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Combined Speed and Current Terminal Sliding Mode Control With Nonlinear Disturbance Observer for PMSM Drive

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ABSTRACT A terminal sliding mode control (SMC) method based on nonlinear disturbance observer is investigated to realize the speed and the current tracking control for the permanent magnet synchronous motor (PMSM) drive system in this paper. The proposed method adopts the speed-current single-loop control structure instead of the traditional cascade control in the vector control of the PMSM. First, considering the nonlinear and the coupling characteristic, a single-loop terminal sliding mode controller is designed for PMSM drive system through feedback linearization technology. This method can make the motor speed and current reach the reference value in finite time, which can realize the fast transient response. Although the SMC is less sensitive to parameter uncertainties and external disturbance, it may produce a large switching gain, which may cause the undesired chattering. Meanwhile, the SMC cannot keep the property of invariance in the presence of unmatched uncertainties. Then, a nonlinear disturbance observer is proposed to the estimate the lump disturbance, which is used in the feed-forward compensation control. Thus, a composite control scheme is developed for the PMSM drive system. The results show that the motor control system based on the proposed method has good speed and current tracking performance and strong robustness.

INDEX TERMS PMSM drive, terminal sliding mode control, feedback linearization, nonlinear disturbance observer.

I. INTRODUCTION

Due to the inherent advantages of low rotor inertia, high efficiency, and high power density, permanent magnet synchronous motor (PMSM) has received much attention in various industrial applications, such as electric vehicle, wind power system, robot [1]. The field-orientation mechanism is usually employed in the control system of PMSM, which results in a cascade control structure with an inner current loop and an outer speed loop. This technology makes the PMSM achieve similar torque control performance as a DC motor, and the proportional plus integral(PI) control is used in the speed or current loop, but the dynamic performance will be affected by the accuracy of the motor parameters.

In addition, owing to the nonlinear, strong coupling and vibration characteristics of the motor [2], [3], the traditional cascade control structure cannot deal well with the nonlinear problems in the mechanical and electrical aspect. These factors will certainly affect the transient response of the control system [4], [5], and it may not satisfy the special requirement in some areas. Meanwhile, although both inner loop and outer loop controllers are designed for their closed-loop systems to be stable, respectively, there is no stability guarantee for the entire closed-loop system combining the inner loop and out loop control systems. This is also a limitation of the cascade control strategy [6]. In recent years, various new control approaches with the single-loop control structure and the modern control technology have been put forward for the PMSM drive system, such as adaptive back-stepping control [7], passivity control [8], model predictive control [9], sliding mode control [10], neural control [11], which improves the performance of PMSM in different aspects.

Among these methods, sliding mode control(SMC) has been shown to be a potentially useful approach in PMSM because it exhibits advantages such as quick response, strong robustness and simple implementation [12]–[14]. In [15], a sliding mode control method based on a novel reaching law is proposed for the speed-loop control of PMSM, and the chattering is reduced, meanwhile, a sliding mode observer is designed to estimate the disturbance, which improves the robustness. In [16], the sliding mode control is used in the current-loop control of PMSM to realize the precise current tracking performance. In [17], a sliding mode observer is designed to estimate the parameter variations and model uncertainties for the current control of PMSM. It is well known that the chatting is the main drawback of the SMC. To reduce the phenomenon, the boundary layer integral sliding mode control technique is adopted for the speed control of PMSM [18]. With the development of sliding mode control theory, a terminal sliding mode speed controller is proposed for PMSM [19], and a nonlinear term is introduced to the sliding mode control through choosing the reaching law, which is effective to reduce the chatting and improve the convergence rate. In addition, by applying the fractional calculus, the fractional sliding mode speed controller [20] is designed for PMSM, and the chattering is also reduced. But the designed motor controllers above all adopt the cascade control structure, where the outer speed-loop has a relatively slow transient response in comparison with the inner current-loop to guarantee a stable control [21].

Besides, PMSM drive system faces inevitable parameter variations and external disturbance, and it is difficult to derive the exact motor model and parameters in the practical system. The traditional PI control method can suppress the disturbance, but it usually works in a relatively slow speed [22]. Although the sliding mode control is less sensitive to parameter uncertainties and external disturbance, the upper bound of the disturbance is difficult to determine, thus its robustness is normally obtained by a large switching gain, which will cause the undesired chattering phenomenon [23]. To alleviate above drawbacks, combining the SMC with other approaches which estimate the disturbance is an attractive proposition. The disturbance observer technology may be a candidate solution for this problem. It can estimate the lump disturbance of the system, including the parameter variations and external disturbance, and corresponding compensation is generated by making use of the estimate [24], [25]. This technology has a different but complementary mechanism to widely used robust control and adaptive control [26]. Up to now, various disturbance observer methods have been used in the speed or current control of PMSM drive system [27], [28]. But the designed observers above are only applicable for the matched uncertainties, which means that the uncertainties exist in the same channel as that of the control input [29]. In fact, the mismatched uncertainties are existed when the single-loop controller is designed in the PMSM control. Meanwhile, the sliding mode control loses the property of invariance in the presence of unmatched uncertainties [23], [30]. Thus, these methods cannot deal with the lump disturbance in the system. Recently, the nonlinear disturbance observer control methods for mismatched uncertainties [31], [32] have been thoroughly studied, which show that the mismatched disturbance can be eliminated from the output by designing the observer for the feed-forward compensation, and the system performance will not be affected simultaneously. In [33]–[35], this approach has been practically tested on the robotics, the converters and the motor drives, which reveal that the good robustness performance can be achieved.

In this paper, a novel terminal sliding mode controller based on feedback linearization theory is proposed for the speed and current control of PMSM drive system, instead of the traditional cascade control, which considers the nonlinear and coupling relationship of PMSM, and it could improve the transient response effectively. Then, considering the lump disturbance, such as parameter variations and external disturbance, a nonlinear disturbance observer is designed to estimate the disturbance, and it is used as the feed-forward compensation control to be added to the sliding mode control part. Meanwhile, it can help to reduce the switching gain of terminal sliding mode controller. The contributions of the paper are 1) a speed-current single-loop controller based on terminal sliding mode control method is designed for PMSM. 2) the nonlinear disturbance observer is introduced to the terminal sliding control to estimate the lump disturbance, instead of the traditional load torque observer. 3) The controller has the strong disturbance rejection ability for all of the uncertain parameters and load torque. In the end, the simulation is implemented, and the results show that the motor control system based on the proposed method has good tracking performance and strong robustness.

This paper is organized as follows. In Section II, the mathematical model of PMSM is introduced. The terminal sliding mode controller based on linearization method is constructed in Section III. The nonlinear disturbance observer is studied in Section IV. Simulation is demonstrated to verify the effectiveness of the proposed method in Section V, which is followed by conclusion in Section VI.

II. MATHEMATICAL MODEL OF PMSM

Assume the magnetic circuit is unsaturated, hysteresis and eddy current loss are ignored, and the three-phase stator windings are sinusoidal in space. According to field oriented theory, the mathematical model of the PMSM in the dq-axes rotor reference frame can be expressed as

$$\begin{cases} \dfrac{di_d}{dt} = \dfrac{-R_s i_d + n_p \omega L_q i_q}{L_d} + \dfrac{1}{L_d} u_d + f_d \\ \dfrac{di_q}{dt} = \dfrac{-R_s i_q - n_p \omega L_d i_d - n_p \omega \Phi}{L_q} + \dfrac{1}{L_q} u_q + f_q \\ \dfrac{d\omega}{dt} = \dfrac{n_p\left[(L_d - L_q) i_d i_q + \Phi i_q\right] - B\omega}{J_m} + f_w \end{cases} \tag{1}$$

where L_d and L_q are d-axes and q-axes stator inductances, i_d and i_q are stator current, u_d and u_q are stator input voltage in dq-axes reference frame, R_s is the per-phase stator resistance, n_p is the number of pole pairs, ω is the mechanical angular speed of the rotor, Φ is the rotor flux, J_m is the moment of inertia, B is the viscous friction coefficient.

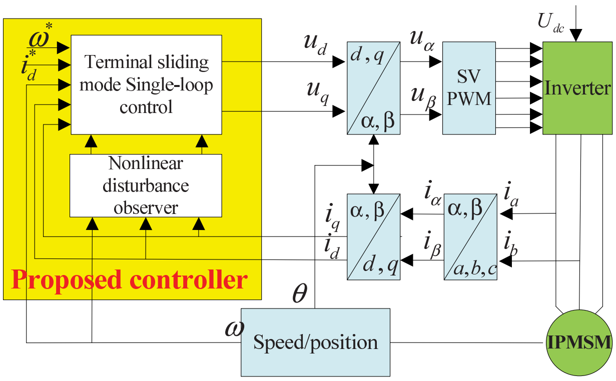

FIGURE 1. Block diagram of PMSM control system.

Note that it is difficult to always know the exact values of the electrical and mechanical parameters, because these values would vary as the operating conditions are changed [4]. Moreover, the load torque varies frequently according to the actual operation. Thus, f_d, f_q and f_w are defined to represent the disturbance caused by the parameter variation and external load torque, and they are given by

$$\begin{cases} f_d = -\frac{1}{L_d}(\Delta R_s i_d - \Delta L_q n_p \omega i_q + \Delta L_d \frac{di_d}{dt}) \\ f_q = -\frac{1}{L_q}(\Delta R_s i_q + \Delta L_d n_p \omega i_d + \Delta \Phi n_p \omega + \Delta L_q \frac{di_q}{dt}) \\ f_w = -\frac{1}{J_m}(\Delta J_m \omega + \Delta B \omega + \tau_L - n_p(\Delta L_d - \Delta L_q) i_d i_q \\ \qquad - n_p \Delta \Phi i_q) \end{cases} \tag{2}$$

where τ_L is the load torque, $\Delta R_s = R_{st} - R_s$, $\Delta L_d = L_{dt} - L_d$, $\Delta L_q = L_{qt} - L_q$, $\Delta\Phi = \Phi_t - \Phi$, $\Delta J_m = J_{mt} - J_m$, $\Delta B = B_t - B$, in which R_s, L_d, L_q, Φ, J_m, B denote the nominal parameter values. R_{st}, L_{dt}, L_{qt}, Φ_t, J_{mt}, B_t are the actual parameter values.

In practical PMSM system, the parameters of the motor are mainly influenced by the temperature. Therefore, the deviations of the internal parameters are ranged in a finite scale. The load torque is also limited by its nominal value. Hence, the lumped disturbance f_d, f_q and f_w and their derivatives are all bounded.

The general PMSM drive system structure investigated in this work is shown in Fig.1. The control system includes an interior mounted PMSM, an inverter, a pulse width modulation (PWM) module, two coordinate transformation modules and the speed-current single loop controller. The d-axes reference current i_d^* is usually set to zero to ensure a constant flux operating condition [36]. ω^* is the reference speed. The main work in this paper is to design the speed-current single-loop controller to realize the speed and current tracking control by the terminal sliding mode method and nonlinear disturbance observer.

III. CONTROL SCHEMES FOR PMSM CONSIDERED

This section introduces the main steps of the proposed method for PMSM drive. Different from sliding mode control methods with the cascade control structure in the literature [16], where the sliding mode controllers are designed in the speed or current loop, in this paper, the speed and current controller are integrated design by terminal sliding mode control based on linearization technology. The variables to be controlled are the components of the output speed and current. The objective of the controller is to find the input action to realize the speed and current tracking control.

A. LINEARIZATION OF PMSM MODEL

The motor model (1) can be considered as a nonlinear system with the state variable [10] $x = (x_1\ x_2\ x_3)^T = (i_d\ i_q\ \omega)^T$, the input variable $u = (u_d\ u_q)^T$ and the output variable $y = (y_1\ y_2)^T = (i_d\ \omega)^T$. Meanwhile, the system has the disturbance $d = (f_d\ f_q\ f_w)^T$.

Because $i_d = 0$ is used in PMSM, from the equation (1), the mechanical equation can be described as

$$\frac{d\omega}{dt} = \frac{n_p \Phi i_q - B\omega}{J_m} + f_\omega. \tag{3}$$

According to the principle of feedback linearization, the repeated differentiation of the output variable up to the appearance of the input variable with respect to time can be derived as

$$\begin{cases} \frac{dy_1}{dt} = \frac{-R_s i_d + n_p \omega L_q i_q}{L_d} + \frac{1}{L_d} u_d + f_d \\ \frac{dy_2}{dt} = \frac{n_p \Phi i_q - B\omega}{J_m} + f_w \\ \frac{d^2 y_2}{dt^2} = \frac{n_p \Phi}{J_m L_q}(-R_s i_q - n_p \omega L_d i_d - n_p \omega \Phi + u_q + L_q f_q) \\ \qquad - \frac{B}{J_m}(\frac{n_p \Phi i_q - B\omega}{J_m} + f_w) + \dot{f}_w \end{cases} \tag{4}$$

Then, by define $A_1 = \frac{-R_s i_d + n_p \omega L_q i_q}{L_d} + f_d$, $A_2 = \frac{n_p \Phi}{J_m L_q}(-R_s i_q - n_p \omega L_d i_d - n_p \omega \Phi + L_q f_q) - \frac{B}{J_m}(\frac{n_p \Phi i_q - B\omega}{J_m} + f_w) + \dot{f}_w$, $B_{11} = \frac{1}{L_d}$, $B_{12} = B_{21} = 0$ and $B_{22} = \frac{n_p \Phi}{J_m L_q}$, the equation (4) can be rewritten as

$$\begin{cases} \frac{dy_1}{dt} = A_1 + B_{11} u_d + B_{12} u_q \\ \frac{d^2 y_2}{dt^2} = A_2 + B_{21} u_d + B_{22} u_q \end{cases} \tag{5}$$

Next, define the intermediate variables $v_1 = \frac{dy_1}{dt}$ and $v_2 = \frac{d^2 y_2}{dt^2}$, then

$$\begin{bmatrix} v_1 \\ v_2 \end{bmatrix} = \begin{bmatrix} A_1 \\ A_2 \end{bmatrix} + B \begin{bmatrix} u_d \\ u_q \end{bmatrix} \tag{6}$$

where,

$$B = \begin{bmatrix} B_{11} & B_{12} \\ B_{21} & B_{22} \end{bmatrix}.$$

By transformation of above equation, the controller with the feedback linearization can be derived as

$$\begin{bmatrix} u_d \\ u_q \end{bmatrix} = B^{-1} \begin{bmatrix} v_1 - A_1 \\ v_2 - A_2 \end{bmatrix} \tag{7}$$

The controller laws calculated in the equation (7) are the reference voltage in the PMSM control system based on feedback linearization, which is used in the PWM module. However, the intermediate variables are included in the equation, meanwhile, the feedback linearization controller is sensitive to the motor parameters.

B. DESIGN OF TERMINAL SLIDING MODE CONTROLLER FOR PMSM

To eliminate the intermediate variables in the controller, a terminal sliding mode control is proposed. First, the sliding mode controller for the d-axes current is designed, and define $e_d = i_d^* - i_d$. In order to achieve good performance, such as fast convergence and better tracking precision [19], a non-singular terminal sliding mode manifold is designed as

$$s_1 = e_d + \beta_1 \int e_d^{p_1/q_1} \tag{8}$$

where $\beta_1 > 0$, p_1, q_1 are positive odd integers, $1 < p_1/q_1 < 2$.

Then, v_1 can be designed as $v_1 = \beta_1 e_d^{p_1/q_1} + \varepsilon_1 sgn(s_1)$, where, $\varepsilon_1 > 0$. And the terminal sliding mode controller of the d-axes current can be derived as

$$\begin{aligned} u_d &= L_d(\beta_1 e_d^{p_1/q_1} + \varepsilon_1 sgn(s_1) + \frac{R_s i_d - n_p \omega L_q i_q}{L_d} - f_d) \\ &= L_d(\beta_1 e_d^{p_1/q_1} + \varepsilon_1 sgn(s_1)) + R_s i_d - n_p \omega L_q i_q - L_d f_d \end{aligned} \tag{9}$$

Proof: Choose Lyapunov function $V_d = \frac{1}{2}s_1^2$, and taking the derivative of V_d, yields

$$\begin{aligned} \dot{V}_d &= s_1 \dot{s}_1 = s_1(\dot{e}_d + \beta_1 e_d^{p_1/q_1}) = s_1(-v_1 + \beta_1 e_d^{p_1/q_1}) \\ &= s_1(-\beta_1 e_d^{p_1/q_1} - \varepsilon_1 sgn(s_1) + \beta_1 e_d^{p_1/q_1}) = -s_1 \varepsilon_1 sgn(s_1) \end{aligned} \tag{10}$$

Then, it has $\dot{V}_d \leq 0$, the existence and arrival condition of sliding mode control can be satisfied, and the d-axes current error e_d can converge to zero in a limited time.

Define the speed tracking error $e_\omega = \omega^* - \omega$, then $\dot{e}_\omega = \dot{\omega}^* - \dot{\omega}$, and according to the equation (6), $\ddot{e}_\omega$ can be derived as

$$\ddot{e}_\omega = \ddot{\omega}^* - v_2 = \ddot{\omega}^* - A_2 - B_{22} u_q. \tag{11}$$

To achieve the good speed tracking performance, a second-order non-singular terminal sliding mode manifold is designed as

$$s_2 = e_\omega + \frac{1}{\beta_2} \dot{e}_\omega^{p_2/q_2} \tag{12}$$

where, $\beta_2 > 0$, p_2, q_2 are positive odd integers, $1 < p_2/q_2 < 2$.

TABLE 1. Parameters of PMSM.

Description	Value	Unit
rated speed	3000	r/min
rated torque	2.3	$N \cdot m$
stator resistance	4.8	Ω
d-axes inductance	19.5	mH
q-axes inductance	27.5	mH
rotor flux	0.15	Wb
moment of inertia	0.001	$kg \cdot m^2$

Then, the second-order terminal sliding mode controller can be designed as

$$\begin{aligned} u_q &= \frac{1}{B_{22}}(\ddot{\omega}^* - A_2 + \beta_2 \frac{q_2}{p_2} \dot{e}_\omega^{2-p_2/q_2} + \varepsilon_2 sgn(s_2)) \\ &= \frac{J_m L_q}{n_p \Phi}(\ddot{\omega}^* - \frac{n_p \Phi}{J_m L_q}(-R_s i_q - n_p \omega L_d i_d - n_p \omega \Phi + L_q f_q) \\ &\quad + \frac{B}{J_m}(\frac{n_p \Phi i_q - B\omega}{J_m} + f_w) - \dot{f}_w + \beta_2 \frac{q_2}{p_2} \dot{e}\omega^{2-p_2/q_2} \\ &\quad + \varepsilon_2 sgn(s_2)) \\ &= \frac{J_m L_q}{n_p \Phi} \ddot{\omega}^* + R_s i_q + n_p \omega L_d i_d + n_p \omega \Phi - L_q f_q \\ &\quad + \frac{B L_q}{n_p \Phi}(\frac{n_p \Phi i_q - B\omega}{J_m} + f_w) - \frac{J_m L_q}{n_p \Phi}(\dot{f}_w \\ &\quad - \beta_2 \frac{q_2}{p_2} \dot{e}\omega^{2-p_2/q_2} - \varepsilon_2 sgn(s_2)) \end{aligned} \tag{13}$$

where $\varepsilon_2 > 0$.

Proof: Choosing Lyapunov function $V_q = \frac{1}{2}s_2^2$, and the derivative of it can be calculated as

$$\begin{aligned} \dot{V}_q &= s_2 \dot{s}_2 = s_2(\dot{e}\omega + \frac{1}{\beta_2} \frac{p_2}{q_2} \dot{e}_\omega^{p_2/q_2 - 1} \ddot{e}\omega) \\ &= s_2 \frac{1}{\beta_2} \frac{p_2}{q_2} \dot{e}_\omega^{p_2/q_2 - 1}(\ddot{e}_\omega + \beta_2 \frac{q_2}{p_2} \dot{e}_\omega^{2-p_2/q_2}) \\ &= s_2 \frac{1}{\beta_2} \frac{p_2}{q_2} \dot{e}_\omega^{p_2/q_2 - 1}(\ddot{\omega}^* - A_2 - B_{22} u_q + \beta_2 \frac{q_2}{p_2} \dot{e}_\omega^{2-p_2/q_2}) \\ &= s_2 \frac{1}{\beta_2} \frac{p_2}{q_2} \dot{e}_\omega^{p_2/q_2 - 1}(-\varepsilon_2 sgn(s_2)) \end{aligned} \tag{14}$$

where p_2, q_2 are positive odd integers and $1 < p_2/q_2 < 2$, thus $\dot{e}_\omega^{p_2/q_2 - 1} \geq 0$. Then $\dot{V}_q \leq 0$ can be proved.

Although the sliding mode controller has some robustness for the system disturbance, the mismatched uncertainties are existed when the single-loop terminal sliding mode controller is applied in the PMSM control, and the sliding mode control will lose the property of invariance for these uncertainties. The control performance will be influenced when the system suffers the strong disturbance, such as the load torque, the severe parameters uncertainties. From the equations (9) and (13), the lump disturbance f_d, f_q and f_ω are included in the controller, thus it is necessary to derive the disturbance to further improve the robustness of the system.

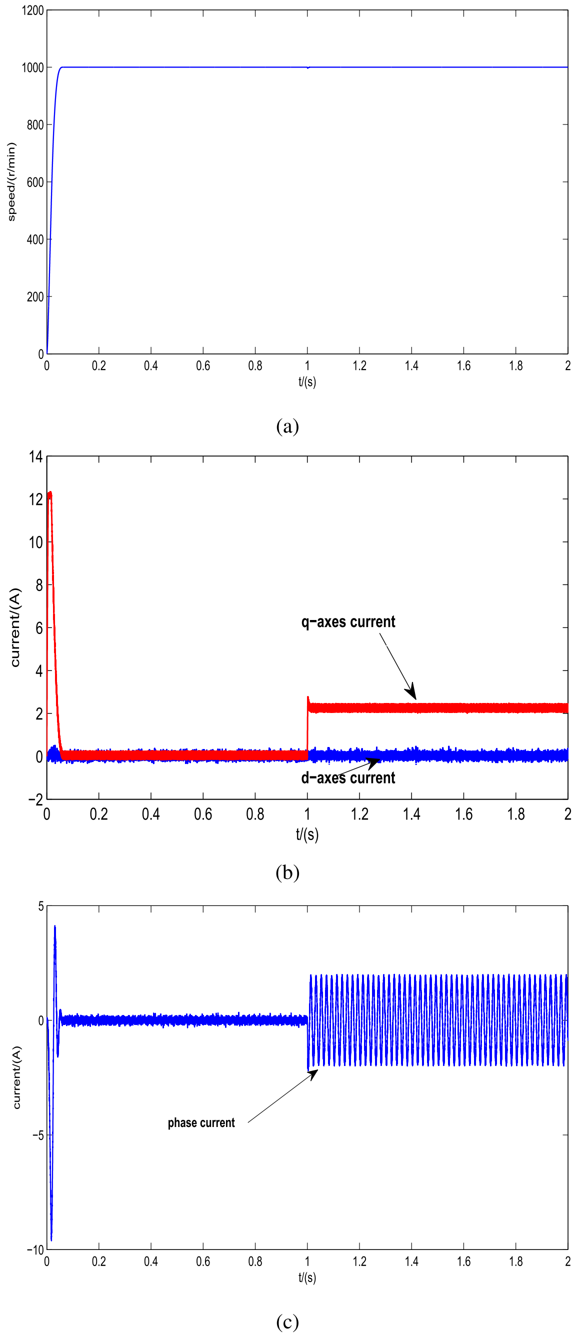

FIGURE 2. **The motor response waveforms of the proposed method: (a) motor speed (b) dq-axes current (c) phase current.**

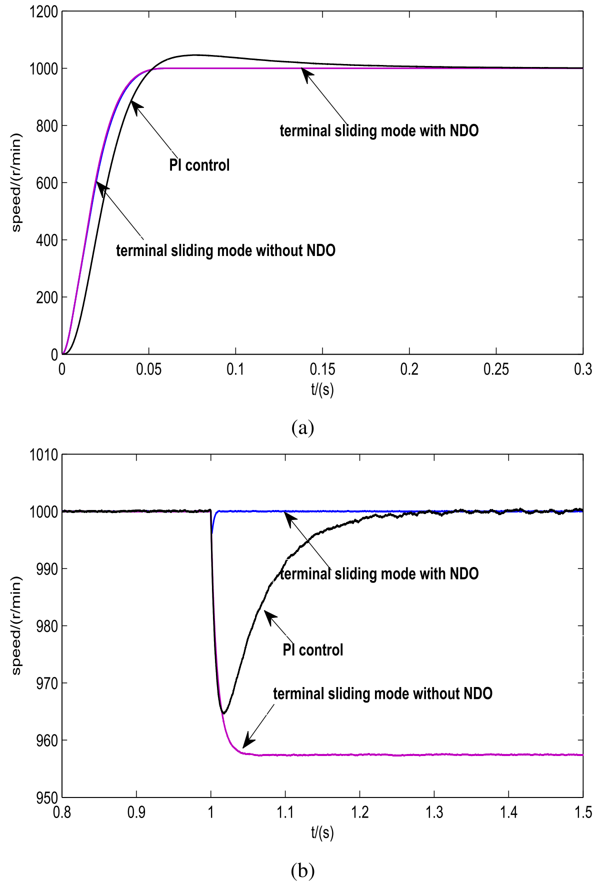

FIGURE 3. **The speed waveforms of three methods: (a) the speed when the motor starts (b) the speed with load disturbance.**

C. DESIGN OF NONLINEAR DISTURBANCE OBSERVER FOR PMSM

In practical PMSM control system, the disturbance is unavoidable and undetectable. To strengthen the robust performance, a nonlinear disturbance observer [31] is designed to estimate the lump disturbance, which includes the matched and mismatched disturbance, and then used for the feed-forward compensation of the terminal sliding mode controller.

According to the model of PMSM in (1), define

$$f(x) = \begin{bmatrix} f_1(x) \\ f_2(x) \\ f_3(x) \end{bmatrix} = \begin{bmatrix} \dfrac{-R_s i_d + n_p \omega L_q i_q}{L_d} \\ \dfrac{-R_s i_q - n_p \omega L_d i_d - n_p \omega \Phi}{L_q} \\ \dfrac{n_p\left[(L_d - L_q) i_d i_q + \Phi i_q\right] - B\omega}{J_m} \end{bmatrix}$$

and

$$g_1(x) = \begin{bmatrix} \dfrac{1}{L_d} & 0 & 0 \\ 0 & \dfrac{1}{L_q} & 0 \end{bmatrix}^T.$$

Then, a nonlinear disturbance observer is designed as

$$\begin{cases} \dot{z}_d = -l(x) z_d - l(x)(\lambda(x) + f(x) + g_1(x) u) \\ \hat{d} = z_d + \lambda(x) \end{cases} \tag{15}$$

where $\hat{d} = \left[\hat{f}_d\ \hat{f}_q\ \hat{f}_w\right]^T$ is the estimated disturbance, z_d is the internal state variable of the observer, $\lambda(x)$ is a nonlinear function designed for the observer, $l(x)$ is the observer gain, and

$$l(x) = \frac{\partial \lambda(x)}{\partial x} \tag{16}$$

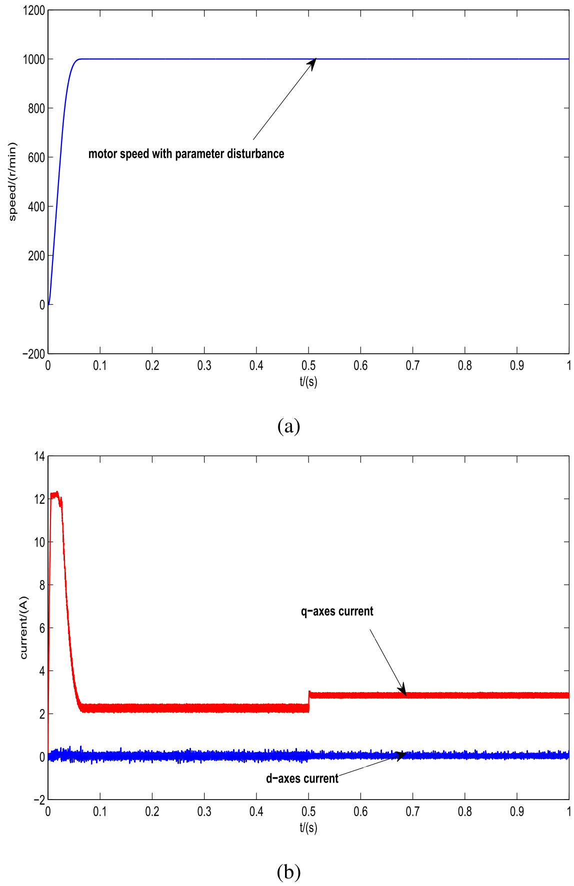

FIGURE 4. The motor waveforms with the parameter disturbance. (a) motor speed (b) dq-axes current.

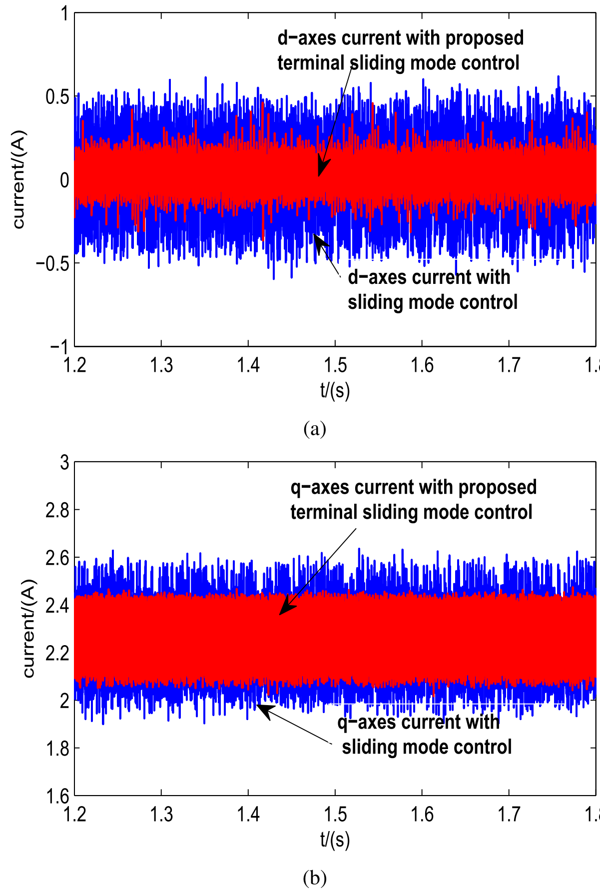

FIGURE 5. The contrastive results with the common sliding mode control method. (a) d-axes current (b) q-axes current.

Define the disturbance error $\tilde{d} = d - \hat{d}$, then

$$\dot{\tilde{d}} = -l(x)\tilde{d} + \dot{d} \tag{17}$$

Define a new Lyapunov function

$$V = \frac{1}{2}s_1^2 + \frac{1}{2}s_2^2 + \frac{1}{2}\tilde{d}^2 \tag{18}$$

Then the derivative of V can be derived

$$\dot{V} = -s_1\varepsilon_1 sgn(s_1) - s_2\frac{1}{\beta_2}\frac{p_2}{q_2}\dot{e}\omega^{p_2/q_2-1}\varepsilon_2 sgn(s_2) - l(x)\tilde{d}^2 \leq 0 \tag{19}$$

Thus, the asymptotically stability of the entire closed-loop system can be proved. Combine the equations (9), (13) and (15), the single-loop controller for the PMSM can be designed, which can realize the speed and current tracking control for the motor.

IV. SIMULATION AND ANALYSIS

The proposed control techniques are tested by means of simulations in MATLAB-Simulink environment. The proposed terminal sliding mode control law with nonlinear disturbance observer(TSMC+NDO) is used for the speed and current controller, which has a single-loop structure. The parameters of the PMSM are listed in Table 1.

The reference speed of the motor is given as $1000r/min$, and the motor starts without load torque. At $t = 1s$, the load torque is changed to $1N \cdot m$. The motor response waveforms are shown in Fig.2, which includes the speed of PMSM, dq-axes current, phase current. From the figures, it can be seen that the proposed method can complete the precise speed control, and $i_d = 0$ can also be well realized. The results show that the proposed method has good speed and current control performance.

To demonstrate the efficient control and superior disturbance attenuation of the proposed (TSMC+NDO) controller, different comparative methods, such as PI control, terminal sliding mode control (TSMC) without nonlinear disturbance observer, are applied to the motor, respectively. The speed response waveforms of these three methods from 0 to $1000r/min$ are shown in Fig.3(a), and the speed response waveforms with the abrupt load disturbance are shown in Fig.3(b).

As shown in Fig.3, compared to the PI control, the proposed method has smaller overshoot and shorter settling time when the motor starts. The two curves based on sliding mode control coincide with each other. When the load torque is changed suddenly, compared to other methods, the designed composite controller has smaller speed drop, and the speed can recover to the reference speed quickly. Above results verifies the proposed method has better disturbance attenuation performance.

The robustness of the proposed control method is also tested while the motor parameters have perturbation. Firstly, the motor starts with $1N \cdot m$ load torque, then the values of rotor flux linkage, stator resistance and the dq-axes inductances in the motor are changed to 80%, 200% and 150% of the normal values at $t = 0.5s$. The motor waveforms are shown in Fig.4. It can be seen that the speed and current waveforms are almost not affected because the nonlinear disturbance observer can modify the control to cancel the offset caused by the parameter disturbance. The precise speed and current control are completed quickly.

To further verify the performance of the proposed method, finally, this method is compared with the sliding mode single-loop control method with exponential convergence rate. The load torque is set as $1N \cdot m$, when the motor runs stable, the contrastive dq-axes current results are shown in Fig.5. The results show that the proposed terminal sliding mode control method has smaller current fluctuations, thus according to the torque expression, this will produce smaller torque ripple for the PMSM.

V. CONCLUSION

In this paper, a novel control method based on terminal sliding mode control through feedback linearization technology has been studied for PMSM drive system. The controller adopts the speed-current single-loop structure, which has the fast transient response. With the designed terminal sliding mode controller, the speed and current stabilizing control is achieved. Then, considering the lump disturbance in the drive system, a nonlinear disturbance observer is designed to deal with the mismatched disturbance, and it is used for the feed-forward compensation, and the robustness is improved effectively. Simulation results have proved that the controller has good robust performance and speed tracking performance under various conditions. But the speed and current control problems in the flux-weakening control areas are not considered at present, which will be the future research emphases.

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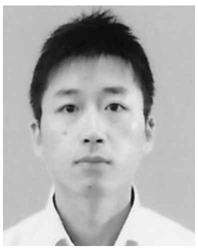

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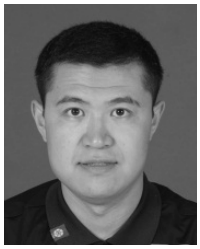

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