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Disturbance Observer Based Terminal Sliding Mode Control Method for PMSM Speed Regulation System

LI Shihua[1], ZHOU Mingming[1], YU Xinghuo[2]

1. School of Automation, Southeast University, Key Laboratory of Measurement and Control of CSE, Ministry of Education, Nanjing 210096, P. R. China
E-mail: lsh@seu.edu.cn

2. Platform Technologies Research Institute, RMIT University, VIC 3001, Australia

Abstract: This paper investigates the permanent magnet synchronous motor (PMSM) speed regulation system using terminal sliding mode control method. By introducing a non-singular terminal sliding mode manifold, a novel terminal sliding mode controller is designed for the speed loop. This controller can make the states not only reach the manifold in finite time, but also converge to the equilibrium point in finite time. Thus, the controller could make the motor speed reach the reference value in finite time, obtaining a faster convergence and a better tracking precision. Meanwhile, considering the large chattering phenomenon caused by high switching gains, a composite terminal sliding mode control method based on disturbance observer is proposed to reduce chattering. Through disturbance estimation for feed-forward compensation, the composite terminal sliding mode controller may take a smaller value for the switching gain without sacrificing disturbance rejection performance. Simulation results and comparisons are given to show the superiority of the proposed method.

Key Words: Permanent magnet synchronous motor, Speed regulation system, Terminal sliding mode control, Finite time control, Disturbance observer

1 Introduction

High performance permanent magnet synchronous motor (PMSM) control system should possess the characteristics of rapid response , small overshoot, high tracking precision and strong anti-disturbance ability. It is well known that linear control schemes, e.g., the PI control scheme, are already widely applied in the PMSM control system due to its simple implementation [1]. However, the PMSM servo system is nonlinear, time-varying, and complex system with unavoidable and unmeasured disturbances, as well as parameter variations. It is very difficult to achieve a satisfactory performance in the entire operating range by only using linear control algorithm [2, 3].

In recent years, with the development of modern control theory and motion control, various methods of nonlinear control theory have been used in the PMSM control system, such as neural network control [1], adaptive control [4, 5, 6, 8], active disturbance rejection control [6, 7, 13], backstepping control [8], finite-time control [9, 10], sliding mode control [11, 12, 13], robust control [14], predictive control [15], and intelligent control [16] etc. These advanced nonlinear control methods considering the external disturbances and mode uncertainties, have improved the performance of the PMSM system from different aspects.

Among these methods, the sliding mode control methods are regarded to be efficient methods to improve the disturbance rejection and robustness properties of PMSM systems. However, since these methods in [11, 12, 13] employ conventional linear sliding surfaces, the convergence rates of such methods can only at best be exponential with infinite settling time. To further improve the dynamic response of closed loop system, a direct way is to introduce nonlinear sliding surfaces. One of such nonlinear sliding surfaces is terminal sliding surface (TSM) [17, 18], which can ensure the finite-time convergence during the sliding mode stage. The TSM control method thus developed [17, 18, 19] can guarantee that the states converge to the origin in finite time. The finite-time control of dynamical systems is of interest because systems with finite-time convergence demonstrate some nice features such as better robustness and disturbance rejection properties.

One obvious disadvantage for sliding mode control method is the chattering phenomenon caused by discontinuous control law and frequent switching action near sliding surface. For the reduction or elimination problem of chattering, different methods have been studied. One method is to use saturation function to replace the signum function, which can alleviate the chattering. However, the performance of anti-disturbance is sacrificed to some extent [20]. Another method is to select suitable switching gain for the sliding control law since unsuitably large switching gain leads to large chattering. If the switching control gain is selected to be bigger than the upper bound of disturbances, the disturbances can be completely rejected. Since the upper bound of disturbances is difficult to obtain, this often results in a conservative control law with large switching gain, causing large chattering. In [21], an adaptive sliding mode control method is proposed for the position control problem, where a simple adaptive algorithm is utilized to estimate the bound of disturbances. In [22], a total sliding mode controller is proposed for the position control problem of PMSM system, where a recurrent-fuzzy-neural-network is adopted as a bound observer to facilitate adaptive control gain adjustment. In [13], an extended state observer is employed to estimate the viscous friction and load torque. After feedforward compensation for these two kinds of disturbances, it is pointed out that the switching gain of sliding mode controller can be selected smaller to reduce chattering.

For the PMSM speed regulation system, the vector con-

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trol scheme includes a speed loop and two current loops. In the traditional control design for the speed loop, usually a first-order model is used to approximately describe the relationship between the reference q-axis current and the speed output, i.e., the reference q-axis current i_q^* is regarded the same as the q-axis current i_q [6, 9]. Considering the developing trend in high performance servo systems, the relative differences in control periods between speed loop and current loops are becoming smaller or even vanishing. In this case, neglecting the current dynamics will degrade the closed loop performance of PMSM system. To this end, in [13], a second-order model is built to describe the relationship between i_q^* and the speed output for PMSM system.

In this paper, by introducing a non-singular terminal sliding control method, a novel controller is designed for the speed loop. Two current loops still employ two standard PI controllers. The second-order model of speed regulation system in [13] is introduced to describe the relationship between the reference q-axis current and the speed output. Moreover, to reduce chattering, a feed-forward compensation based on observation for the lumped disturbances of system is added to the TSM feedback part. The disturbances are estimated by using disturbance observer (DOB). This feed-forward compensation design helps to select a smaller value for the switching gain of terminal sliding mode controller and reduce chattering. Finally, a composite control scheme is developed for the PMSM speed regulation system. Simulation results are provided to show that the proposed control method has excellent robustness and dynamic behavior.

Since the DOB is one of the key techniques here, the motivation as well as some remarkable results of disturbance observer, should not be ignored. The DOB technique was originally presented by Ohnishi in 1987 [24]. Following this direction, many DOB-based control schemes for linear and nonlinear systems have been put forward, e.g., [25, 26, 27] and the references therein.

2 The Second-Order Model of PMSM Speed Regulation System

Assume that magnetic circuit is unsaturated, hysteresis and eddy current loss are ignored and the distribution of the magnetic field is sine space. Under this condition, the model of surface mounted PMSM in d-q coordinates can be expressed as follows [23]:

$$\begin{pmatrix} \dot{i}_d \\ \dot{i}_q \\ \dot{\omega} \end{pmatrix} = \begin{pmatrix} -\frac{R_s}{L_d} & n_p\omega & 0 \\ -n_p\omega & -\frac{R_s}{L_q} & -\frac{n_p\psi_f}{L_q} \\ 0 & \frac{1.5n_p\psi_f}{J} & -\frac{B}{J} \end{pmatrix} \cdot \begin{pmatrix} i_d \\ i_q \\ \omega \end{pmatrix} + \begin{pmatrix} \frac{u_d}{L_d} \\ \frac{u_q}{L_q} \\ -\frac{T_L}{J} \end{pmatrix} \quad (1)$$

where u_d, u_q the stator d- and q- axes voltages, i_d, i_q the stator d- and q- axes currents, L_d, L_q the stator d- and q-axes inductances $L_d = L_q = L$, R_s the stator resistance, ω the rotor angular velocity, n_p the number of pole pairs, ψ_f the flux linkage, T_L the load torque, B the viscous friction coefficient, and J the moment of inertia.

The general structure of the PMSM speed regulation system based on vector control is shown in Fig. 1. In order to decouple the speed and currents, the vector control strategy of $i_d^* = 0$ is used. Here two PI controllers, which are used to stabilize the d-q axes current errors, are adopted in the two current loops respectively. In this paper, we mainly design a controller for the speed loop.

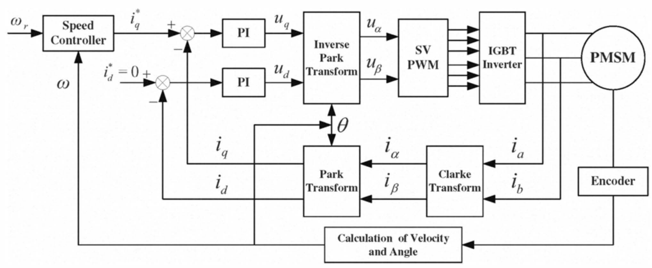

Fig. 1: Schematic diagram of the PMSM system based on vector control

The output of PMSM system is the feedback speed ω. From (1), the motor dynamic equation can be rewritten as

$$\dot{\omega} = bi_q + a(t) \quad (2)$$

where $b = \frac{1.5n_p\psi_f}{J}$, $a(t) = -\frac{B}{J}\omega - \frac{T_L}{J}$ can be considered as the system disturbances including friction and external load disturbances. For the control design of speed loop, usually the q-axis stator current i_q is approximately replaced by the reference q-axis current i_q^*, i.e.,

$$\dot{\omega} \approx bi_q^* + a(t) \quad (3)$$

According to previous analysis, this approximation degrades the closed loop performance of PMSM system. In [13], a second-order model between the reference q-axis current and the speed output is proposed, its frequency domain description form is as follows

$$(s^2 + \frac{k_i}{k_p}s)\Omega(s) = U(s) - \frac{b}{k_p}sU_q(s) + (s + \frac{k_i}{k_p})A(s) \quad (4)$$

where $\Omega(s)$, $U_q(s)$ and $A(s)$ are the Laplace transformation of ω, u_q and $a(t)$, respectively; k_p and k_i are the proportional and integral gains of PI controller in the current loop of i_q, respectively; $U(s)$ is defined as

$$U(s) = b(s + \frac{k_i}{k_p})I_q^* \quad (5)$$

where I_q^* is the Laplace transformation of reference q-axis current. The inverse Laplace transformation of (4) is

$$\ddot{\omega} = -\alpha\dot{\omega} + d(t) + u \quad (6)$$

where $\alpha = \frac{k_i}{k_p}$, $d(t) = -\frac{b}{k_p}\dot{u}_q + \dot{a}(t) + \frac{k_i}{k_p}a(t)$ can be considered as the lumped disturbances of the system, u is the control signal that should be designed firstly. The second-order model between the reference q-axis current and the speed output for PMSM system is described by (6).

3 Speed Controller Design

3.1 A Speed Controller Design Using Terminal Sliding Mode Control Method

Setting ω_r as the reference speed signal, we further define the state variables of speed error and its derivative as follows:

$$\begin{cases} x_1 = \omega_r - \omega \\ x_2 = \dot{x}_1 \end{cases} \quad (7)$$

The function of speed controller is to track the given speed. The second-order model of PMSM speed regulation system described by (6) can be represented in the following state-space form

$$\begin{cases} \dot{x}_1 = x_2 \\ \dot{x}_2 = \dot{\omega}_r - \dot{\omega} = \ddot{\omega}_r + \alpha\dot{\omega} - d(t) - u \end{cases} \tag{8}$$

In order to achieve good performances, such as fast convergence and better tracking precision, a non-singular terminal sliding mode manifold is designed as [18]

$$v = x_1 + \frac{1}{\beta} x_2^{p/q} \tag{9}$$

where $\beta > 0$; p, q are positive odd integers, $1 < p/q < 2$.

And a non-singular terminal sliding mode (NTSM) controller can be designed as

$$u = \ddot{\omega}_r + a\dot{\omega} + \beta \frac{q}{p} x_2^{2-p/q} + ksgn(v) \tag{10}$$

where $k > 0$ is the switching gain, and $sgn(\cdot)$ is the standard signum function.

Assumption 3.1. The lumped disturbances $d(t)$ is bounded and there exists a constant $l > 0$, and it satisfies $0 \leq |d(t)| \leq l$. Now, we reach the following theorem.

Theorem 3.1. If the Assumption 3.1 holds, under the control law of (10), the speed error of PMSM system can converge to zero in finite time if the switching gain satisfies $k > l$.

Proof: Choosing Lyapunov function $V = \frac{1}{2}v^2$, and taking the derivative of it, yields

$$\begin{aligned} \dot{V} &= v\dot{v} = v(x_2 + \tfrac{1}{\beta}\tfrac{p}{q}x_2^{p/q-1}\dot{x}_2) \\ &= v\tfrac{1}{\beta}\tfrac{p}{q}x_2^{p/q-1}(\dot{x}_2 + \beta\tfrac{q}{p}x_2^{2-p/q}) \\ &= v\tfrac{1}{\beta}\tfrac{p}{q}x_2^{p/q-1}(\ddot{\omega}_r + \alpha\dot{\omega} - d(t) - u + \beta\tfrac{q}{p}x_2^{2-p/q}) \\ &= v\tfrac{1}{\beta}\tfrac{p}{q}x_2^{p/q-1}(-ksgn(v) - d(t)) \\ &\leq -\tfrac{1}{\beta}\tfrac{p}{q}x_2^{p/q-1}k|v| + \tfrac{1}{\beta}\tfrac{p}{q}x_2^{p/q-1}|d(t)||v| \\ &= -\tfrac{1}{\beta}\tfrac{p}{q}x_2^{p/q-1}|v|(k - |d(t)|) \\ &< -\tfrac{1}{\beta}\tfrac{p}{q}x_2^{p/q-1}|v|(k - l) \end{aligned} \tag{11}$$

Since p and q are positive odd integers and $1 < p/q < 2$, there is $x_2^{p/q-1} \geq 0$, then it has $\dot{V} \leq 0$ for $v \neq 0$. Two different cases will be discussed as follows [18]:

1) When $x_2^{p/q-1} > 0$, it satisfies $\dot{V} < 0$.

2) When $x_2^{p/q-1} = 0$, for $v \neq 0$, from (9), we will get $x_1 \neq 0$, which means the state variables of speed error will not always stay on the point $(x_1 \neq 0, x_2 = 0)$ and will continue to cross the axis $x_2 = 0$ in the phase plane $0 - x_1x_2$, so the state of $\dot{V}$ is not always equal to zero.

From the above analysis, the existence condition of the sliding mode is guaranteed. The system states can reach the non-singular terminal sliding manifold $v = 0$ from any initial condition within finite time.

Supposing t_r is the time when v reaches zero from $v(0) \neq 0$, when $v = 0$, we have $x_1 + \frac{1}{\beta}x_2^{p/q} = 0$, that is $x_1^{-q/p}\dot{x}_1 = -\beta^{q/p}$. After simple calculation, the total time from $v(0) \neq 0$ to $x_1(t_s) = 0$ can be described as follows

$$t_s = t_r + \tfrac{p}{\beta^{q/p}(p-q)}|x_1(t_r)|^{1-q/p} \tag{12}$$

Therefore, the speed error can converge to zero along the sliding surface in finite time t_s. This completes the proof.

The speed controller output i_q^* can be obtained from the following expression

$$\dot{i}_q^* + \alpha i_q^* = \tfrac{1}{b}(\ddot{\omega}_r + \alpha\dot{\omega} + \beta\tfrac{q}{p}x_2^{2-p/q} + ksgn(v)) \tag{13}$$

According to the above design procedure, a non-singular terminal sliding mode control scheme based on the second-order model of PMSM speed regulation system is shown in Fig. 2. Note that the generalized plant in Fig. 2 represents the two current loops which include PMSM and other components the same as that of Fig. 1.

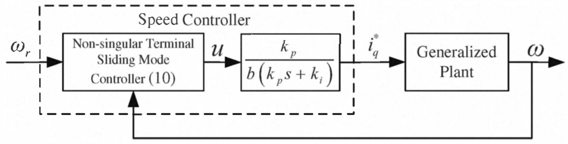

Fig. 2: Terminal sliding mode control scheme of PMSM speed regulation system

3.2 Simulation Results

To demonstrate the performance of the proposed control scheme, some simulations studies have been done. The PMSM speed regulation system is simulated by using the Simulink of MATLAB. Two methods, i.e., SMC and NTSM, are both tested in the PMSM system.

The sliding mode control (SMC) method can be described as follows [13]. The linear sliding mode manifold is designed as

$$\bar{v} = cx_1 + x_2, c > 0 \tag{14}$$

The output of sliding mode controller for speed loop can be obtained from the following expression

$$\dot{i}_q^* + \alpha i_q^* = \tfrac{1}{b}\left(cx_2 + \ddot{\omega}_r + \alpha\dot{\omega} + k \cdot sgn(\bar{v}) \right) \tag{15}$$

The parameters of the PMSM used in the simulation are shown in Table 1.

Table 1: Parameters of the PMSM

Rated Power P_N	750W
Rated Voltage U_N	200V
Rated Speed n_N	3000rpm
Stator Resistance R_s	1.74 Ω
Stator Inductances L	4mH
Rotor Flux Linkage ψ_f	0.402wb
Moment of Inertia J_n	$1.78 \times 10^{-4} kg \cdot m^2$
Viscous Friction Coefficient B	7.403×10^{-5} N · m · s/rad
Number of Pole Pairs n_p	4

To have a fair comparison, the switching gains of SMC and NTSM are both selected as $k = 400$. The PI parameters of both current loops are selected to be $k_p = 200$ and $k_i = 5000$. Saturation limit of i_q^* is ± 10A. The reference speed is 1500rpm, and the disturbance load torque $T_L = 4N \cdot m$ is added at $t = 1s$. The simulation results are shown in Figs. 3-4.

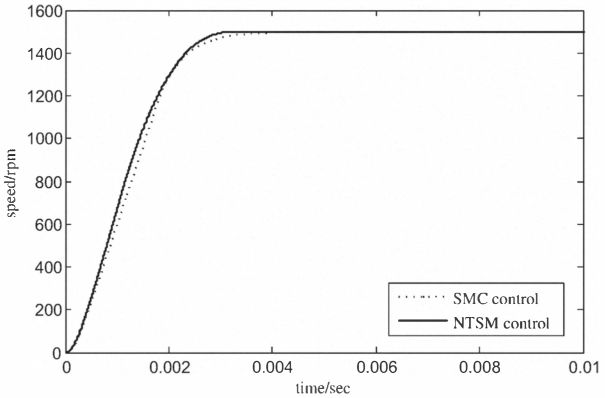

Fig. 3: Speed responses of PMSM system under SMC and NTSM control methods

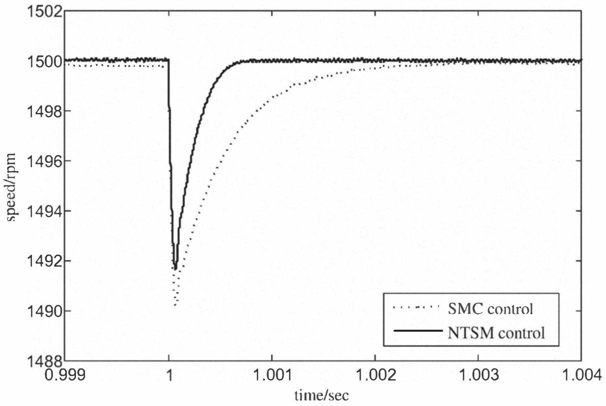

Fig. 4: Speed responses of PMSM system with sudden load under SMC and NTSM control methods

The speed responses of PMSM speed regulation system from 0 to 1500rpm are shown in Fig. 3. It can be seen that the NTSM control scheme has a shorter settling time, and both methods show small overshoots. Simulation results about load disturbance rejection properties of the two control schemes are shown in Fig.4. It can be seen that the speed response of PMSM system under NTSM control scheme has a less speed drop and a better disturbance rejection ability when the disturbance load is added suddenly.

4 Chattering Reduction Based on Disturbance Observer

The sliding mode control is essentially a kind of switching control. It uses discontinuous terms to restrict the impact from external disturbances and parameter variations. In general, the switching gain value required must be larger than the upper bound of the lumped disturbances, which can be seen from the proof and conclusion of Theorem 3.1. As the upper bound of the lumped disturbances is not easy to be determined, the switching gain k will be selected to be over-large, which will worse the system chattering phenomenon.

Thus, if disturbances are observed and feed-forward compensation based on the observed value, the switching gain k required just need to be larger than the upper bound of the disturbance compensation error which is usually much smaller than that of the lumped disturbance, then the system chattering will be reduced effectively.

4.1 Design of DOB-based Composite Controller

The diagram of disturbance observer (DOB) is shown in Fig. 5. In the diagram, transfer functions $G_p(s)$, $G_n(s)$, $K(s)$ and $Q(s)$ denote the plant model, the nominal model, the feedback controller and the filter of DOB, respectively. Signals $R(s)$, $U'(s)$, $D(s)$, $\hat{D}(s)$, $U(s)$ and $Y(s)$ represent the tracking reference, the feedback controller output, the lumped disturbances, the disturbance estimates obtained by DOB, the plant input and output, respectively.

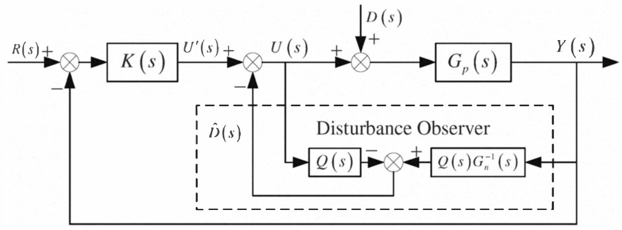

Fig. 5: Block diagram of disturbance observer

From Fig. 5, we can see that the design of disturbance observer is to design $G_n(s)$ and $Q(s)$ rationally. From (6), take the nominal model $G_n = \frac{1}{s^2+\alpha s}$. Considering easy implementation of the disturbance observer and $Q(s)$ should have a relative degree larger than or equal to the relative degree of the nominal model $G_n(s)$, a second-order low-pass filter is used as follow:

$$Q(s) = \frac{1}{(\tau s+1)^2} \tag{16}$$

where τ is a time constant. Then, the disturbance estimator is derived as:

$$\hat{d} = \frac{(s^2+\alpha s)\omega - u}{(\tau s+1)^2} \tag{17}$$

It can be obtained from the DOB theory, that $\hat{d}(t) \to d(t)$ as time goes to infinity, which means the estimation of DOB could eventually converge to the lumped disturbances of the PMSM system. The observing dynamic process is determined by τ.

The control signal u can be redesigned as

$$u = u' - \hat{d}(t) \tag{18}$$

where u' is the output of terminal sliding mode controller. Substituting the above control law into (6), yields

$$\ddot{\omega} = -\alpha\dot{\omega} + d(t) + u' - \hat{d}(t) \tag{19}$$

Then, (8) can be rewritten as

$$\begin{cases} \dot{x}_1 = x_2 \\ \dot{x}_2 = \ddot{\omega}_r + \alpha\dot{\omega} + [-d(t) + \hat{d}(t)] - u' \end{cases} \tag{20}$$

The non-singular terminal sliding manifold is still designed as (9), then the new terminal sliding mode controller can be redesigned as

$$u' = \ddot{\omega}_r + \alpha\dot{\omega} + \beta\frac{q}{p}x_2^{2-p/q} + k' sgn(v) \tag{21}$$

And the composite terminal sliding mode controller for speed loop can be obtained from the following expression

$$\dot{i}_q^* + \alpha i_q^* = \frac{1}{b}(\ddot{\omega}_r + \alpha\dot{\omega} + \beta\frac{q}{p}x_2^{2-p/q} + k' sgn(v) - \hat{d}(t)) \tag{22}$$

Remark 1: When the parameter selection of DOB is appropriate, $\hat{d}(t)$ will be a good estimate of $d(t)$ and the upper bound of $d(t) - \hat{d}(t)$ can be less than $d(t)$. In this case, the switching gain k' required usually is smaller than k, which means the discontinuous terms of the composite terminal sliding mode controller will be much smaller and the chattering will be reduced.

The block diagram of the composite terminal sliding mode scheme based on DOB is showed in Fig. 6.

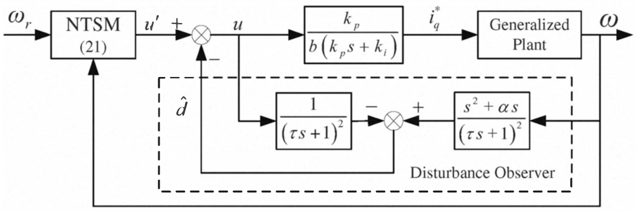

Fig. 6: Composite terminal sliding mode control scheme based on DOB (NTSM+DOB).

4.2 Simulation Results

In order to validate the proposed composite terminal sliding mode control method, some simulations studies about the NTSM+DOB control scheme of PMSM system have been done. The parameters of the PMSM are the same as Section 3.2.

The switching gain of the composite terminal sliding mode controller is $k' = 200$, the time constant parameter of DOB is $\tau = 0.001$. The reference speed is 1500rpm, and the load torque $T_L = 4N \cdot m$ is added at $t = 1s$. The simulation results of NTSM and NTSM+DOB comparison control schemes are shown in Fig. 7-9.

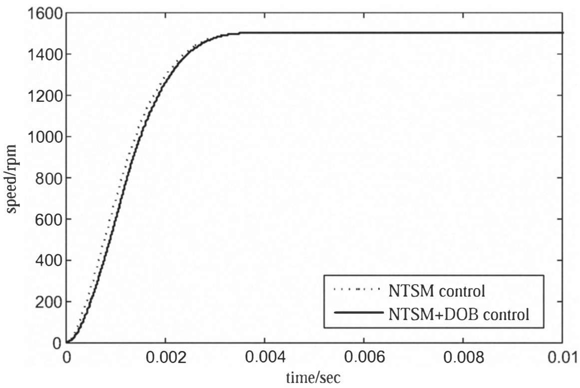

Fig. 7: Comparison of speed step responses

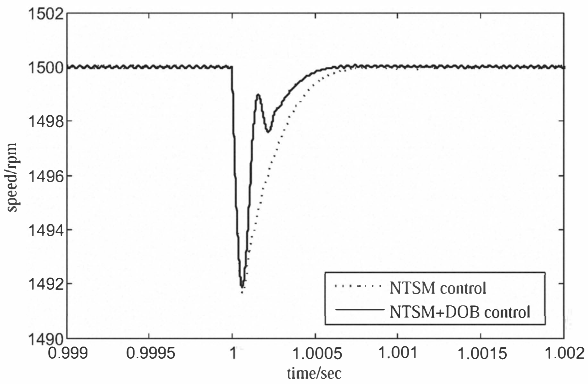

Fig. 8: Comparison of speed responses with sudden load

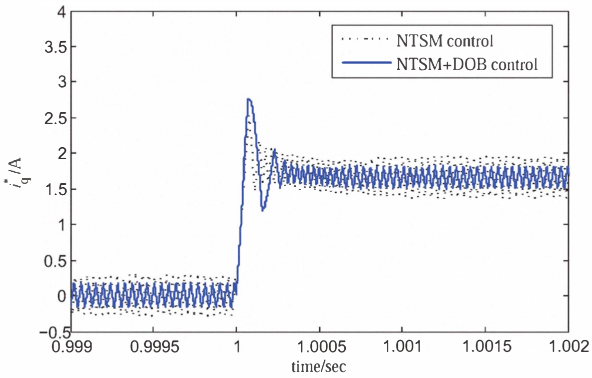

Fig. 9: Comparison of i_q^* with sudden load

Simulation results of speed step responses are shown in Fig. 7. It can be seen that the rising time of NTSM+DOB is a little longer compared with NTSM. The comparison of speed and current i_q^* responses with sudden disturbance load are shown in Fig. 8 and Fig. 9, respectively. When the same disturbance load is added, the maximum fluctuation of NTSM+DOB is smaller, and the recovering time is shorter. As using smaller switching gain and adding disturbance estimation for feed-forward compensation, the closed loop system under NTSM+DOB shows a less chattering than that under NTSM.

5 Conclusions

In this paper, a composite terminal sliding mode control method based on disturbance observer has been proposed for PMSM speed regulation system. A nonsingular terminal sliding mode control has been introduced in the speed controller design to improve the dynamic response of closed loop system. Through disturbance estimation for feed-forward compensation, the compensator generates a corrective input signal to reject disturbances so that the terminal sliding mode controller can take a smaller value for the switching gain without sacrificing disturbance rejection performance. Simulation results have shown the effectiveness of the proposed control method.

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