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Adaptive Nonsingular Fast Terminal Sliding Mode Control for Permanent Magnet Synchronous Motor Based on Disturbance Observer

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ABSTRACT To shorten the response time of permanent magnet synchronous motor (PMSM) control system, improve the robustness of the system, and avoid the influence of system structure and parameters on the control effect, an adaptive non-singular fast terminal sliding mode control scheme based on disturbance observer (DOBANFTSMC) is proposed. Firstly, a nonsingular fast terminal sliding mode surface is used to design the sliding mode controller. Secondly, the disturbance observer is used to compensating for the unknown model of the system, so that the controller design does not need to know the structure and parameters of the system. At the same time, considering the unknown estimation error bounds of the observer, an adaptive law is designed in the controller to adjust the unknown estimation. The stability of the system is proved by the Lyapunov principle. Finally, the simulation and experimental results show that this method can track the load torque quickly, and the system has the advantages of small overshoot, small static error, fast speed, and high robustness.

INDEX TERMS PMSM, nonsingular terminal sliding mode, disturbance observer, adaptive control.

I. INTRODUCTION

PMSM has the characteristics of simple structure, small size, lightweight, high efficiency, high factor, rotor heating, good overload performance, a small moment of inertia and small torque ripple. It is widely used in CNC machine tools, medical devices, instruments, aerospace and other fields [1]–[4]. As we all know, traditional control schemes such as PID (proportional-integral-differential) have been widely used in the PMSM control system [5], [6] because of its simple implementation. However, the PMSM system is a non-linear, time-varying and complex system. The traditional control algorithm [7]–[9] can't achieve satisfactory performance in the whole working range.

In recent years, to improve the different performance of the PMSM control system, various advanced control technologies [10]–[17] have been proposed. Among these methods, sliding mode control (SMC) is considered to be an effective method to improve the anti-jamming ability and robustness of PMSM system, and has been improved in further research [18]–[20]. To further improve the dynamic performance of SMC, a nonlinear sliding surface is introduced directly. As a nonlinear sliding surface, the terminal sliding mode can ensure that the finite time converges to the specified trajectory [21], [22], [23]. To solve the singular problem of terminal sliding mode, [24] proposes a nonsingular terminal sliding mode control (NTSMC). To solve the problem of convergence time of non-singular terminal sliding mode, a nonsingular fast terminal sliding mode control (NFTSMC) scheme is proposed in [25]. To avoid the unknown PMSM system model and external disturbance, a disturbance observer-based control method is proposed [26]–[28]. In [29], an adaptive nonsingular sliding mode control method with a disturbance observer is proposed. In [30], a robust SMC scheme based on fast nonlinear tracking differentiator and disturbance observer is proposed. In [31], an adaptive control scheme for the PMSM speed control system based on extended state observer (ESO) is proposed. In [32], an adaptive funnel control (Fc) scheme for an unknown dead-zone servo mechanism is proposed. The unknown dead-zone and unknown nonlinear functions are approximated by a neural network. In [33], in view of the time-varying characteristics of load torque and system parameters, the design of feed-forward compensation

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controller based on disturbance estimation is a better solution. A PCC method based on the generalized proportional integral observer is studied to deal with load torque disturbance and time-varying parameter uncertainty. In [34], an unknown input observer is proposed for servo mechanisms with unknown dynamics, such as non-linear friction, parameter uncertainty, and external disturbance. However, all the disturbance observers mentioned above have the disadvantage that the estimation effect of disturbance depends entirely on the prior knowledge of disturbance, but it is difficult to obtain the prior knowledge of disturbance in practice. At the same time, the influence of the estimation error of the observer on the system is not considered.

To shorten the response time of the PMSM control system and avoid the influence of system structure parameters and disturbance prior knowledge on controller design and control effect, an adaptive nonsingular fast terminal sliding mode control scheme based on disturbance observer is proposed in this paper. The main contributions of this paper are as follows:

1) A nonsingular fast terminal sliding mode controller is designed for the mathematical model of the table-mounted PMSM system. In the case of finite-time convergence and avoiding the singularity problem, the convergence speed of sliding mode is accelerated.

2) To solve the influence of disturbance prior knowledge and system structural parameters on the control system, a nonlinear disturbance observer is designed to compensate the unknown model of the system, so that the design of the controller does not need to know the structure and parameters of the system. At the same time, the problem of disturbing prior knowledge is avoided.

3) To improve the robustness of the system, an adaptive law is designed to adjust the estimation error existing in the system control. The effectiveness and superiority of the proposed method are proved by comparing the physical simulation results of the PMSM system.

The rest of this paper is organized as follows. Firstly, the mathematical model of the PMSM is established in the second section. Secondly, the third section introduces the design process and stability proof of the adaptive nonsingular fast terminal sliding mode control method based on disturbance observer. Then, the fourth section gives the simulation results of the system. Finally, the fifth section gives some conclusions.

A. MATHEMATICAL MODEL OF PMSM

To facilitate the design of control, a mathematical model in $d-q$ the coordinate system is established by using a table-mounted PMSM motor [30].

$$\begin{cases} u_d = Ri_d + L_s\dfrac{di_d}{dt} - p_n\omega_m L_s i_q \\ u_q = Ri_q + L_s\dfrac{di_q}{dt} - p_n\omega_m L_s i_d + p_n\omega_n\psi_f \\ J\frac{d\omega_m}{dt} = \dfrac{3}{2}p_n\psi_f i_q - T_L \end{cases} \tag{1}$$

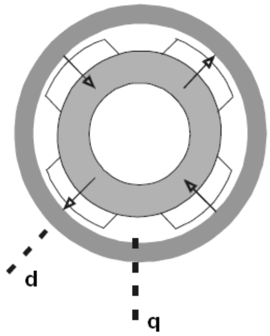

FIGURE 1. The structure diagram of PMSM.

where u_d and u_q are $d-q$ axis components of stator voltage respectively. i_d and i_q are the $d-q$ axis components of stator current respectively. R is the resistance of the stator. ψ_f represents the permanent magnet flux. L_s is the stator inductance. ω_m is the mechanical angular velocity of the motor. J is the moment of inertia. p_n is a polar logarithm. T_L is the load torque.

For surface mounted PMSM, the rotor field orientation control method $i_d = 0$ can achieve a better control effect. At this time, formula (1) can be changed into the following mathematical model:

$$\begin{cases} \dfrac{di_q}{dt} = \dfrac{1}{L_s}(-Ri_q - p_n\omega_m\psi_f + u_q) \\ \dfrac{d\omega_m}{dt} = \dfrac{1}{J}(-T_L + \frac{3p_n\psi_f}{2}i_q) \end{cases} \tag{2}$$

The state variables of the PMSM system are defined as:

$$\begin{cases} x_1 = \omega_{ref} - \omega_m \\ x_2 = \dot{x}_1 = -\dot{\omega}_m \end{cases} \tag{3}$$

where ω_{ref} is the reference speed of the motor, usually constant. Combination equation (2) and equation (3) can be obtained:

$$\begin{cases} \dot{x}_1 = -\dot{\omega}_m = \dfrac{1}{J}(-T_L + \frac{3p_n\psi_f}{2}i_q) \\ \dot{x}_2 = -\ddot{\omega}_m = -\dfrac{3p_n\psi_f}{2J}\dot{i}_q \end{cases} \tag{4}$$

Definition $u = \dot{i}_q, D = \frac{3p_n\psi_f}{2J}$, then formula (4) can be changed to:

$$\begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ 0 & 0 \end{bmatrix}\begin{bmatrix} x_1 \\ x_2 \end{bmatrix} + \begin{bmatrix} 0 \\ -D \end{bmatrix}u \tag{5}$$

II. MAIN RESULT

The control objective of the system is to design a robust controller, which can achieve accurate and fast stability control even when the structure and parameters of the system are unknown and external disturbances exist. To achieve this goal, a DOBANFTSMC is designed.

A. DESIGN OF THE NFTSMC

For system (5), to obtain fast convergence performance infinite time, the following form of the nonsingular fast terminal sliding surface [35]:

$$s = x_1 + \alpha |x_1|^{\gamma} sgn(x_1) + \beta |x_2|^{q/p} sgn(x_2) \tag{6}$$

where α, β, and γ are real numbers. q and p are positive odd numbers and satisfy $1 < q/p < 2, \gamma > q/p$.

Theorem1: For the system (5), the sliding surface (6) is selected. Under the following control law, the system will reach the sliding surface in a finite time, and the system state on the sliding surface will converge to zero in a finite time.

$$u = \frac{1}{D}\left(\frac{p}{\beta q}|x_2|^{2-q/p}\left(1+\alpha r|x_1|^{r-1}\right)sgn(x_2) + k \cdots + w \cdot sgn(s)\right) \tag{7}$$

where k and w are positive real numbers. Because $2-q/p > 0$ and $r-1 > 0$, the exponents of $|x_1|$ and $|x_2|$ are greater than zero, so the controller is completely non-singular.

Proof: To verify the stability of the proposed algorithm, the Lyapunov function is selected:

$$V_1 = \frac{1}{2}s^2 \tag{8}$$

The time derivative of equation (8) is obtained:

$$\dot{V}_1 = s\dot{s} = s\left(x_2 + \alpha r|x_1|^{r-1}x_2 + \beta\frac{q}{p}|x_2|^{q/p-1}(-Du)\right) \tag{9}$$

Substitute equation (7) into the upper equation to obtain:

$$\begin{aligned}\dot{V}_1 &= s\left(\beta\frac{q}{p}|x_2|^{q/p-1}(-k\cdot s - w\cdot sgn(s))\right)\\ &= -\beta\frac{q}{p}|x_2|^{q/p-1}\left(k\cdot s^2 + w\cdot|s|\right)\end{aligned} \tag{10}$$

Due to $1 < q/p < 2$, that is$0 < \frac{q}{p} - 1 < 1$. Because β is positive real, q and q are positive odd, then when $x_2 \neq 0$, $\beta\frac{q}{p}|x_2|^{q/p-1} > 0$, $\dot{V}_1 \leq 0$ holds. It can be seen that under the condition of $x_2 \neq 0$, the system satisfies the Lyapunov stability condition, and the system will reach the sliding surface in finite time.

When $x_2 = 0$ the equation (7) is substituted for equation (5) to obtain:

$$\dot{x}_2 = -k\cdot s - w\cdot sgn(s) \tag{11}$$

When $s > 0$, $\dot{x}_2 = -k\cdot s - w < 0$, that is, x_2 decreases rapidly. When $s < 0$, $\dot{x}_2 = -k\cdot s + w > 0$, that is, x_2 rises rapidly. Therefore, when $x_2 = 0$, $s = 0$ is achieved in a finite time.

When the system state reaches the sliding surface and satisfies $s = \dot{s} = 0$, the equation (6) can be changed to:

$$\begin{aligned}\dot{x}_1 &= -\left(\frac{1}{\beta}\right)^{p/q}(x_1 + \alpha|x_1|^{\gamma}sgn(x_1))^{p/q}\\ &= -\left(\frac{1}{\beta}\right)^{p/q}x_1^{p/q}(1+\alpha|x_1|^{\gamma-1})^{p/q}\end{aligned} \tag{12}$$

Suppose that the time from any initial state $x_1(0) \neq 0$ to $x_1 = 0$ is t_r, that is $x_1(t_r) = 0$. By calculating the time integral on both sides of equation (12), we can obtain:

$$\begin{aligned}&\int_{x_1(0)}^{x_1(t_r)}\left(\frac{1}{x_1^{p/q}}\right)dx_1\\ &= -\int_0^{t_r}\left(\frac{1}{\beta}\right)^{p/q}(1+\alpha|x_1|^{\gamma-1})^{p/q}d\tau\\ &\leq -\int_0^{t_r}\left(\frac{1}{\beta}\right)^{p/q}d\tau\end{aligned} \tag{13}$$

Simplify inequality (13) to obtain:

$$t_r \leq \frac{\beta^{p/q}q}{q-p}x_1(0)^{1-p/q} \tag{14}$$

Therefore, the system state can converge to zero in a limited time.

Remark 1: It can be seen from the above that the time required to reach the equilibrium point along the sliding surface (6) from any initial state is less than the time required for traditional nonsingular fast terminal sliding mode control.

B. DOBANFTSMC

From the expression of the control law (7), it can be seen that the design of the control law (7) needs to obtain the concrete results and parameters of the system. However, the modeling process of the actual nonlinear system is complex and the model may have model uncertainties, and there may be disturbances in the control process, which will affect the control effect of the controller. Therefore, the structure and parameters of the system should be avoided as much as possible in the design of the controller.

To derive the sliding surface s:

$$\begin{aligned}\dot{s} &= x_2 + \alpha r|x_1|^{r-1}x_2 + \beta\frac{q}{p}|x_2|^{q/p-1}(-Du)\\ &= f + (1-b)\,u - u\end{aligned} \tag{15}$$

where $f = x_2 + \alpha r|x_1|^{r-1}x_2$, $b = D\beta\frac{q}{p}|x_2|^{q/p-1}$. Because of the existence of the control input u in $f + (1-b)\,u$, the algebraic ring problem will arise. Using a low pass filter, equation (15) can be written as:

$$\dot{s} = f + (1-b)\,u_f - u + \Delta G \tag{16}$$

where $u_f = B_L(s)u$ is the output signal of the low-pass filter, avoiding the algebraic loop problem, $B_L(s)$ is the low-pass filter, $\Delta G = (1-b)\,u - (1-b)\,u_f$.

In [36], a design method of hyperbolic tangent nonlinear tracking differentiator is proposed. Based on this, a hyperbolic tangent nonlinear disturbance observer is designed to deal with the unknown model of the system. The function $f + (1-b)\,u$ is defined as the disturbance term d of the system (16). The following nonlinear disturbance observer is designed:

$$\begin{cases} \dot{\hat{s}} = \hat{d} + u_f \\ \dot{\hat{d}} = -R_1^2\left(a_1 \tanh\left(b_1\left(\hat{s}-s\right)\right) + a_2 \tanh\left(b_2\hat{d}/R_1\right)\right) \end{cases} \tag{17}$$

where $\hat{d}$ and $\hat{s}$ are the estimates of d and s respectively. R_1, a_1, a_2, b_2, and b_2 are a positive real number (Specific parameter selection methods refer to s [37]).

When $T > 0$:

$$\lim_{R\to\infty}\int_0^T \left|\hat{s}-s\right| dt = 0 \tag{18}$$

So, $\hat{s} \to s$. According to formula (17), (18), $\hat{d} \to d$:

$$f + (b-1)\, u_f = d = \hat{d} + \mu \tag{19}$$

where μ is the estimation error.

Remark 2: For the convenience of application, the following rules are given for the parameters of disturbance observer: (1) R_1, a_1 and b_1 affect the convergence speed and accuracy of observer. The larger the set values of R_1, a_1 and b_1, the faster the convergence speed and the higher the accuracy, but too large will also lead to overshoot. (2) The smaller the a_2 and b_2, the faster the convergence speed and the higher the accuracy, but too small will also lead to overshoot.

The following controller is designed:

$$u = \hat{d} + k\cdot s + w\cdot sgn(s) \tag{20}$$

Substituting equation (20) into equation (16), we can get:

$$\begin{aligned} \dot{s} &= f + (1-b)\, u_f - \left(\hat{d} + k\cdot s + w\cdot sgn(s)\right) + \Delta G \\ &= d - \hat{d} - k\cdot s - w\cdot sgn(s) + \Delta G \\ &= -k\cdot s - w\cdot sgn(s) + \mu + \Delta G \end{aligned} \tag{21}$$

Considering that the bounds of the estimation error μ and the low-pass filtering error ΔG of the disturbance observer are unknown, an adaptive law is designed to adjust the unknown estimation in the controller. For further analysis and proof, assume that $|\mu + \Delta G| < \eta$ and η are unknown constants.

The controller is designed as follows:

$$u = \hat{d} + k\cdot s + \left(w + \hat{\eta}\right)\cdot sgn(s) \tag{22}$$

where $\hat{\eta}$ is the estimated value of η, and it satisfies the adaptive law: $\dot{\hat{\eta}} = \sigma\left(|s| - \hat{\eta}\right), \sigma > 0$.

Theorem 2: For the system (5), the sliding surface (6) is selected. Under the control law (22), the system will converge to the sliding surface $s = 0$ infinite time.

Proof: Selecting positive definite Lyapunov function:

$$V_2 = \frac{1}{2}s^2 + \frac{1}{2\sigma}\hat{\eta}^2 \tag{23}$$

TABLE 1. The parameters of PMSM.

Parameter	Numerical value
Pole pairs p_n	4
Stator inductance $L_s\,(mH)$	8.5
Rotor moment of inertia $J\,(kg\cdot m^2)$	0.003
Permanent magnet flux $\psi_f\,(\omega b)$	0.175
Stator resistance $R(\Omega)$	2.875

By calculating the time derivative of the upper formula and combining formula (16) and formula (22), we can get:

$$\begin{aligned} \dot{V} &= s\dot{s} + \frac{1}{\sigma}\hat{\eta}\dot{\hat{\eta}} \\ &= s\left(f + (1-b)\, u_f - u + \Delta G\right) + \frac{1}{\sigma}\hat{\eta}\dot{\hat{\eta}} \\ &= s\left(-ks - \left(\hat{\eta} + w\right) sgn(s) + \mu + \Delta G\right) + \frac{1}{\sigma}\hat{\eta}\dot{\hat{\eta}} \\ &= -ks^2 - \left(\hat{\eta} + w\right)|s| + (\mu + \Delta G)\, s + \frac{1}{\sigma}\hat{\eta}\sigma\left(|s| - \hat{\eta}\right) \\ &= -ks^2 - \left(\hat{\eta} + w\right)|s| + (\mu + \Delta G)\, s + \hat{\eta}\,|s| - \hat{\eta}^2 \\ &= -ks^2 - w\,|s| + (\mu + \Delta G)\, s - \hat{\eta}^2 \\ &\le -ks^2 - w\,|s| + |\mu + \Delta G|\,|s| - \hat{\eta}^2 \\ &< -ks^2 - (w - \eta)\,|s| - \hat{\eta}^2 \end{aligned} \tag{24}$$

Therefore, when $w > \eta > |\mu + \Delta G|$ is established, $\dot{V} < 0$. it can be obtained. The trajectory of the system converges to the sliding surface in finite time.

It can be seen from Formula (22) that the control law contains symbolic functions. It is precise because of its existence that the strong robustness of sliding mode control can be guaranteed, but also the chattering of parameters will affect the steady-state convergence accuracy of the system, and even stimulate the unmolded dynamics, resulting in the function. Therefore, the control law of the system (5) becomes:

$$sigmoid(x) = \frac{2}{1 + \exp(-ax)} - 1 \tag{25}$$

where $a > 0$ affects the convergence rate of Sigmoid instability of the system. In order to eliminate chattering and retain the strong robustness of sliding mode control, the sigmoid function is used instead of symbolic function. Its expression is:

$$u = \hat{d} + k\cdot s + \left(w + \hat{\eta}\right)\cdot sigmoid(s) \tag{26}$$

III. SIMULATION RESEARCH

To verify the effectiveness of the designed controller, the PMSM experimental platform produced by Hefei Intelligent Company Ltd. was used to simulate and verify the effectiveness of the controller. Fig. 2 is the structure diagram of the speed control system of PMSM. Fig. 3 is the PMSM experimental platform. The specific parameters of PMSM are shown in Table 1.

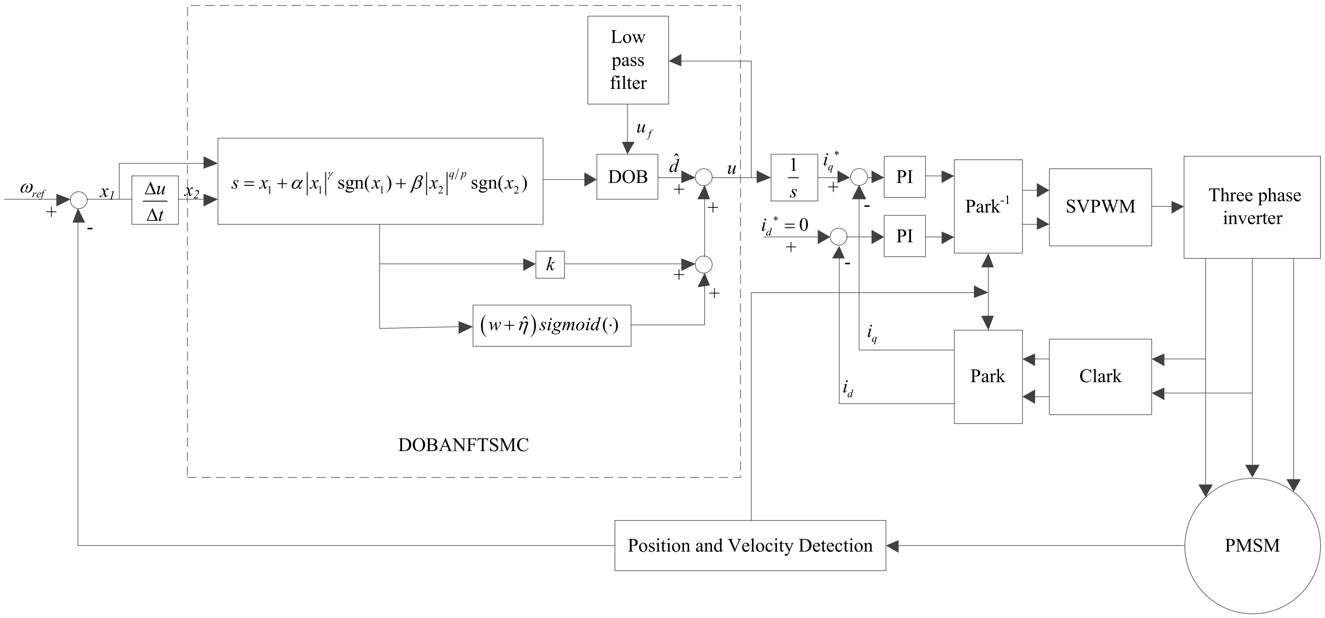

FIGURE 2. The structure diagram of the speed control system of PMSM.

TABLE 2. The parameters of controller.

Parameter	Numerical value
α	10
β	0.001
q	9
p	7
k	0.65
w	0.1
a	5
$a_1 = a_2$	1
$b_1 = b_2$	5
R_1	50

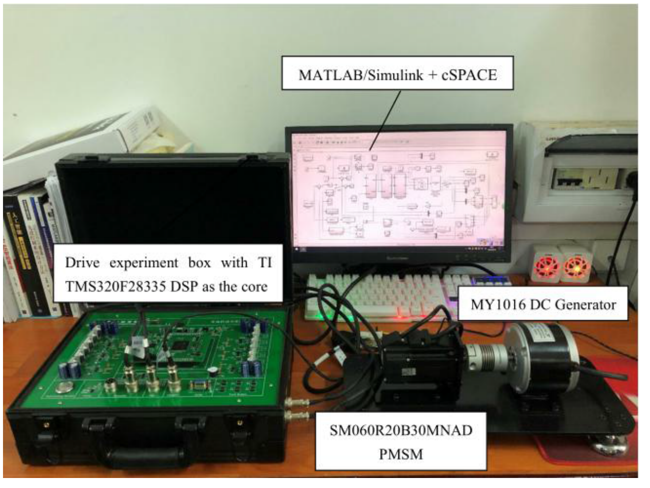

FIGURE 3. The PMSM experimental platform.

The control method is simulated by the cSPACE control and simulation system. The system is developed based on TI TMS320F28335 DSP and MATLAB/SIMULINK. Among them, the processor is a 32-bit floating-point number, the CPU clock is 150 MHz, and the C code generated by one key is downloaded directly to the embedded device, which can observe, modify and store the data in real-time. Support Vector Machine Pulse Width Modulation (SVPWM) technology is also used. The saturation limit of the q-axis reference current is set at ±10A, and the permanent magnet synchronous motor is driven by a three-phase voltage source PWM inverter. The control gains of the two current loops are set to $k_p = 3$ and$k_i = 5$. The simulation results are compared with the sliding mode control method (SMC) adopted in [30] and the non-singular terminal sliding mode control method (NTSMC) designed in [38]. The parameters of the controller are shown in Table 2. DC motor pair bracket is used as load torque, and its given current is 0.5A. The simulation results are shown in Figs. 3–9.

Fig. 4 and Fig. 5 are velocity step response curves and load-free electromagnetic torque curves under different control methods at a given speed of 1000r/min, respectively. As can be seen from Figs. 4–5, compared with other control methods, the speed step response curve of this control method has the advantages of small overshoot and short adjustment time. At the same time, compared with other control methods, the control method in this paper has smaller overshoot and flutter fast torque response. Fig. 6 is the disturbance estimate, which clearly shows that the disturbance observer can converge rapidly. Fig. 7 shows the velocity response curves under different control methods when the given speed suddenly changes from 1000 r/min to 500 r/min. From Fig. 7, it can be clearly seen that compared with other control methods, the control method in this paper has smooth speed change,

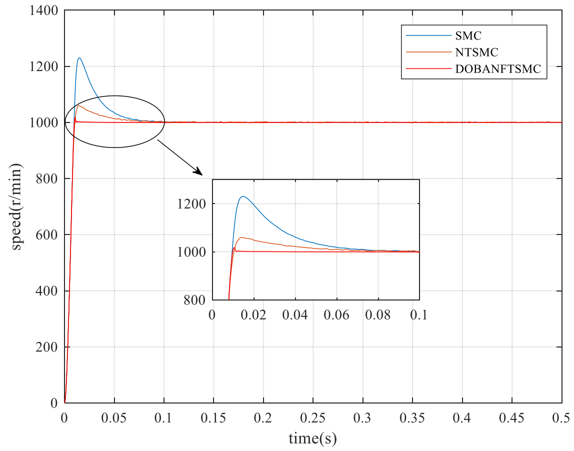

FIGURE 4. Velocity step response curve.

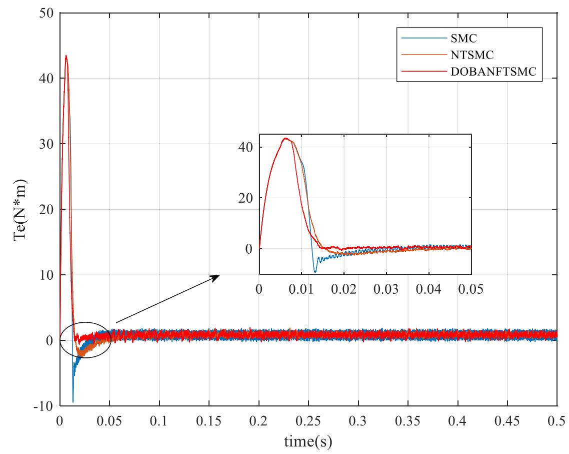

FIGURE 5. The electromagnetic torque change curve.

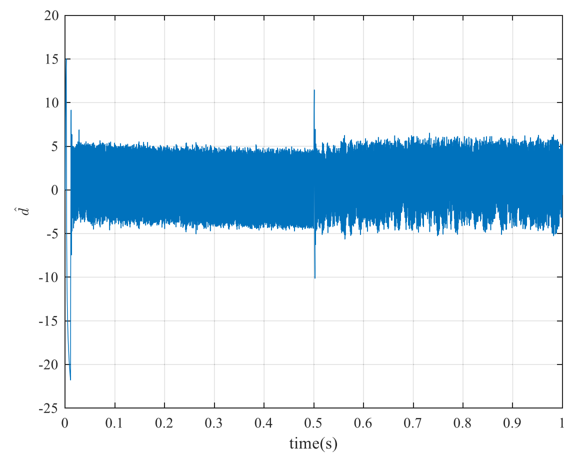

FIGURE 6. The time response curve for estimating disturbance $\hat{d}$.

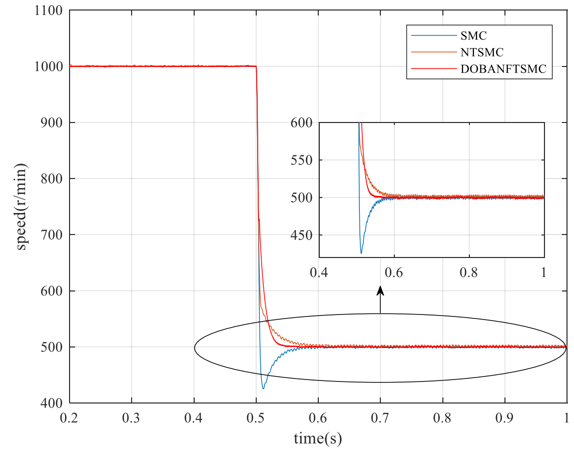

FIGURE 7. The speed response curve of a given speed changes abruptly from 1000 r/min to 500 r/min.

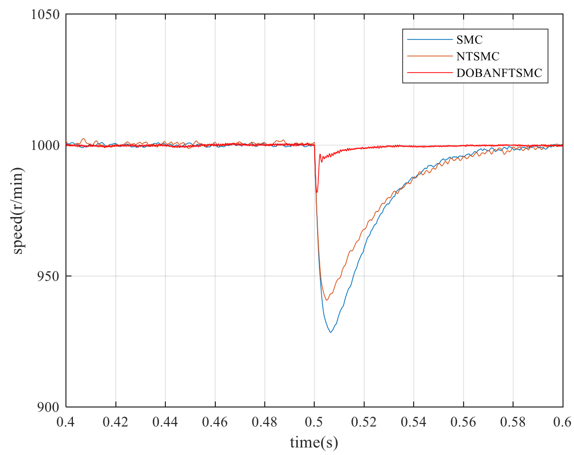

FIGURE 8. The velocity response curve when the load suddenly increases.

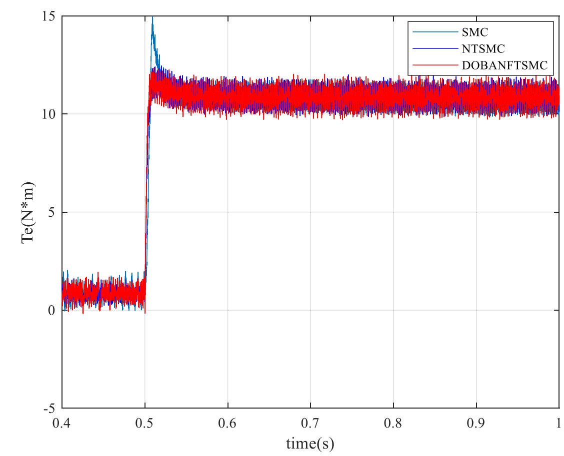

FIGURE 9. Electromagnetic torque curve when the load suddenly increases.

no overshoot phenomenon, fast adjustment time and better tracking performance. Fig. 8 shows the velocity response curves under different control methods when the load is suddenly increased. As can be seen from Fig. 8, when the load suddenly changes, compared with other control methods, the speed fluctuation of this control method is smaller, the disturbance rejection recovery time is shorter, and it has better robustness. Fig. 9 shows the electromagnetic torque curve under different control methods when the load is suddenly

TABLE 3. The speed tracking.

Index / Control scheme	OS (%)	t_s (ms)
SMC	23	58.4
NTSMC	6	41.5
DOBANFTSMC	2	9.5

TABLE 4. The speed change.

Index / Control scheme	OS (%)	t_s (ms)
SMC	14.9	45.5
NTSMC	0	56.5
DOBANFTSMC	0	0.9

TABLE 5. The load increase.

Index / Control scheme	Speed decrease (rpm)	t_s (ms)
SMC	71.5	61.2
NTSMC	59.1	59.5
DOBANFTSMC	18.1	4.1

increased. From Figure 9, it can be clearly seen that compared with other control methods, the control method in this paper has a faster adjusting time of electromagnetic torque and smaller overshoot.

In order to better illustrate the advantages of this control method, the performance indicators of speed overshoot (OS%), regulation time (t_s) and maximum decrease of speed caused by load torque of the control system are numerically compared and analyzed. Table 3 shows the performance indicators in the case of speed step tracking. Table 4 shows the performance indicators under the sudden change of velocity. Table 5 shows performance indicators for sudden load increase.

From the data of system performance indicators in Tables 3, 4 and 5, it can be clearly seen that the control method in this paper has faster adjustment time, smaller overshoot and smaller speed decline than other control methods.

IV. CONCLUSION

An adaptive nonsingular fast terminal sliding mode control method based on disturbance observer is proposed for PMSM systems. The combination of adaptive nonsingular fast terminal sliding mode and nonlinear disturbance observer not only shortens the response time of the system, but also avoids the problem of unknown structural parameters and disturbance prior knowledge, and improves the robustness of the system. The simulation and experimental results show that the method has the advantages of fast speed, small flutter, strong robustness, and high system efficiency.

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