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A Composite Sliding Mode Control for SPMSM Drives Based on a New Hybrid Reaching Law with Disturbance Compensation

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Abstract- This paper presents a composite sliding mode control (CSMC) method for speed control of surface-mounted permanent magnet synchronous motors (SPMSMs). The proposed CSMC consists of a new sliding mode control (SMC) based on a novel hybrid reaching law and an extended sliding mode disturbance observer (ESMDO). The new hybrid reaching law is composed of two parts, a terminal reaching part and an exponential plus proportional reaching part. It can effectively suppress the chattering and reduce the reaching time, compared with the conventional constant plus proportional rate reaching law (CPRL). The ESMDO is designed based on CPRL. It can estimate the extra chattering produced by the drive system's lumped disturbance and compensate for the controller's output. Based on the proposed new SMC and ESMDO, an anti-disturbance sliding mode speed controller is designed to improve the performance of SPMSM drive systems. The performance of the proposed method has been validated experimentally and compared with the CPRL-based SMC methods under different conditions.

Keywords: Surface-mounted permanent magnet synchronous motors (SPMSM), sliding mode control, hybrid reaching law, disturbance observer.

I. INTRODUCTION

Due to the inherent advantages of high efficiency, high torque-inertia ratio and excellent control performance, permanent magnet synchronous motors (PMSMs) have been widely employed in many industrial applications, such as traction systems and robots [1]-[5]. PMSMs produce smaller torque ripples and noise compared with switched reluctance

machines [6]-[9]. To achieve good dynamic performance, several control schemes have been used to PMSMs, like field-oriented control (FOC) [10]-[11].

However, the high sensibility of the controller performance to motor parameters entails the main challenge of the FOC scheme [12]. Therefore, the linear control methods like conventional proportional-integral (PI) control strategy will be difficult to provide a satisfactory control performance. Although PI regulators have the inherent ability to automatically compensate for modeling errors compared to predictive control systems, such compensation may not occur properly. To improve the system's robustness, nonlinear control methods have been investigated, such as robust control [13], adaptive control [14], predictive control [15],[16], state feedback control [17], [18], and sliding mode control (SMC). Among these nonlinear control schemes, the SMC strategy has been paid much attention.

SMC is a variable-structure control strategy which adopts a switching control law to alter the drive system's dynamics. It is insensitivity to parameter variations and holds fast dynamic response [19]-[21]. In [22], a fixed switching period SMC was proposed based on a decoupling method of the control actions, which could improve the PI-based FOC transient response. In [23], an improved direct instantaneous torque control based on adaptive terminal sliding mode control is proposed to suppress torque ripple and enhance the anti-interference ability for switched reluctance motors. In [24], a robust iterative learning control scheme was achieved by using an adaptive SMC technique, which could further reduce the torque ripples and improve the anti-disturbance ability of the motor servo system. An adaptive second order sliding mode observer with compensation of voltage source inverter (VSI) nonlinearity was applied to the sensorless servo system in [25]. The position estimation error can be reduced in wide-speed range while the voltage distortion can be compensated online to improve the model accuracy.

Usually, a large switching control gain of switching function is used to ensure the robustness of the SMC. However, the large switching control gain often causes serious chattering phenomenon [26]. To reduce the chattering level, saturation function is applied to substitute the switching function in the control law. Even though the chattering is reduced by this method, it produces uncertain steady-state error subject to the choice of the boundary layer [27]. Furthermore, some novel methods based on SMC strategy have been proposed to overcome this drawback, including the

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complementary sliding mode method [28], high order sliding mode method [29], and reaching law method [30].

Among these SMC strategies, owing to the direct association with the reaching process, the reaching law method can suppress the chattering significantly through a reasonable design of the reaching law. In [31], an SMC method based on a novel reaching law was introduced to reduce chattering on control input and maintain high tracking performance of the controller. In [32], a new switching type of reaching law for SMC of discrete-time system was proposed to ensure fast convergence and good robustness of the control system without increasing the magnitude of the critical signals. However, the complexity of the controller design entails challenge for its application in dynamical systems. To obtain disturbance observation of the control system, some methods based on extended sliding mode observations have been proposed. In [33], an anti-disturbance sliding mode observer was proposed and combined with sliding mode speed controller, which effectively reduces the torque ripples of the direct torque control of a four-phase switched reluctance motor. In [34], an extended sliding-mode mechanical parameter observer was presented to track system disturbances in real time, which includes the information of mechanical parameters. Furthermore, the equivalent lowpass filtering in the observer can be used to control chattering, thereby extra lowpass filtering can be avoided, and the output signal can be directly used for the parameter estimation. In [35], an extended state observer was designed based on a nonlinear model of electronic throttle to estimate the change of throttle opening angle and total disturbance. The estimation accuracy can be guaranteed by adjusting the gains parameters to change the convergent speed.

In this paper, a new SMC based on a novel hybrid reaching law (HRL) with disturbance observer is designed to suppress sliding chattering. It avoids the influence of switching function term in the constant plus proportional rate reaching law (CPRL) on system control performance. The hybrid reaching law contains two parts, a terminal reaching portion and exponential plus proportional rate reaching portion. In order to achieve real-time online estimation of system disturbance, a model-based extended sliding mode disturbance observer (ESMDO) is proposed to compensate the estimated perturbation to sliding mode speed control. Based on the analysis, a composite sliding mode control (CSMC) strategy consisting of the SMC and ESMDO is developed. The design of the controller combines the advantages of two reaching laws to realize global fast convergence. Furthermore, based on the mechanical equation, the observer can achieve fast-tracking of global disturbance, which is effectively introduced in the structure of the control current to enhance the controller.

The remainder of this paper is organized as follows. Section II illustrates the mathematical model of surface-mounted permanent magnet synchronous motors (SPMSMs) and presents the FOC scheme. In Section III, the proposed HRL is presented, and its performance is analyzed by comparing it with the CPRL. Additionally, the stability of the proposed reaching law is proved. The design of the speed controller is

detailed. Section IV presents model-based ESMDO to compensate the estimated perturbation and the structure of the CSMC scheme. Experimental results are provided in Section V, followed by the conclusion.

II. MATHEMATICAL MODEL AND FOC OF SPMSMS

Assuming that the iron core of the SPMSMs is unsaturated and the eddy currents and hysteresis phenomenon are negligible, the mathematical model of the SPMSMs in the synchronous reference frame can be presented by

$$\begin{cases} u_d = Ri_d + \dot{\psi}_d - \omega_e \psi_q \\ u_q = Ri_q + \dot{\psi}_q + \omega_e \psi_d \end{cases} \quad (1)$$

$$\begin{cases} \dot{\omega}_m = \frac{1}{J}(T_e - T_L - v\omega_m) \\ T_e = \frac{3}{2} p_n \psi_f i_q \end{cases} \quad (2)$$

The flux linkage equation is described as

$$\begin{cases} \psi_d = Li_d + \psi_f \\ \psi_q = Li_q \end{cases} \quad (3)$$

where u_d , u_q and i_d , i_q are the stator voltages and currents in d - q coordinates, respectively. R and L represent the armature winding resistance and synchronous inductance, respectively. ψ_f , J , and v are the permanent magnet flux linkage, rotor inertia and damping coefficient, respectively. ω_m is the rotor mechanical speed, p_n is the number of pole pairs, and $\omega_e = p_n \omega_m$ is the rotor electrical speed. T_e is the electromagnetic torque, and T_L is the load torque.

Fig. 1 shows a typical FOC block diagram for the control SPMSMs under no flux-weakening condition. The scheme adopts the structure of cascade control loops, including a speed loop and two current loops.

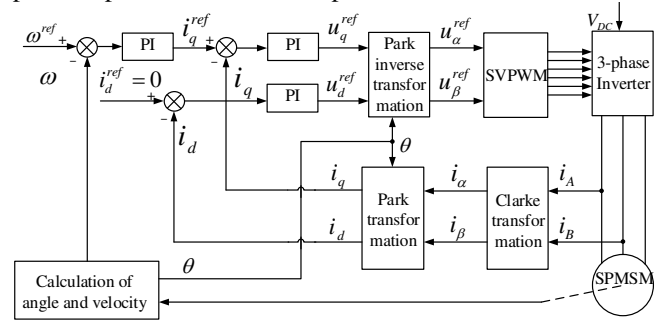


Fig. 1. FOC block diagram for SPMSMs under no flux-weakening condition.

III. SLIDING MODE SPEED CONTROLLER DESIGN

3.1. SMC Design with Constant plus Proportional Rate Reaching Law (CPRL)

Compared with the general sliding mode variable structure control, the reaching law requires that the control system approaches the sliding surface to achieve the stability condition.

The basic form of the CPRL is expressed as follows

$$\dot{s} = -\varepsilon \text{sign}(s) - \lambda s \quad \lambda > 0, \varepsilon > 0 \quad (4)$$

where s and $\text{sign}()$ are the error between estimated and actual state variables (i.e., sliding mode variable) and sign function, respectively. $\varepsilon \text{sign}(s)$ represents the isokinetic reaching term. Its reaching velocity in the approach motion stage is isokinetic, and the approach velocity can be changed by adjusting parameter ε . The approach velocity increases with the increase of the parameter ε and vice versa. λs is the pure constant plus proportional rate term [36].

To illustrate the SMC theory, a second-order nonlinear system with the following state equation is considered as

$$\begin{cases} \dot{x}_1 = x_2 \\ \dot{x}_2 = f(x) + b(x)u + d(x) \end{cases} \quad (5)$$

where $x=[x_1, x_2]$ the system state vector, $d(x)$ represents the system disturbances, and $f(x)$ and $b(x)$ are the bounded nonlinear matrix functions of the system states, respectively.

The sliding mode surface function of the system is defined as

$$s = x_1 + cx_2 \quad (6)$$

where parameter c is the coefficient of the selected sliding mode switching surface, which will affect the convergence rate of the state variable after the system trajectory enters the sliding mode. Such a system sliding surface function ensures the accessibility of the sliding surface and the stability of the sliding mode motion. And the reaching rate is directly affected by the coefficient c .

Substituting (6) into (4) yields

$$\dot{x}_1 + c\dot{x}_2 = -\varepsilon \text{sign}(s) - \lambda s \quad (7)$$

According (5) and (7), the control input can be obtained as follows

$$u = -b(x)^{-1} \left[c^{-1} (x_2 + \varepsilon \text{sign}(s) + \lambda s) + f(x) + d(x) \right] \quad (8)$$

Due to the sign function in control input, the chattering of the SMC is inevitable. And the chattering level is directly affected by the value of ε .

Considering that the system state trajectory moves from the $s>0$ side to the sliding mode surface, (4) can be simplified as

$$\dot{s} = -\varepsilon - \lambda s \quad (9)$$

The sliding mode variable function can be obtained by solving (9).

$$s(t) = -\frac{\varepsilon}{\lambda} + \left[s(0) + \frac{\varepsilon}{\lambda} \right] e^{-\lambda t} \quad (10)$$

where $s(0)$ represents the initial state of the sliding surface.

When the system state reaches the sliding surface, it satisfies $s(t)=0$. The reaching time can be calculated by simplifying (10) as

$$t = \frac{1}{\lambda} \ln \left[1 + s(0) \frac{\lambda}{\varepsilon} \right] \quad (11)$$

According to the above formula, the reaching time of the constant plus proportional rate reaching law can be adjusted by the parameter λ . When the value of λ is increased, the system robustness is improved while the approach speed is increased, but the increase of the value λ will result in a corresponding increase in the chattering level of the control output.

Therefore, the reaching speed and the chattering level are contradictory in terms of the constant plus proportional rate reaching law. In order to solve the essential contradiction, a new reaching law is proposed based on the constant plus proportional rate reaching law.

3.2. Proposed Hybrid Reaching Law (HRL)

The novel HRL based on terminal reaching part control is proposed to further suppress the sliding chattering, which can avoid the influence of switching function term in conventional control law on system control performance. The reaching law is expressed as

$$\dot{s} = -m|x|^a s^{q/p} - \frac{b}{k} (e^{k|s|} - 1)s \quad (12)$$

where $a>0$, $m>0$, $b>0$, and $0<k<1$. x is the system state variable. p and q are positive odd numbers and satisfy that p is greater than q .

The hybrid reaching law consists of two parts, the terminal reaching part and the exponential plus proportional rate reaching part. The terminal reaching portion is represented by $-m|x|^a s^{q/p}$, which combines the power function of the system state variable on the basis of the terminal sliding mode to form a variable terminal approaching manner. The exponential plus proportional rate reaching part is represented by $-\frac{b}{k}(e^{k|s|}-1)s$.

This part introduces the exponential function of the system state variable based on the pure exponential reaching law, which produces a variable exponential reaching mode.

Since the system state variable is introduced in the reaching law, the sliding mode reaching speed is associated with the system state. When the state variable $|x|$ value is large (i.e., the SMC system trajectory is far away from the sliding mode switching surface). In the process of the system state approaching the sliding mode switching surface s , the terminal reaching part and the exponential plus proportional rate reaching part work simultaneously. The reaching coefficient is large enough to speed up the convergence process when the sliding mode switching surface is far away.

On the other hand, when the state variable $|x|$ is relatively small (i.e., the SMC system trajectory is close to the sliding mode switching surface), the reaching speed of the variable exponential plus proportional rate reaching portion approaches zero. Therefore, the system state approaches the sliding mode switching surface s with the variable terminal sliding mode. The state variable $|x|$ enters the sliding mode switching surface and moves to the equilibrium point under the control output, which makes the reaching speed of the terminal reaching part decrease continuously. Thereby, the reaching speed is reduced when the system enters the sliding surface, and the chattering is effectively suppressed.

Summarily, in the case where the system state is relatively close to the sliding mode surface, the terminal reaching mode holds a fast reaching speed. The constant rate reaching mode approaches the sliding mode surface faster when the state trajectory is far away from the equilibrium point. The proposed hybrid reaching law combines the advantages of both to achieve global fast convergence. Furthermore, the

power function of the system state variable is introduced in the reaching law, which suppresses the system chattering. Referring to the derivation process in [27], the reaching time can be calculated from 0 to t as

$$t_1 = \frac{kp}{b(e^{k|x|}-1)(p-q)} \ln \left[1 + \frac{b(e^{k|x|}-1)s(0)^{\frac{p-q}{p}}}{km|x|^a} \right] \quad (13)$$

When the reaching speed of the hybrid reaching law is equal to the conventional exponential reaching law (i.e., $t=t_1$), it can be obtained that

$$\begin{cases} \frac{kp}{b(e^{k|x|}-1)(p-q)} = \frac{1}{\lambda} \\ \frac{b(e^{k|x|}-1)s(0)^{\frac{p-q}{p}}}{km|x|^a} = s(0) \frac{\lambda}{\varepsilon} \end{cases} \quad (14)$$

Define $\frac{q}{p}$ as ζ , which satisfies $0 < \zeta < 1$. The relationship of the parameters in the reaching laws can be simplified as

$$\begin{cases} \lambda = \frac{b}{k}(e^{k|x|}-1)(1-\zeta) \\ m(1-\zeta)|x|^a s(0)^{(1-\zeta)} \end{cases} \quad (15)$$

From (15), it can be further obtained that

$$\frac{\lambda k}{b(e^{k|x|}-1)} = 1 - \zeta < 1 \quad (16)$$

$$\frac{\varepsilon}{m|x|^a} = (1-\zeta) \cdot s(0)^{(1-\zeta)} \quad (17)$$

Therefore, the reaching coefficient of variable exponential reaching part in the proposed HRL is larger than the CPRL, which indicates that the variable exponential reaching part in the hybrid reaching law has the greater reaching speed.

Furthermore, the following inequality (18) can be obtained as

$$\begin{cases} \frac{\varepsilon}{m|x|^a s(t)^{(1-\zeta)}} > 1, s(t) < s(0)(1-\zeta)^{\frac{1}{\zeta}} \\ \frac{\varepsilon}{m|x|^a s(t)^{(1-\zeta)}} \leq 1, s(t) \geq s(0)(1-\zeta)^{\frac{1}{\zeta}} \end{cases} \quad (18)$$

The terminal reaching part takes a major role when the system state is relatively close to the sliding surface, while the isokinetic reaching term is critical in the CPRL. It can be seen from (18) that the terminal reaching part in the proposed HRL takes smaller reaching speed compared with the isokinetic reaching term in the CPRL, which indicates the smaller chattering.

3.3. Speed Control Law

SMC aims to guarantee that the speed strictly follows its reference signal ω_m^* when the parameter changes in SPMSMs. Further, the basic idea of the sliding mode speed controller is to guide the state trajectory to progressively reach the sliding surface from any starting points by using the control law.

Therefore, the state variables of the system can be defined as

$$\begin{cases} x_1 = \omega_m - \omega_m^* \\ x_2 = \dot{\omega}_m \end{cases} \quad (19)$$

where ω_m^* is the reference mechanical speed, and ω_m is the actual output speed.

Substituting (2) into (19) yields

$$\dot{x}_2 = \frac{1}{J} \left(\frac{3p_n \psi_f}{2} i_q - T_L - v \omega_m \right) \quad (20)$$

Derivation of (20) has the form as

$$\dot{x}_2 = \frac{1}{J} \left(\frac{3p_n \psi_f}{2} i_q - \dot{T}_L - v \dot{\omega}_m \right) = -\frac{v}{J} x_2 + \frac{3p_n \psi_f}{2J} i_q - \frac{\dot{T}_L}{J} \quad (21)$$

Hence, the state equation of the system can be expressed as

$$\begin{cases} \dot{x}_1 = x_2 \\ \dot{x}_2 = Ax_2 + Bu + C \end{cases} \quad (22)$$

where $A = -\frac{v}{J}$, $B = \frac{3p_n \psi_f}{2J}$, $C = -\frac{\dot{T}_L}{J}$, $u = i_q$.

Since the change of load disturbance \dot{T}_L not considered, it satisfies $C = 0$.

Select the linear sliding mode surface as follows.

$$s = x_2 + \eta x_1 \quad (23)$$

where η is a constant.

Substituting (22) into the derivation of (23) yields

$$\dot{s} = (A + \eta)x_2 + Bu \quad (24)$$

Since the speed tracking error is a significant system performance indicator, it is selected as the state variable related to the reaching speed. Therefore, $x = x_1$ is substituted into (12), and the following equation can be obtained by combining (12) and (24).

$$-m|x_1|^a s^{q/p} - \frac{b}{k}(e^{k|x_1|}-1)s = (A + \eta)x_2 + Bu \quad (25)$$

Define $\zeta = q/p$, then the output of the controller can be obtained from (25) as

$$u = \frac{1}{B} \left[-m|x_1|^a s^\zeta - \frac{b}{k}(e^{k|x_1|}-1)s - (A + \eta)x_2 \right] \quad (26)$$

Therefore, the reference q -axis current is written as

$$i_q^{ref} = \frac{1}{B} \int \left[-m|x_1|^a s^\zeta - \frac{b}{k}(e^{k|x_1|}-1)s - (A + \eta)x_2 \right] dt \quad (27)$$

The flowchart of the variable structure of the system parameter i_q^{ref} is illustrated in Fig. 2.

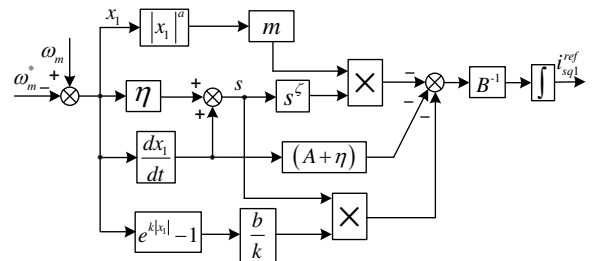


Fig. 2. Flow chart of the variable structure of system parameter i_q^{ref} .

IV. DESIGN OF SLIDING MODE DISTURBANCE OBSERVER

4.1. Extended Sliding Mode Disturbance Observer (ESMDO)

There are various disturbances in SPMSM drive systems under complex operating conditions. If these disturbances are not effectively suppressed, the system control performance will be affected. Therefore, to realize real-time online estimation of system disturbances, this paper proposes an ESMDO.

When the system disturbances are taken into consideration, (19) can be rewritten as

$$\begin{aligned} x_2^* &= \frac{3p_n\psi_f}{2(J+\Delta J)}i_q - \frac{T_L+\Delta T_L}{J+\Delta J} - \frac{v+\Delta v}{J+\Delta J}\omega_m \\ &= \left(\frac{3p_n\psi_f}{2J} - \Delta_1\right)i_q - \left(\frac{1}{J} - \Delta_2\right)(T_L+\Delta T_L) - \left(\frac{v}{J} - \Delta_3\right)\omega_m \quad (28) \\ &= x_2 - \Delta_1 i_q - \left(\frac{1}{J} - \Delta_2\right)T_L + \Delta_2 \cdot \Delta T_L + \Delta_3 \omega_m \end{aligned}$$

where ΔJ , Δv and ΔT_L represent the perturbation of the corresponding mechanical parameters, respectively. For the sake of simplicity, Δ_1 , Δ_2 , and Δ_3 indicate the uncertainties.

The disturbances of the SPMSM drive systems consisting of mechanical parameter disturbance and load disturbance, which can be expressed as

$$D = -\Delta_1 i_q - \left(\frac{1}{J} - \Delta_2\right)\Delta T_L + \Delta_2 \cdot \Delta T_L + \Delta_3 \omega_m \quad (29)$$

The comprehensive disturbance should satisfy the following constraints

$$\begin{cases} |D| \leq \bar{D} \\ \dot{D} = d \end{cases} \quad (30)$$

where \bar{D} is the limit value of the comprehensive disturbance of the motor system and d represents the variation rate of the comprehensive disturbance.

Taking the comprehensive perturbation into consideration, (22) is written as

$$\begin{cases} \dot{x}_1 = x_2 \\ \dot{x}_2 = Ax_2 + Bu + C + \dot{D} \end{cases} \quad (31)$$

Then, the reference q -axis current can be obtained as

$$i_q^{ref} = \frac{1}{B} \int \left[-m|x_1|^a s^\zeta - \frac{b}{k} (e^{k|x_1|} - 1) s - (A + \eta)x_2 - C - \dot{D} \right] dt \quad (32)$$

From (32), it can be observed that the comprehensive disturbance is of significant effect on the control performance. If the system disturbance is negative and considered as 0, the parameters m and b may increase to generate the same control output i_q^{ref} , which leads to severe system chattering.

Using D as the extended state variable of the system, combined with (30) and (31), the extended state equation of the system can be obtained as

$$\begin{cases} \dot{\omega}_m = -\frac{v}{J}\omega_m + D + Bi_q - \frac{T_L}{J} \\ \dot{D} = d \end{cases} \quad (33)$$

The sliding mode disturbance observer is constructed as

$$\begin{cases} \dot{\hat{\omega}}_m = -\frac{v}{J}\hat{\omega}_m + \hat{D} + Bi_q - \frac{T_L}{J} + y \\ \dot{\hat{D}} = ry \end{cases} \quad (34)$$

where $\hat{\omega}_m$ and \hat{D} represent the estimations of the speed and perturbation, respectively, r is the control law gain coefficient, and y is the observer function to ensure that speed error converges to 0. The schematic diagram of the ESMDO is shown in Fig. 3.

According to (33) and (34), the error equation of the observer can be written as

$$\begin{cases} \dot{e}_\omega = -\frac{v}{J}e_\omega + e_D - y \\ \dot{e}_D = d - ry \end{cases} \quad (35)$$

where e_ω and e_D are the errors of speed and disturbance observation, respectively.

The CPRL is employed to ensure that the sliding mode surface is chosen as $s_\omega = e_\omega$. Therefore, it can be obtained as

$$\dot{s}_\omega = \dot{e}_\omega = -\varepsilon \text{sign}(s_\omega) - \lambda s_\omega \quad (36)$$

Substituting (36) into (35) yields

$$y = -\frac{v}{J}e_\omega + e_D + \varepsilon \text{sign}(s_\omega) + \lambda s_\omega \quad (37)$$

Therefore, the observer with the control law y can reach the sliding mode surface in finite time. Then, the following equations can be obtained as

$$\begin{cases} \dot{s}_\omega = s_\omega = 0 \\ \dot{e}_\omega = e_\omega = 0 \end{cases} \quad (38)$$

Substituting (38) into the error (35) yields

$$\begin{cases} e_D - y = 0 \\ d - ry = \dot{e}_D \end{cases} \quad (39)$$

From (39), the differential equation is obtained as follows

$$\dot{e}_D + re_D = d \quad (40)$$

Solving (40), the disturbance estimation error can be obtained as

$$e_D = e^{-rt} \left(K + \int d \cdot e^{rt} dt \right) \quad (41)$$

where K is a constant. Similarly, to ensure that the disturbance error converges to 0, it must be satisfied that

$$r > 0 \quad (42)$$

Furthermore, the convergence speed of sliding mode disturbance observer is directly determined by the value of r .

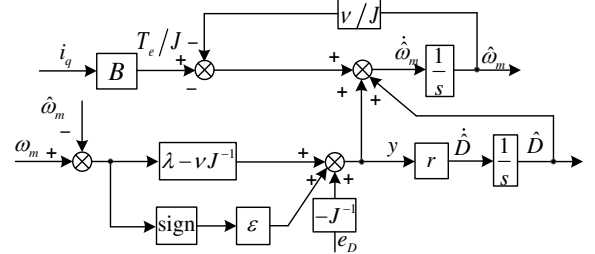


Fig. 3. Schematic diagram of the ESMDO.

4.2. Proof of Stability

In order to verify the stability of the control system with the proposed observer, the Lyapunov function $V = s^2/2$ is selected.

SPMSM drive system. The reference speed is 360 rpm, and the sampling time is set as 0.1 ms. A step change of the load torque from 0 to 10 Nm is applied to the control system at $t=0.5$ s. Compared with the CPRL-based SMC control method, the proposed HRL method maintains better dynamic performance. It can be observed that the HRL method produces smaller speed overshoot when the load torque changes. Meanwhile, the HRL method produces smaller fluctuation than the CPRL method. Furthermore, the proposed CSMC with extended disturbance observer shows better performance in terms of speed tracking and torque. The specific comparative results of these three control schemes are listed in Table II.

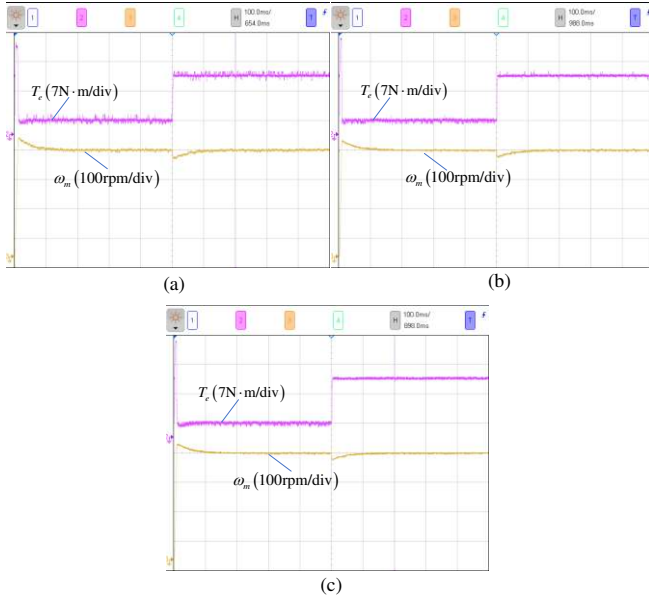


Fig. 7. Experimental performance under load torque step increase, (a) conventional CPRL-based method, (b) proposed HRL-based SMC method, and (c) the proposed CSMC method.

Table II. Performance Parameters of the Three Control Schemes under an Increase of Load Torque

	CPRL method	HRL method	CSMC (CPRL+ESMDO)
Speed fluctuation (rpm)	10	7.8	5.4
Torque fluctuation (Nm)	1.05	0.83	0.72
Settling time (s)	0.013	0.011	0.010

Fig. 8 shows the performance of the proposed ESMDO under load torque increase condition. As shown, with the increase of the load torque at $t=0.5$ s, the SMC law y produces a fluctuation of -1700 rad/s^2 . The disturbance estimation value \hat{D} changes stepwise to about -2300 rad/s^2 , which is mainly caused by load change. From Figs. 8(c) and (d), the error of the speed observation is small. Its maximum is -1.6 rad/s when the step load torque is applied to the system. Therefore, the proposed ESMDO performs well in the presence of disturbance and speed observation, which contributes to the anti-disturbance sliding mode speed control.

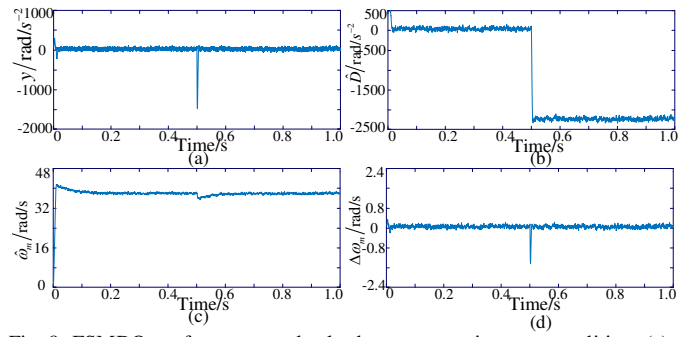


Fig. 8. ESMDO performance under load torque step increase condition: (a) SMC law of the ESMDO, (b) disturbance estimation value, (c) mechanical speed estimation value, and (d) speed observation error.

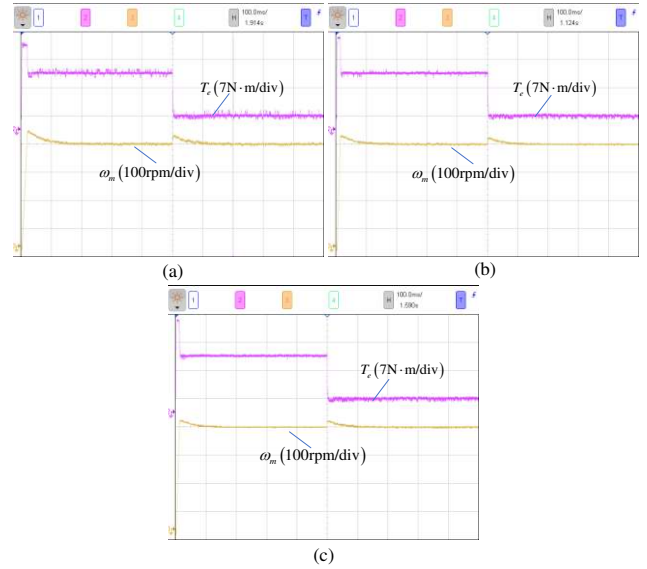


Fig. 9. Experimental performance under load torque step decrease condition: (a) CPRL-based SMC method, (b) proposed HRL-based SMC method, and (c) proposed CSMC method.

5.2. Performance Comparison under a Step Decrease of Load Torque

Fig. 9 illustrates the dynamic responses of three control schemes under a step decrease of load torque T_L for the SPMSM drive system. A step-change in the reference torque from 10 to 0 Nm is applied to the control system at $t=0.5$ s. Compared with the CPRL method, the proposed HRL method performs better in dynamic performance as well.

Fig. 10 shows the performance of the proposed ESMDO in this scenario. As shown, the step change of disturbance estimation value \hat{D} is from -2300 to 0 rad/s^2 , which is mainly determined by the second term $-\left(\frac{1}{J}-\Delta_2\right)\Delta T_L$ of the lumped disturbance. Therefore, the observation can estimate the disturbance exactly and quickly with small chattering, and the observation error of the rotational speed further verifies the performance of the observer.

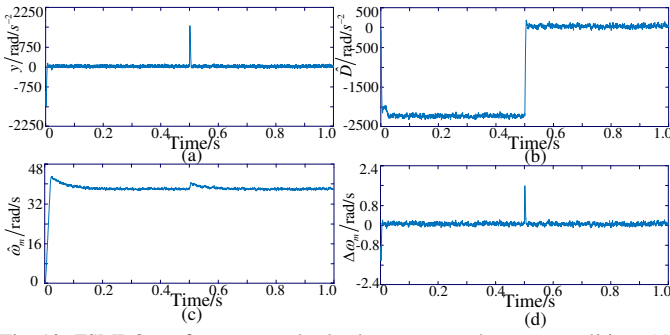


Fig. 10. ESMDO performance under load torque step decrease condition: (a) SMC law of the ESMDO, (b) disturbance estimation value, (c) mechanical speed estimation value, and (d) speed observation error.

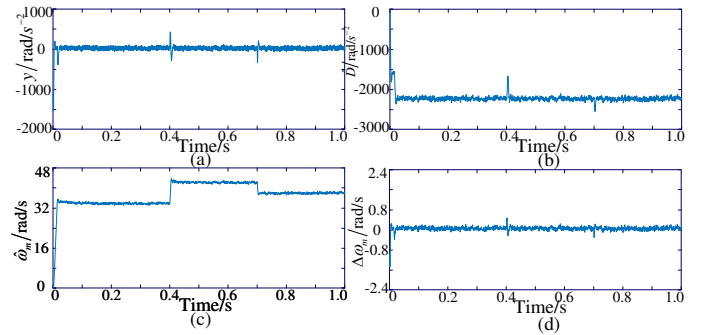


Fig. 12. ESMDO performance under reference speed step-change condition: (a) SMC law of the ESMDO, (b) disturbance estimation value, (c) mechanical speed estimation value, and (d) speed observation error.

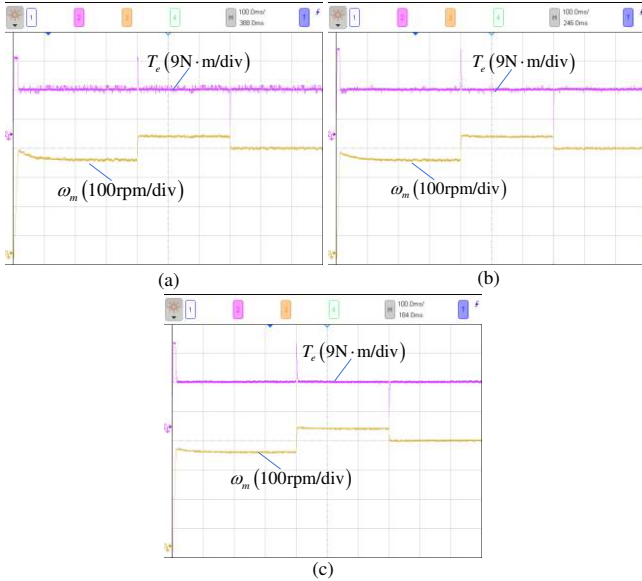


Fig. 11. Experimental performance under reference speed step-change condition: (a) CPRL-based SMC method, (b) proposed HRL-based SMC method, and (c) proposed CSMC method.

5.3. Performance Comparison Under Step Changes to the Reference Speed

Fig. 11 illustrates the dynamic responses of three control methods when step changes are applied to the reference mechanical speed. Two step-changes, 320 to 400 rpm and 400 to 360 rpm, are applied to the system at the time instants $t_1=0.4$ s and $t_2=0.7$ s, respectively. The load torque is set to 10 Nm. As shown, the proposed HRL-based SMC method presents better dynamic performance than the SMC scheme based CPRL. The fluctuation in the mechanical speed ω_m and load torque T_L is reduced with the HRL method. Furthermore, the HRL method shows a faster response in speed tracking.

As shown in Fig. 12, the ESMDO performs well in disturbance estimation, and the CSMC scheme presents the ability of disturbance suppression compared with CPRL method. The oscillations in the estimated disturbance \hat{D} converge to zero in 0.02 s, and the transient-state error of the mechanical speed is kept within 0.5 rad/s.

VI. CONCLUSION

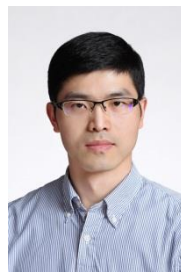
A CSMC method composed of a novel HRL and an ESMDO was presented in this paper. The chattering of the sliding mode speed controller can be significantly suppressed by introducing a hybrid reaching law into the SMC. Compared with the CPRL, it was verified that the new reaching law yields smaller chattering and performs better dynamic response. In order to estimate system disturbance online, the ESMDO based on constant plus proportional rate reaching law was introduced. Furthermore, considering the uncertainty of motor parameters, the stability of the ESMDO was proved by solving the differential equation when the state variable of disturbance reaches the sliding mode surface. It can be concluded that the proposed ESMDO performs well in the presence of disturbance and speed observation, which contributes to the anti-disturbance sliding mode speed control.

The composite sliding mode speed controller has the advantages of reducing the speed and torque fluctuation under various conditions. Therefore the CSMC scheme presents the ability of disturbance suppression compared with CPRL method and the oscillations in the estimated disturbance converge to zero quickly. Due to the complexity of the new reaching law, the design of the sliding mode controller is more complicated than the traditional constant plus proportional law. The computation load of the whole control system will increase as well due to the introduction of the disturbance observer. In addition, for the sliding mode observer, the performance of the observer needs to be further studied for more accurate and fast observations.

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