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Extended State Observer Based on Fixed Time Sliding Mode Control of Permanent Magnet Synchronous Motor

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ABSTRACT

A fixed time integral sliding mode control (FTISMC) method based on extended state observer (ESO) is proposed for permanent magnet synchronous motor (PMSM) servo system with unknown disturbance. Firstly, the total disturbance of the system is observed by the ESO, and the observed total disturbance is incorporated into the control design to compensate the unknown disturbance. Secondly, a fixed-time sliding mode controller based on an improved integral sliding mode surface is designed to make the system state converge in fixed time, then the closed-loop stability of the system is proved via the Lyapunov theory. Finally, compared with the traditional PID control, the simulation results show that the proposed control scheme can improve the tracking performance, and effectively enhance the control precision and anti-disturbance ability of the PMSM servo system.

1. Introduction

In recent years, permanent magnet synchronous motor has been widely studied due to its small size, light weight and simple structure and widely used in aerospace, numerically-controlled machine tool, machining and flexible manufacturing [1-9]. However, as a typical multi-variable strongly coupled nonlinear system, pmsm's parameters are easily changed after being subjected to unknown disturbances, thereby reducing the control performance of the system. Therefore, it is necessary to design an effective control strategy to compensate the motor servo system. Improve the control accuracy and anti-disturbance ability of the system.

Proportional-integral (PI) control has been widely used in motor drive control as a traditional permanent magnet synchronous motor speed regulation method due to its simple theory and easy implementation [10]. However, Parameter disturbances and load changes in the motor control system will affect it and reduce the control accuracy, In order to solve this problem, many advanced control methods are proposed to improve the control performance of the motor system, such as direct torque control [11], active disturbance rejection control (ADRC) [12], adaptive control [13-16] and sliding mode control (SMC) [17]. Among these advanced control methods, SMC has become a research hotspot because of its low requirements on model accuracy and strong robustness to external interference. In addition, SMC has been successfully applied to motor speed control system [18-19]. Even so, SMC is not perfect. In fact, there will be a time delay in switching the control law in practical applications, which will cause the system state to switch rapidly and cause chattering.

In order to solve the chattering problem in SMC, many scholars have proposed different solutions. Reference [20] a composite sliding mode control method for speed control of surface mount permanent magnet synchronous motor is proposed, which can effectively suppress chattering and shorten the time for the system state to approach the sliding mode surface. Reference [21] for the load disturbance, an integral sliding mode variable structure controller based on the load torque observer is designed. The observation value obtained from the observer is fed back to the sliding mode controller, so that the motor control system has rapidity and no overshoot. It has the advantages of strong robustness to load disturbance. Reference [22] a composite control method combining a non-singular fast terminal sliding mode controller and a disturbance observer is proposed, and then a new sliding mode reaching law is improved, which can reduce the chattering of the control output while maintaining the high tracking performance of the controller. It can dynamically adapt to the changes of the controlled system, and has good chattering suppression effect, fast dynamic response and anti-interference ability. However, in the application of motor, it is difficult to obtain the initial value of the state variable, and the

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convergence time cannot be guaranteed.

Therefore, a fixed time integral sliding mode controller is designed for the difficulty in obtaining the initial value of state variables and the unguaranteed convergence time. The lumped disturbance of the system is estimated by expanding state observer, and then the disturbance is compensated by using the designed controller. In this paper, selection of fixed time sliding mode surface is different from the traditional linear sliding mode surface, the integral term of sliding mode surface can effectively suppress chattering, ensure the system state can be fixed time convergence, accelerate the system response speed, improve the anti-disturbance ability of the system.

The structure of this paper is as follows: The second section is an overview of permanent magnet synchronous motor mathematical model and fixed time lemma, the third section is the design process of extended state observer, the fourth section is the design and stability analysis of fixed time sliding mode controller, and the fifth section is the comparative demonstration of simulation results. The sixth section is the conclusion of the thesis.

2. Permanent Magnet Synchronous Motor Mathematical Model and Fixed Time Lemma

2.1 Overview of fixed time lemma.

To solve the problem more conveniently, the following lemmas are introduced:

Lemma 1[23]: Consider the system as follows:

$$x = f(x), \quad f(0)=0, \quad x \in R^n \tag{1}$$

where $f(\bullet): R^n \to R^n$ is a continuous function, if the equilibrium $x=0$ of system (1) is lyapunov stable and convergent in finite time, then it is a finite time stable equilibrium, that is to say, there exist a $t \geq T(x_0)$ satisfy the equation $x(t,x_0)=0$, where $x(t,x_0)=0$ is the solution for system (1) start at $x(0)=x_0$, if the equilibrium $x=0$ of system (1) is a finite time stable equilibrium, and the previous finite convergence time $T(x_0)$ is independent of the initial state, that is to say, $T(x_0)$ is a constant for all $x_0 \in R^n$.

Lemma 2[23]: For system (1), if there is exist a continuous positive definite function $V(x)$ such that, $\dot{V}(x) \leq -\alpha V^p(x) - \beta V^q(x) + v \;\; x \in R^n$,where, $\alpha > 0, \beta > 0, 0 < p < 1, q > 1$,then the system is actually fixed time stable, and the fixed establishment time is expressed as $T \leq 1/(\alpha\theta(1-p)) + 1/(\beta\theta(q-1))$, where, $0 < \theta < 1$.

Lemma 3[23]: For system (1), if there is exist a continuous positive definite function $V(x)$ such that, $\dot{V}(x) \leq -\alpha V^p(x) - \beta V^q(x)$, $x \in R^n$, where, $\alpha > 0$, $\beta > 0$, $0 < p < 1$, $q > 1$, then the system is actually fixed time stable, and the fixed establishment time is expressed as $T \leq 1/(\alpha(1-p)) + 1/(\beta(q-1))$.

2.2 Permanent Magnet Synchronous Motor Mathematical Model.

Select the rotor coordinate axis (axis) of permanent magnet synchronous motor as the reference coordinate, then the mathematical model of surface mount permanent magnet synchronous motor ($L_d = L_q = L$) can be described as:

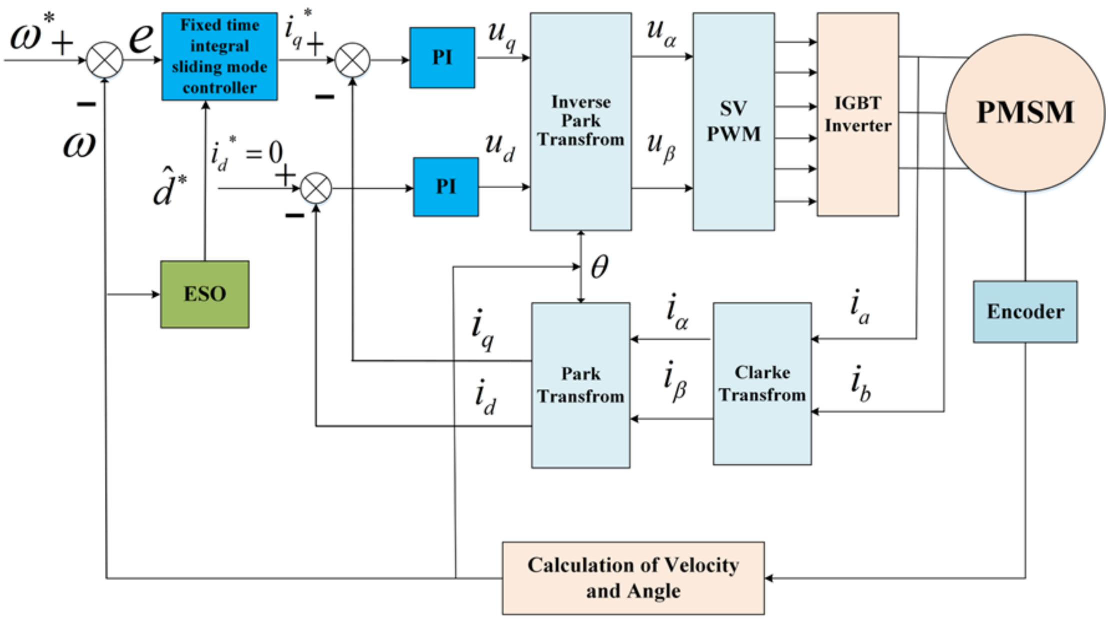


Figure 1: PMSM speed control system block diagram based on ESO and FTISMC

$$\begin{cases} \dot{i}_d = -\dfrac{R_s i_d}{L_d} + n_p \omega i_q + \dfrac{U_d}{L_d} \\ \dot{i}_q = -\dfrac{R_s i_q}{L_q} - n_p \omega i_d - \dfrac{n_p \omega \psi_f}{L_q} + \dfrac{U_q}{L_q} \\ J\dot{\omega} = \dfrac{3}{2} n_p \psi_f i_q - T_L - B\omega \end{cases} \tag{2}$$

where i_d and i_q are the current of the d axis and the q axis respectively; U_d and U_q are the voltage of d axis and q axis respectively; R_s is the stator winding resistance; L_d and L_q are the inductance of the d axis and the q axis respectively; ψ_f is the flux generated by the permanent magnet; n_p is the polar logarithm of permanent magnet synchronous motor; ω is the angular velocity of the motor mechanical rotor; T_L is the load torque; J is the rotational inertia ; B is the friction damping.

The main purpose of this paper is to design a fixed time integral sliding mode controller for the speed loop of permanent magnet synchronous motor based on extended state observer so that the whole system has good adaptability to unknown disturbance. The schematic diagram of control system structure is shown in Figure 1. The system includes inverter, pulse width modulation module, permanent magnet synchronous motor, coordinate transformation module, encoder, fixed time integral sliding mode controller and extended state observer. Two PI control algorithms are used in two current circuits respectively. In order to approximately eliminate the coupling between angular velocity and stator current, it is generally set i_d^* to 0 to achieve approximate decoupling [24].

3. Design of Extended State Observer

To facilitate the design of the extended state observer, equation (2) is transformed as follows:

$$\begin{aligned} \dot{\omega} &= \frac{b}{J} i_q - \frac{T_L}{J} - \frac{B}{J}\omega \\ &= \frac{b}{J} i_q^* - \frac{T_L}{J} - \frac{B}{J}\omega - \frac{b}{J}(i_q^* - i_q) \\ &= \frac{u}{J} - d^* \end{aligned} \tag{3}$$

where $b = \dfrac{3}{2} n_p \psi_f$, $u = b i_q^*$ is the control input, its physical meaning is electromagnetic torque, and $d^* = \dfrac{T_L}{J} + \dfrac{B}{J}\omega + \dfrac{b}{J}(i_q^* - i_q)$ is the total disturbance of the system. According to equation (3), it can be seen that it is a lumped disturbance d^* composed of load torque, disturbance inertia and friction damping. After the disturbance d^* is observed and compensated by the observer, the system can be approximated as a first-order integral system.

Assume1[25]: assumes that disturbance d^* is unknown and bounded and its derivatives satisfy $\sup_{t\ge 0}\left|\dot{d}^*\right| \le d_m$, where $d_m \ge 0$ is constant.

The principle and analysis of the specific extended state observer can be directly given by reference [26-27], as shown in the following formula:

$$\begin{cases} \dot{\hat{\omega}} = \hat{d}^* - p_1(\hat{\omega} - \omega) + \dfrac{b}{J} i_q^* \\ \dot{\hat{d}}^* = p_2(\hat{\omega} - \omega) \end{cases} \tag{4}$$

where p is the poles of ESO, $p_1 = 2p$, $p_2 = -p^2$, $\hat{\omega}$ is the estimation of velocity ω , and $\hat{d}^*$ is the estimation of total disturbance d^* of the system.

The observation error of the extended state observer is defined as

$$\begin{cases} \eta_1 = \hat{\omega} - \omega \\ \eta_2 = \hat{d}^* - d^* \end{cases} \tag{5}$$

where η_1 is the observation error of velocity and η_2 is the observation error of disturbance. Then, the dynamic equation of observation error of the observer can be expressed as:

$$\begin{cases} \dot{\eta}_1 = \eta_2 - p_1\eta_1 \\ \dot{\eta}_2 = p_2\eta_1 - \dot{d}^* \end{cases} \tag{6}$$

4. Design of Fixed Time Integral Sliding Mode Controller

4.1 Design of Controller.

A Select ω^* is the expected speed, ω is the actual output speed, then the tracking error can be expressed as

$$e = \omega^* - \omega \tag{7}$$

Thus, the dynamic equation of velocity error can be obtained as

$$\dot{e} = \dot{\omega}^* - \frac{b}{J} i_q^* + d^* \tag{8}$$

where $\dot{\omega}^* = d\omega^*/dt$.

On the premise of ensuring the stability of the system, the integrated sliding mode surface at fixed time was selected as

$$s = e + \int_0^t k_1 \operatorname{sgn}(e)|e|^\alpha + k_2 \operatorname{sgn}(e)|e|^\beta d\tau \tag{9}$$

where k_1、k_2 is a positive real number and $\beta > 1$ $0 < \alpha < 1$.

Derivative of equation (9) can be obtained derivatives of sliding surfaces as follows:

$$\begin{aligned} \dot{s} &= \dot{e} + k_1 \operatorname{sgn}(e)|e|^\alpha + k_2 \operatorname{sgn}(e)|e|^\beta \\ &= \dot{\omega}^* - \frac{b i_q}{J} + d^* + k_1 \operatorname{sgn}(e)|e|^\alpha + k_2 \operatorname{sgn}(e)|e|^\beta \\ &= -b i_q^*/J + \dot{\omega}^* - b\left(i_q - i_q^*\right)/J + d^* \\ &\quad + k_1 \operatorname{sgn}(e)|e|^\alpha + k_2 \operatorname{sgn}(e)|e|^\beta \end{aligned} \tag{10}$$

In order to keep the sliding mode state on the sliding mode surface, the fixed-time integral sliding mode controller is designed as

$$i_q^* = \frac{J}{b}\begin{pmatrix} \dot{\omega}^* + \hat{d}^* + k_1 \operatorname{sgn}(e)|e|^\alpha + J k_2 \operatorname{sgn}(e)|e|^\beta \\ + k_0 s + k_3 \operatorname{sgn}(s)|s|^{\alpha_1} + k_4 \operatorname{sgn}(s)|s|^{\alpha_2} \end{pmatrix} \tag{11}$$

where k_0、k_3、k_4 is a positive real number and $k_0 > 0.5$, $0 < \alpha_1 < 1$, $\alpha_2 > 1$.

4.2 Stability analysis.

Substituting (11) into (10) to obtain

$$\begin{aligned}\dot{s} &= -k_0 s - k_3 \operatorname{sgn}(s)|s|^{\alpha_1} - k_4 \operatorname{sgn}(s)|s|^{\alpha_2} \\ &+ b\left(i_q - i_q^*\right)/J\end{aligned} \tag{12}$$

Might as well set $n = b\left(i_q - i_q^*\right)/J$ and $|n| \le n^*$ where n^* is a positive real number.

Theorem 1: Considers a closed-loop control system consisting of a permanent magnet synchronous motor servo system (2), a fixed-time integral sliding mode controller (11) and an extended state observer (4). The state of the system is stable and the tracking error can converge to a small enough region within a fixed time.

Prove: Select the first Lyapunov function

$$V = \frac{1}{2}s^2 + \frac{1}{2}\eta_2{}^2 \tag{13}$$

The derivative of equation (13) is

$$\dot{V} = -k_0 s^2 - k_3|s|^{\alpha_1+1} - k_4|s|^{\alpha_2+1} + sn + \eta_2\dot{\eta}_2 \tag{14}$$

According to Young's inequality, we get

$$sn \le \frac{1}{2}s^2 + \frac{1}{2}n^2 \tag{15}$$

$$\eta_2\dot{\eta}_2 \le \frac{1}{2}\eta_2{}^2 + \frac{1}{2}\dot{\eta}_2{}^2 \tag{16}$$

Substituting (15), (16) into (14), we get

$$\begin{aligned}\dot{V} &\le -k_0 s^2 - k_3|s|^{\alpha_1+1} - k_4|s|^{\alpha_2+1} + \frac{1}{2}s^2 \\ &+ \frac{1}{2}\eta_2{}^2 + \frac{1}{2}n^2 + \frac{1}{2}\dot{\eta}_2{}^2 \\ &\le -L_1 V + L_2\end{aligned} \tag{17}$$

where L_1, L_2 is a bounded constant value and

$L_1 = \min\{2k_0 - 1, 2k_3, 2k_4, -1\}$, $L_2 = 1/2\,n^2 + 1/2\,\dot{\eta}_2{}^2$

Because the estimation error is also bounded, according to reference [28], the system is stable in finite time, and then it is further proved that the error system can be stabilized to the sliding mode surface in fixed time.

Select the second Lyapunov function

$$V_1 = \frac{1}{2}s^2 \tag{18}$$

The derivative of V_1 is

$$\begin{aligned}\dot{V}_1 &\le -k_0 s^2 - k_3|s|^{\alpha_1+1} - k_4|s|^{\alpha_2+1} + sn \\ &\le -\left(k_0 - \frac{1}{2}\right)s^2 - k_3 V^{\frac{\alpha_1+1}{2}} - k_4 V^{\frac{\alpha_2+1}{2}} + \frac{1}{2}n^2 \\ &\le -k_3 V^{\frac{\alpha_1+1}{2}} - k_4 V^{\frac{\alpha_2+1}{2}} + v\end{aligned} \tag{19}$$

where $v = 1/2\,n^2$, $|n| \le n^*$, according to lemma 2, the error system will reach the sliding mode surface at a fixed time, convergence time satisfies $T \le 1/\left(\alpha\theta(1-p)\right) + 1/\left(\beta\theta(q-1)\right)$ and $\alpha = k_3$, $\beta = k_4$, $p = (\alpha_1+1)/2$, $q = (\alpha_2+1)/2$, $0 < \theta < 1$.

When the tracking error stabilizes to the sliding mode surface, equation (9) can be written

$$\dot{e} = -k_1 \operatorname{sgn}(e)|e|^{\alpha} - k_2 \operatorname{sgn}(e)|e|^{\beta} \tag{20}$$

Select the third Lyapunov function

$$V_2 = \frac{1}{2}e^2 \tag{21}$$

The derivative of V_2 is

$$\begin{aligned}\dot{V}_2 &= e\dot{e} \\ &= e\left(-k_1 \operatorname{sgn}(e)|e|^{\alpha} - k_2 \operatorname{sgn}(e)|e|^{\beta}\right)\end{aligned} \tag{22}$$

To calculate we can get $\dot{V}_2 \le 0$, according to lemma 3, the error state will converge to zero in a fixed time.

Theorem 2: Assuming that the tracking error dynamic equation (8) satisfies assume 1, under the proposed control strategy, the sliding mode converges to $|s| \le \Theta = \min\left\{(n/k_3)^{1/\alpha_1}, (n/k_4)^{1/\alpha_2}\right\}$ in fixed time, and the tracking error converges to $|e| \le \Phi = \min\left\{(\Lambda/k_1)^{1/\alpha}, (\Lambda/k_2)^{1/\beta}\right\}$ in fixed time, where $\Lambda = -k_0\Theta - k_3\Theta^{\alpha 1} - k_4\Theta^{\alpha 2} + n$.

Prove: From equation (19), we can get

$$\begin{aligned}\dot{V}_1 &\le -k_0 s^2 - k_3|s|^{\alpha_1+1} - k_4|s|^{\alpha_2+1} + sn \\ &\le -k_3|s|^{\alpha_1+1} - k_4|s|^{\alpha_2+1} + |s||n| \\ &\le -k_3|s|\left(|s|^{\alpha_1} - \frac{n^*}{k_3}\right) - k_4|s|^{\alpha_2+1}\end{aligned} \tag{23}$$

According to lemma 3, the state of the system tends to the sliding mode surface within a fixed time. In order to ensure the fixed time stability of the system, it is necessary to satisfies the condition $\left(|s|^{\alpha_1} - n/k_3\right) > 0$,that is to say $|s| > (n/k_3)^{1/\alpha_1} = \Theta_1$. Therefore, according to reference [29], as long as $|s| > \Theta_1$, the sliding mode variable can arrive $|s| \le \Theta_1$ within a fixed time.

Similarly, equation (19) can be written as

$$\begin{aligned}\dot{V}_1 &\le -k_0 s^2 - k_3|s|^{\alpha_1+1} - k_4|s|^{\alpha_2+1} + sn \\ &\le -k_3|s|^{\alpha_1+1} - k_4|s|^{\alpha_2+1} + |s||n| \\ &\le -k_4|s|\left(|s|^{\alpha_2} - \frac{n^*}{k_4}\right) - k_3|s|^{\alpha_1+1}\end{aligned} \tag{24}$$

According to the same principle, we can get $\left(|s|^{\alpha_2} - n/k_4\right) > 0$, namely, $|s| > (n/k_3)^{1/\alpha_1} = \Theta_1$ as long as $|s| > \Theta_2$, the sliding mode variable can arrive $|s| \le \Theta_2$ in a fixed time.

Table 1: Permanent magnet synchronous motor system parameters

System parameters	The numerical	Units
Rotational inertia J	0.003	$kg \cdot m^2$
Polar logarithm n_p	4	/
Stator winding resistance R_s	0.93	Ω
Stator inductance L_d	0.0085	H
Rotor inductance L_q	0.0085	H
Friction damping	0.008	/
Flux ψ_f	0.29	Wb

Table 2: Controller parameters

Controller	Parameters						
PID	$k_p = 15$	$k_i = 800$	$k_d = 0$				
ESO+LSMC	$k_0 = 20$	$k_1 = 100$	$k_2 = 100$	$\alpha = 1$	$p = 500$		
ESO+FTISMC	$k_0 = 20$	$k_1 = 100$	$k_2 = 100$	$k_3 = 15$	$k_4 = 15$	$\alpha = 0.7$	$\beta = 1.3$
	$\alpha_1 = 0.88$	$\alpha_2 = 1.55$	$p = 500$				

From equation (10), we can get

$$\dot{e} = -k_1 |e|^{\alpha} - k_2 |e|^{\beta} + \dot{s} \tag{25}$$

Because $|s| \le \Theta$, so equation (12) can be rewritten as

$$|\dot{s}| \le -k_0 \Theta - k_3 \Theta^{\alpha_1} - k_4 \Theta^{\alpha_2} + n = \Lambda \tag{26}$$

Equation (22) can be rewritten as

$$\begin{aligned} \dot{V}_2 &= -k_1 |e|^{\alpha+1} - k_2 |e|^{\beta+1} + e\dot{s} \\ &\le -k_1 |e|^{\alpha+1} - k_2 |s|^{\beta+1} + |e| \Lambda \\ &\le -k_1 |e| \left(|e|^{\alpha} - \frac{\Lambda}{k_1} \right) - k_2 |e|^{\beta+1} \end{aligned} \tag{27}$$

Therefore, as long as $|e| > (\Lambda/k_1)^{1/\alpha} = \Phi_1$, the sliding mode variable can arrive $|e| \le \Phi_1$ in a fixed time.

Similarly, equation (26) also can be written as

$$\begin{aligned} \dot{V}_2 &= -k_1 |e|^{\alpha+1} - k_2 |e|^{\beta+1} + e\dot{s} \\ &\le -k_1 |e|^{\alpha+1} - k_2 |s|^{\beta+1} + |e| \Lambda \\ &\le -k_2 |e| \left(|e|^{\beta} - \frac{\Lambda}{k_2} \right) - k_1 |e|^{\alpha+1} \end{aligned} \tag{28}$$

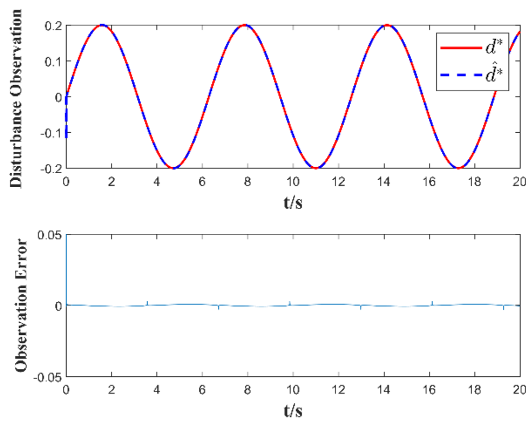
Therefore, as long as $|e| > (\Lambda/k_2)^{1/\beta} = \Phi_2$, the sliding mode variable can arrive $|e| \le \Phi_2$ in a fixed time.

5. Analysis of Simulation Results

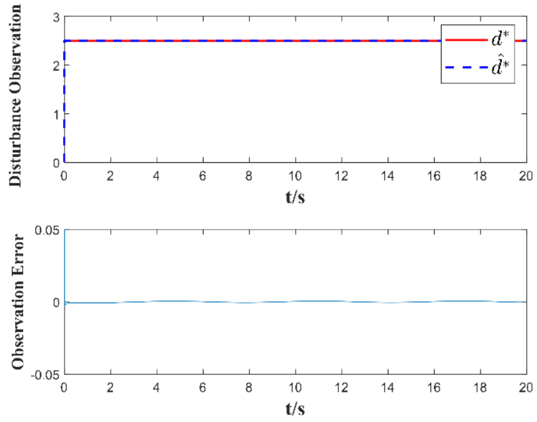
In order to verify the effectiveness of the proposed algorithm, the linear sliding mode controller based on the traditional extended state observer and the classical PID controller are selected for comparison. The simulation parameters of the model are shown as follows Table 1, the controller parameters are shown in Table 2.

Firstly, the effectiveness of the designed extended state observer is proved. Lumped disturbance signals are set as sinusoidal signals $d^* = 0.2\sin(t)\ N$ and step signals $d = 2.5\ N$ respectively, and the observation results are shown in Figure 2, the simulation results show that the designed extended state observer can achieve effective and fast observation and tracking even if the lumped disturbances are different signals, which provides a strong theoretical basis for the $\hat{d}^*$ replacement of d^* the later design of the fixed time integral sliding mode controller.

Next, the validity of the proposed algorithm is further verified. In the first case, the sinusoidal signal is tracked and the reference signal is set as. In the second case, the step signal is tracked and the reference signal is set as. In order to highlight the robustness of the proposed control method, a step external disturbance is added or subtracted at 0.5 seconds and 1 second respectively. Figure 3 is further verified. In the first case, the sinusoidal signal is tracked and the reference signal is set as.



(a)

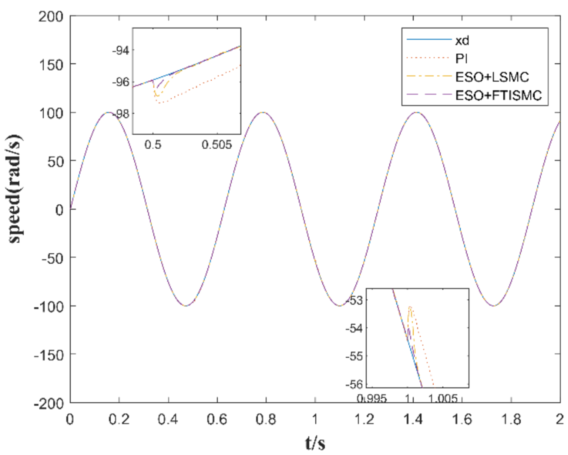


(b)

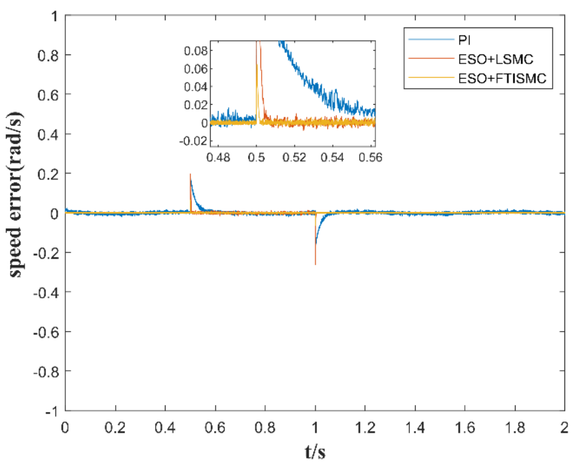
Figure 2: Observation effect of extended state observer

(a) sine signal (b) step signal

In the second case, the step signal is tracked and the reference signal is set as. In order to highlight the robustness of the proposed control method, a step external disturbance is added or subtracted at 0.5 seconds and 1 second respectively. Figure 3 and figure 4 show PMSM velocity tracking (a), velocity tracking error (b) and control input (c) images under sinusoidal signal and step signal expectation respectively.



(a)



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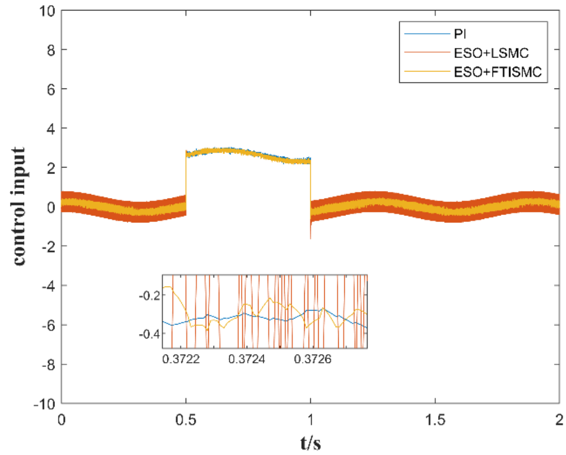
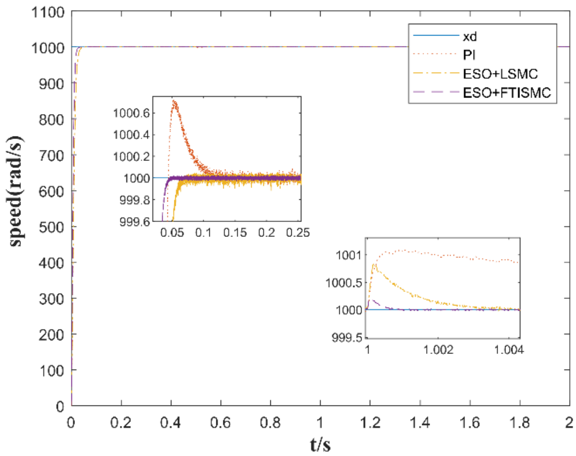


(c)

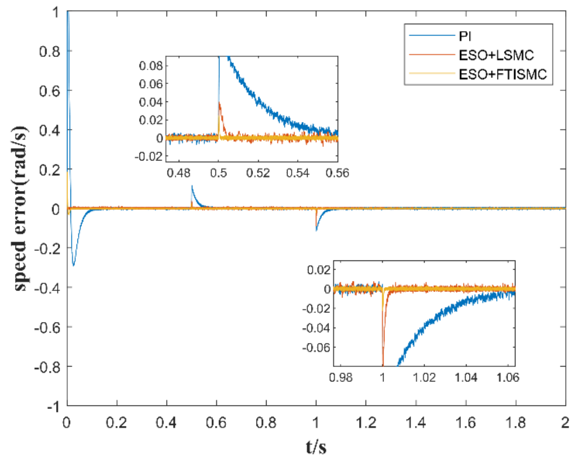
Figure 3: Sine simulation results (a) motor speed

(b) speed error, and (c) control input

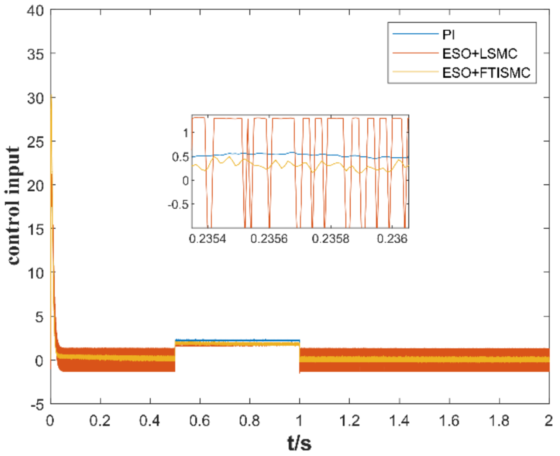
Results of Figure3 simulation show that the fluctuation of the three control methods after disturbance is 0.3, 0.6 and 1.5 respectively, and compared with the traditional linear sliding mode control, the proposed control method has no obvious chattering.



(a)



(b)



(c)

Figure 4:Step simulation results (a) motor speed

(b) speed error, and (c) control input

Results of Figure 4 simulation show that the proposed control method has no overshoot, the recovery time of the three methods is 0.14 seconds, 0.07 seconds and 0.055 seconds respectively, and the fluctuation is 1,0.8 and 0.45 respectively when disturbed. The results show that the proposed control method has faster response speed and smaller fluctuation when disturbed, and has good robustness. The simulation results show that the system has good control performance and anti-disturbance ability even if the system is disturbed by external disturbance.

Results of Figure4 simulation show that the proposed control method has no overshoot, the recovery time of the three methods is 0.14 seconds, 0.07 seconds and 0.055 seconds respectively, and the fluctuation is 1,0.8 and 0.45 respectively when disturbed. The results show that the proposed control method has faster response speed and smaller fluctuation when disturbed, and has good robustness. The simulation results show that the system has good control performance and anti-disturbance ability even if the system is disturbed by external disturbance.

6. Conclusions

In this paper, combines the extended state observer and the fixed time integral sliding mode surface to design a composite controller, ensure that the system state can accurately and quickly track the reference signal, proposed control method can not only converge rapidly, but also observe the lumped disturbance of the system through the extended state observer and embed it into the controller to compensate the disturbance. the selected sliding mode surface contains the integral term can effectively suppress chattering and enhance the performance of the controller.

In order to prove the effectiveness of the method, Sinusoidal and step signals are selected for simulation verification when the system is disturbed by external disturbance, the results show that the proposed control method can quickly compensate for the disturbance, improve the robustness of the system. Finally, compared with classical PID control and traditional sliding mode control, the proposed control method has better tracking performance, smaller error and higher accuracy. It has good chattering suppression effect, and can ensure the control precision of the system even in the case of unknown disturbance.

Data Availability

The simulation data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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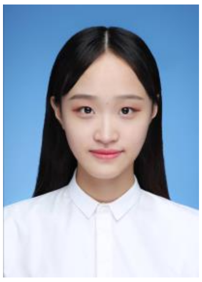

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