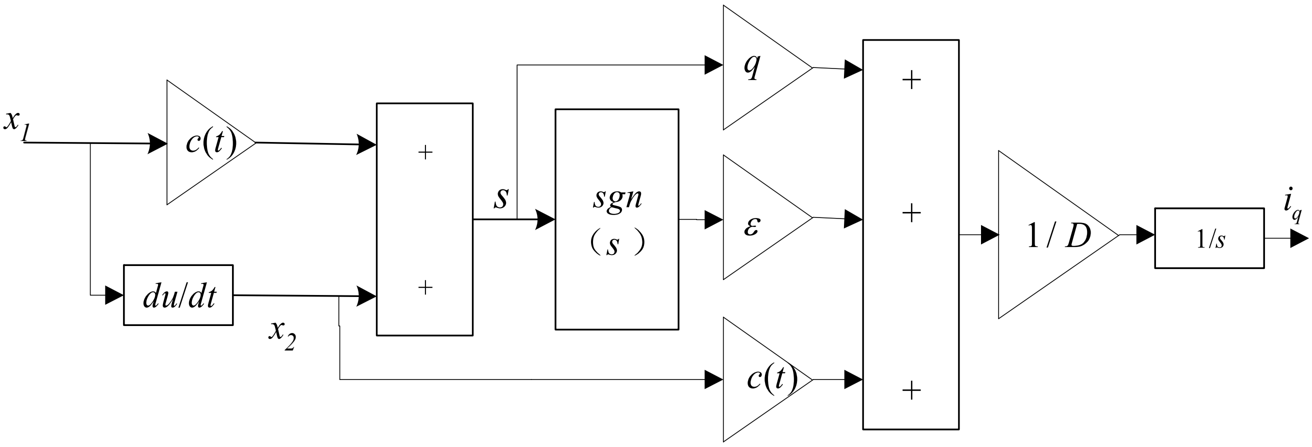

Figure 1. Block diagram of improved sliding mode controller structure

3.3. Cross-coupled controller design

Motor cross-coupling controllers are mainly used to control multi-motor systems, especially when multi-motors work together to solve the mutual interference and coupling problems between motors. In this paper, the cross-coupled controller is selected for dual-motor synchronous control. Its structure is shown in Figure 2.

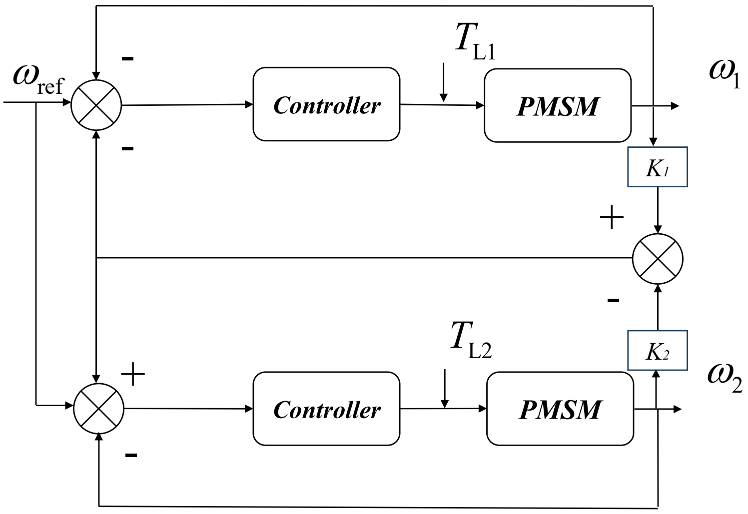

Figure 2. Block diagram of cross-coupled structure

4. Simulation and Verification

4.1. Analysis of single motor simulation results

In order to verify the validity of the method in this paper, the vector control strategy adopted by the surface-mounted permanent magnet synchronous motor as the research object, the system adopts the double closed-loop control, the current loop is the inner loop with PI control, and the speed loop is the outer loop with improved sliding mode control, and the simulation system is built by using MATLAB/Simulink.

The parameters of the surface-mounted three-phase PMSM used in the simulation are shown as follows: stator resistance Rs = 2.875 Ω, stator inductance $L_d = L_q$ = 8.5 mH, magnetic chain Ψ_f = 0.175 Wb, pole-pair number P = 4, and rotational inertia J = 0.003 kg-m.

The target rotational speed is set to be 1000r/min and a load of 10N-m is applied abruptly at 0.5s. The velocity response curves of the improved sliding mode and the conventional sliding mode are shown in Fig. 2. Where Table 1, Table 2 shows the dynamic performance and anti-interference ability of the control method.

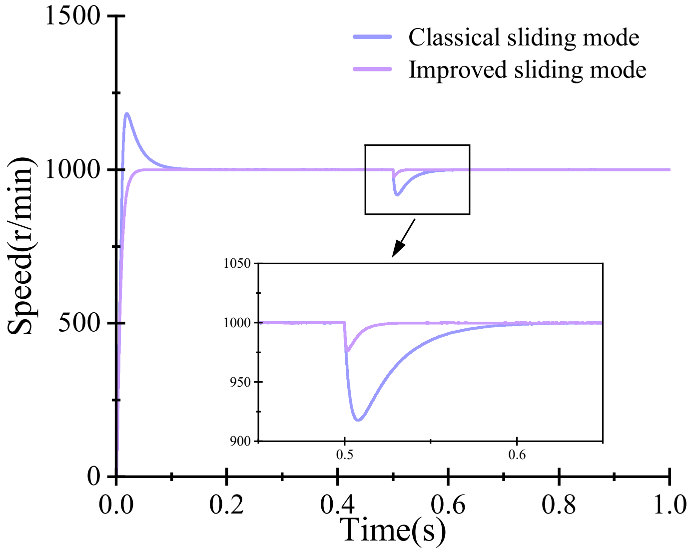

Figure 3. Variation curve of single motor speed

Table 1. Dynamic performance comparison

	Overtone (r/min)	Adjustment time (t/s)
traditional sliding mode	182.5	0.09
improved sliding mode	0	0.02

Table 2. Comparison of anti-interference performance

	Reduced RPM (r/min)	recovery time (t/s)
traditional sliding mode	82.3	0.09
improved sliding mode	23.7	0.025

From Fig. 3, Table 1 and Table 2, it can be seen that the overshoot of the improved sliding mode is 0 when the setting speed is 1000 r/min, and its regulation time decreases by 77.8% compared with the traditional sliding mode control. When facing a sudden load of 10N-m, the falling speed of the improved sliding mode decreases by 72.2% compared with the traditional sliding mode control, and the recovery time decreases by 71.2% compared with the traditional sliding mode control. The results show that the proposed improved sliding mode controller outperforms the conventional sliding mode in improving the dynamic performance and anti-interference performance of the speed control system.

4.2. Analysis of dual motor synchronization simulation results

The target speed of dual motor synchronization is set to be 1000r/min, and a load of 10N-m is applied abruptly at 0.5s. The speed response curve of the traditional sliding mode dual-motor synchronization is shown in Fig. 4, the speed response curve of the improved sliding mode dual-motor synchronization is shown in Fig. 5, and the curve of the speed difference is shown in Fig. 6. Where Table 3 shows the anti-interference capability of dual motor synchronization.

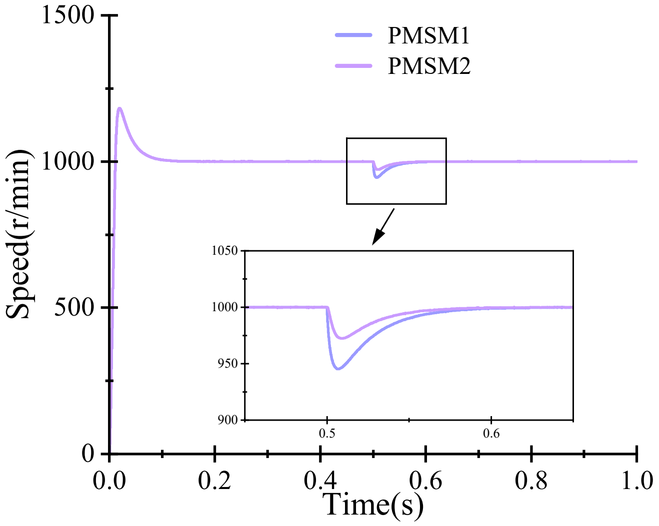

Figure 4. Variation curve of speed of dual motors of conventional sliding mode

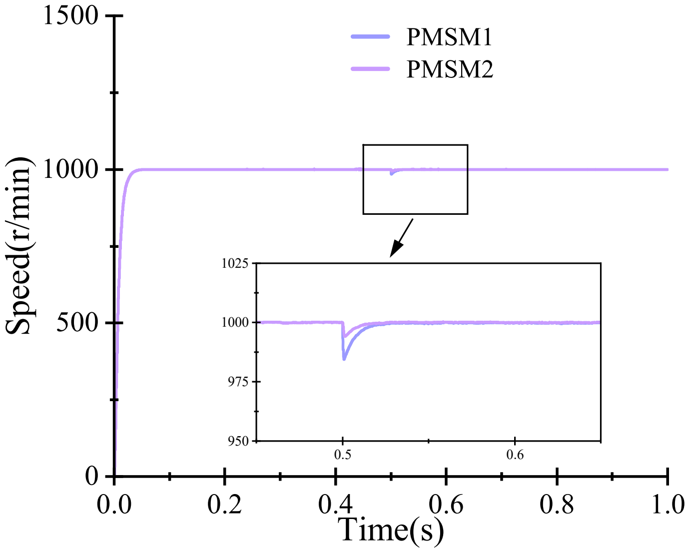

Figure 5. Improved sliding mode dual motor speed change curve

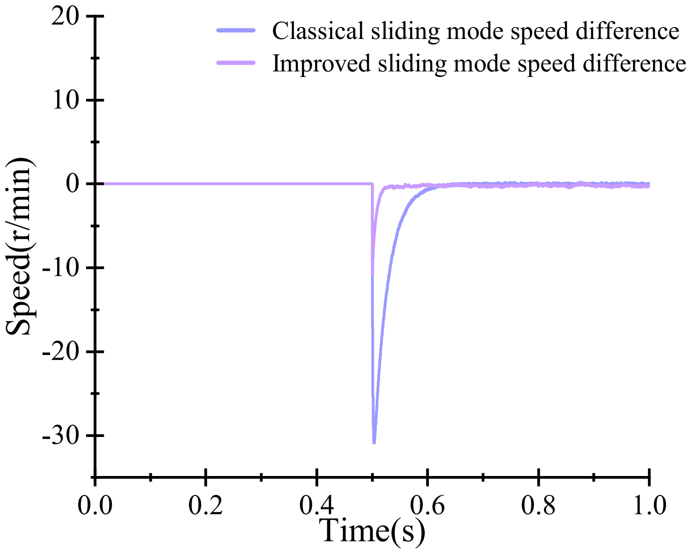

Figure 6. Dual motor speed difference change curve

Table 3. Comparison of anti-interference performance of dual motors

	Dual motor speed difference (r/min)	recovery time (t/s)
traditional sliding mode	10.8	0.11
improved sliding mode	30.9	0.03

From Figures 4, 5 and 6 and Table 3, it can be seen that when setting the synchronous speed of the dual motors at 1000 r/min, the dual motor speed difference of the improved sliding mode decreases by 65% compared with that of the traditional sliding mode control and the recovery time decreases by 72.7% compared with that of the traditional sliding mode control in the face of a suddenly applied load of 10 N-m. The results show that the anti-interference performance of the improved sliding mode controller is better than that of the traditional sliding mode in the dual motor control system.

5. Conclusion

In this paper, based on the traditional sliding mode controller, an improved sliding mode controller is designed by replacing the traditional constant sliding mode surface with a sliding mode surface with excellent integral performance, and the sign function is selected to replace the exponential convergence rate. Through simulink simulation, it can be concluded that, relative to the traditional sliding mode control, the improved sliding mode control can effectively reduce the overshooting amount and regulation time, so that the permanent magnet synchronous motor can react faster, so that the reaction time and the speed difference of the two-motor synchronous system are reduced significantly.

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