Composite Speed Control of PMSM Drive System based on Finite Time Sliding Mode Observer

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ABSTRACT The robust nonlinear speed control technique has been proposed for the speed regulation of permanent magnet synchronous motor (PMSM) by adopting a new fast terminal sliding mode control (FTSMC) based on the finite time sliding mode observer (FTSMO). The proposed technique can ensure the robustness against load disturbances, which has the capability of high tracking precision, fast finite time convergence and smooth dynamic operation in both transient and steady state conditions. Moreover, the requirement of high switching gain to reach the upper bound limit of total disturbances may produce the steady state error and chattering. To address this issue, one robust FTSMO based FTSMC is designed to alleviate those limitations aforementioned. The FTSMO can successfully estimate the total disturbances of the system, then the estimated disturbances can be compensated by the feed-forward compensation technique. The FTSMO based FTSMC should require the smaller switching gain to meet upper bound limit of the disturbances compared with the conventional SMC (CSMC) and FTSMC. The stability of the close loop control system is fully verified by the Lyapunov theory. Comprehensive simulation and experimental results have fully demonstrated that the proposed method is robust against load disturbances.

Index Terms—Permanent magnet synchronous motor (PMSM), sliding mode control (SMC), fast terminal sliding mode control (FTSMC), finite time sliding mode observer (FTSMO).

I. INTRODUCTION

Due to the high power and torque density, the permanent magnet synchronous motor (PMSM) has been applied in many emerging applications, such as electric vehicle (EV) [1]. The linear control algorithms have been widely employed in PMSM drive systems since they are easy to implement in practice [2]. As the practical PMSM system is nonlinear, time variant and complex with uncertainties, the linear algorithms may fail to attain the adequate performance in the whole operating range [3]. In order to increase the PMSM drive performance, great efforts in recent years have been made to develop nonlinear control techniques, such as adaptive control [4], disturbance rejection [5] [6], finite time control [7], linear sliding mode control (SMC) [8], robust control, predictive control [9], fuzzy and neural control [10], back stepping and intelligent control [1], [7], [10], and so on. These nonlinear control techniques are used to improve the drive performance from different application requirements. Fortunately, the SMC techniques are found more effective to enhance the system robustness against load disturbances and uncertainties of PMSM drive systems [11]. However, the conventional SMC techniques can only improve the convergence rate of the system in the reaching time, but not in the sliding time. Thereof, the nonlinear terminal sliding mode (TSM) surface of the SMC is used to guarantee the system robustness, which can ensure the convergence in finite time at the reaching period and in sliding mode as well. The TSM has the capability to improve the system convergence in finite time and robust against nonlinearities. The prominent drawback of nonlinear TSM is the chattering phenomena, which is brought by the discontinuous control
law and periodic switching action near to the sliding surface. To alleviate the chattering phenomena in the SMC, different techniques are proposed as the saturation function instead of sign function, but the anti-disturbance performance has been compromised to some extent [12]. The selection of switching gain is a big issue in linear and TSM SMC techniques, which should choose one large value to reach the upper bound limit of disturbance and uncertainties. The chattering phenomenon would be produced in the control input due to the high value of the switching gain for the control law, as needed for the disturbance rejection process. The potential disadvantage of high switching gain can be solved by the full order SMC [13] and continuous terminal SMC [14].

In this paper, a new fast terminal SMC (FTSMC) has been adapted for the PMSM drive system, which has the capability of fast finite time convergence, high tracking precision, excellent steady state process, and effective chattering alleviation in the whole system. The problem of the high switching gain selection can be solved through the implementation of the observers in the close loop system. The disturbances can be estimated by the observers, then the estimated disturbances would be brought for the feed forward compensation method of the close loop system. The adaptive SMC is used to estimate the disturbances for the position control [15]-[17]. Many other techniques have been used to estimate the nonlinearities for compensation, e.g. the extended state observer based on the SMC.

Due to the stunning performance, the FTSMC is designed in this paper for its fast finite time convergence and robust against nonlinearities in the sliding trajectory. It is observed that the high value of switching gain in the control law is needed to meet the upper bound limit of the disturbances of the control system, the chattering would be induced in the control input due to the requirement of the high switching gains for control law. Consequently, due to that one estimation process is needed to alleviate the aforementioned problems in the system, the total or partial estimation technique of the disturbances can reduce the switching gain in the control law, which would alleviate the chattering of the whole system.

Hence, in this paper, one improved FTSMO based FTSMC is proposed to solve the defects of conventional methods. The FTSMO can estimate the total disturbance of the system, in which the estimated disturbances are compensated by the feed-forward compensation technique. The proposed technique can alleviate the chattering phenomena in the system effectively. This paper is organized by six sections. In Section I, the relevant literature review is fully made. The dynamic modeling of the PMSM is presented in Section II. The speed controller is designed by FTSMC, which is represented in Section III. In Section IV, the FTSMO is designed to estimate the disturbances of the system for feed-forward compensation process. Comprehensive simulation and experimental results are given out in Section V, which have fully confirmed that the FTSMO can get stronger anti-disturbances ability, greater robust capability, faster convergence speed, and so on. Finally, conclusions have been drawn in Section VI.

II. MODELLING OF THE PMSM DRIVE SYSTEM

The PMSM dynamic model can be obtained with the help of the synchronous reference frame. The speed and dynamic dq-axis currents can be described as

\[ J \frac{d\omega}{dt} = X_i q - B \omega - n_i T_L \quad (1) \]

\[ L_i \frac{di_\alpha}{dt} = -R s_i + L_n \omega i_\alpha + u_d \quad (2) \]

\[ L_i \frac{di_\beta}{dt} = -R s_i + L_n \omega i_\beta - n_i \omega \psi_f + u_q \quad (3) \]

where \( X_i = 3/2 n_p^2 \psi_f \) , \( F_i = X_i / J \) , \( n_p \) is the number of pole pairs, \( \psi_f \) the flux linkage, \( J \) the moment of inertia, \( B \) the viscous damping co-efficient, and \( R_s \), \( u_d \), \( u_q \) are the d- and q- axis voltages and currents, respectively. \( R \) and \( L_i \) the resistance and inductance of the stator, respectively, \( \omega \) is the mechanical angular speed, and \( T_L \) the load torque.

FIGURE 1. Diagram of the PMSM drive under the FOC control.

In this paper, the speed loop is considered with load disturbances, hence the speed equation with disturbances can be written as

\[ \dot{\omega} = F_i i_\alpha + y_\omega(t) \quad (4) \]

where \( y_\omega(t) = -\frac{B}{J} \omega - \frac{n_i}{J} T_L \) is the total disturbances for the drive system. The simple diagram of field-oriented control (FOC) for the PMSM is shown in Fig. 1, which contains two main loops (one for the speed and another for the current loop), respectively. In order to decouple the speed and current loops, it is supposed \( i_\alpha = 0 \), and the PI based current controllers are adopted to stabilize the current dynamics in dq-axis for current loops, separately. In this paper, the speed loop has been designed for the speed regulation.

III. DESIGN OF THE SPEED CONTROLLER

A. The Design of the Speed loop Controller under the FTSMC

In this work, the actual and reference speeds of the PMSM are \( \omega \) and \( \omega^* \), respectively. The speed error \( E \) can be
described as
\[ E = \omega^* - \omega \quad (5) \]

Taking the derivation of (5) and combining with (4), it will get the mathematical expression on \( \hat{E} \) by
\[ \dot{E} = \omega^* - F_i q - y_w(t) \quad (6) \]

In general, the conventional sliding surface can be described as
\[ \dot{\vartheta} = \dot{E} + \mu \times E^\delta, \mu > 0, 0 < \mu < 1 \quad (8) \]
\[ \dot{\vartheta} = E + \mu \times \dot{E}^\delta, \mu' > 0, 0 < \mu' < 1 \quad (9) \]

It can be noted that (7) would be the same as (8) when \( \dot{\delta} = 1 \), due to 0 < \( \delta \) < 1, \( \delta \) can be selected as \( \dot{\delta} = q/p \), where \( q \) and \( p \) are the positive odd integers, and likewise \( \dot{\delta} \) is adopted as \( u = q/p \), respectively. Furthermore, the NTSMC has the slow convergence rate when the states are far away from the equilibrium point [19]. Moreover, to enhance the convergence of the system states, one new FTSMC has been proposed in this paper, which has the capability of high tacking precision, fast convergence and robust against load disturbances. The new FTSMC technique is illustrated as
\[ \dot{\vartheta} = \dot{E} + \mu_1 [E_1^{\delta_1} \text{sign}(\dot{E})] + \mu_2 [E_2^{\delta_2} \text{sign}(E)] \quad (10) \]

where coefficients \( \mu_1 > 0, \mu_2 > 0 \), 0 < \( \delta_1 < 2, \delta_2 > \sigma_1 \), and \( \sigma_1 = t/u \), both \( t \) and \( u \) are the odd positive number. One novel terminal sliding reaching law (TSRL) type is employed to enhance the speed response of motor system in transient process and reduce the chattering phenomenon [20]. The TSRL can be illustrated as
\[ \dot{\vartheta} = -\lambda_1 (\vartheta) - \lambda_2 |\vartheta|^\delta \text{sign}(\vartheta) \quad (11) \]

where \( \lambda_1, \lambda_2 \) and \( \delta_2 \) are carefully designed for the robustness of speed control loop under speed and load change. The \( \lambda_1 \) and \( \lambda_2 \) are positive constants and the value of \( \delta_2 \) is bounded as 0 < \( \delta_2 < 1 \).

Statement 1. The speed error in (5) is chosen as state variable for the design of the speed controller under FTSMC with TSRL of the PMSM drive system. The E can converge to the sliding mode surface (10) with TSRL (11) as \( \dot{\vartheta} = 0 \). Therefore, the control law for the speed controller can be described as
\[ \dot{\vartheta} = F_i (H_{eq} + H_b) \quad (12) \]

The block diagram of the sliding mode speed controller based on the FTSMC is shown in Fig.2. Some assumption and statement are given out and discussed as follows.

The stability can be verified by the Lyapunov function, the According to (6) the (10) can be rewritten as
\[ \dot{\vartheta} = \dot{E} + \mu_1 [E_1^{\delta_1} \text{sign}(\dot{E})] + \mu_2 [E_2^{\delta_2} \text{sign}(E)] \quad (15) \]
\[ = \omega^* - F_i q - y_w(t) + \mu_1 [E_1^{\delta_1} \text{sign}(\dot{E})] + \mu_2 [E_2^{\delta_2} \text{sign}(E)]. \]

Substituting (12) - (14) into (15), the sliding mode surface can be derived as
\[ \dot{\vartheta} = \omega^* - F_i [F_i^{-1}(H_{eq} + H_b)] - y_w(t) + \mu_1 [E_1^{\delta_1} \text{sign}(\dot{E})] + \mu_2 [E_2^{\delta_2} \text{sign}(E)] \quad (16) \]

Meanwhile, Eq. (16) can be simplified as
\[ \dot{\vartheta} = -H_b - y_w(t) \quad (17) \]

Then, the Lyapunov function is considered as \( \gamma = \frac{1}{2} \vartheta \) in this work. By taking derivative of (17) and combining with the error of PMSM system (6), it will get
\[ \dot{\vartheta} = -H_b - \dot{y}_w(t) \quad (18) \]
\[ = -\lambda_1 (\vartheta) - \lambda_2 |\vartheta|^\delta \text{sign}(\vartheta) - \dot{y}_w(t). \]

Hence, the following relationship can be obtained by
\[ \dot{\vartheta} = [-\lambda_1 (\vartheta) - \lambda_2 |\vartheta|^\delta \text{sign}(\vartheta) - \dot{y}_w(t)] \delta \quad (19) \]

According to Statement 1, Eq. (19) can be rewritten as
\[ H_{eq} = \dot{\vartheta} + \mu_1 [E_1^{\delta_1} \text{sign}(\dot{E})] + \mu_2 [E_2^{\delta_2} \text{sign}(E)] \quad (13) \]
\[ H_b = \int_0^t \lambda_1 (\vartheta) + \lambda_2 |\vartheta|^\delta \text{sign}(\vartheta) \, dt \quad (14) \]
\[ V = \dot{y} \theta = -\lambda_1 \theta^2 - \lambda_2 [\theta^{1/(\eta+1)} - \hat{y}_m(t) \theta] \]
\[ \leq -\lambda_1 \theta^2 - \lambda_2 [\theta^{1/(\eta+1)} - \hat{y}_m(t)] [\theta] \]
\[ \leq -\lambda_1 \theta^2 - [\lambda_2 + \frac{\hat{y}_m(t)}{\theta}] [\theta^{1/(\eta+1)}] \]
\[ \leq -\lambda_1 \theta^2 - \left[ \lambda_2 + \frac{\hat{y}_m(t)}{\theta} \right] \theta^{1/(\eta+1)} \]
\[ = -2r_1 V - 2^{-\frac{2}{3}} r_2 V^2 \]

where \( r_1 \) and \( r_2 \) are the positive constants. From (20), it is confirmed from (20) that the speed error of the controller would converge to zero in finite time when the inequality \( \lambda_2 > \hat{y}_m(t) \), and the finite time \( t_f \), as expressed by
\[ t_f = \frac{E(0)}{E(0) - \frac{\lambda_1}{\lambda_2} \theta^{1/(\eta+1)}} = \frac{\lambda_2 E(0)^{-1}}{\lambda_2 (\sigma_1 - 1)} \]
\[ R \left( \frac{1}{\eta}; \left[ \frac{\sigma_1 - 1}{\sigma_1 (\sigma_2 - 1) \sigma_1} : \sigma_2 \right] \right) \lambda_2 E(0)^{-1} \]

where \( R(\cdot) \) shows the Gauss Hyper-Geometric [21]. Meanwhile, Eq. (21) shows that the states would approach to the sliding surface in the finite time, i.e. getting convergence to zero gradually.

Remark 1. It can be noted that the gains \( \lambda_1 \) and \( \lambda_2 \) in the reaching law must be larger value to handle the effect of nonlinearities [21], [22]. The large switching gain value can produce the saturation problem in the drive system, while small values cannot ensure the finite time convergence and not good enough for the anti-disturbance. However, the FTSMO has been developed in this paper to estimate the nonlinearities in the system and compensate the system gains, which depends on the upper bound of estimation, as designed in the latter section regarding the FTSMO in details.

IV. OBSERVER DESIGN FOR THE ESTIMATION

A. Estimation on Disturbances and Uncertainties

It is known that the rejection ability of the load disturbances in CSMC is poorer than the FTSMC. Therefore, the FTSMC has been designed to improve the load disturbance rejection ability of the system. The FTSMC has the ability of fast convergence, high tracking precision and robust against the load disturbance. Furthermore, the estimation of the total disturbances is important for the composite controller to compensate the total disturbances. The feed forward compensation technique is used to reduce the system disturbances. Moreover, the FTSMO is employed for estimation of the system disturbances.

The FTSMO is adopted for the estimation of disturbances because the conventional disturbance observers have some limitations, i.e. the Luenberger observer brings the steady state error in the system, and then the sliding mode observer would produce the inherent chattering phenomenon in the system. Moreover, the high order differentiator (HOD) is designed and adopted for the numerical calculation. Then, the HOD is modified as the improved FTSMO in this paper for estimation on total disturbances of the PMSM drive system.

The FTSMO can be designed and implemented by considering a first order system \( m = f(m) + y(t) \), where \( m \) is the system state, and \( y(t) \) the system disturbances. Then the FTSMO is written as
\[ \dot{z}_o = w_o + f(m) \]
\[ w_o = -\gamma o k^{1/3} |z_o - m|^{2/3} \text{sign}(z_o - m) + z_1 \]
\[ \dot{z}_1 = w_1, \]
\[ w_1 = -\gamma k^{1/2} |z_1 - w_o|^{2/3} \text{sign}(z_1 - w_o) + z_2 \]
\[ \dot{z}_2 = -\gamma k \text{sign}(z_2 - w_1) \]

where \( \gamma_0, \gamma_1, \gamma_2 \) and \( k \) are the observer co-efficients, \( z_o, z_1 \) and \( z_2 \) the observer variables, respectively. Therefore, \( z_1 \) can converge to \( y(t) \) in the finite time with the proper selection of the FTSMO gains.

B. Improved FTSMO Designed for the Speed Loop

The speed loop (4) has been modified according to the load disturbances of the system. One improved FTSMO has been implemented for the estimation of the system disturbances. Then, the FTSMO can be described by the feed-forward compensation technique, as illustrated by
\[ \dot{\omega} = \frac{3}{2} n_r^2 \psi_f \hat{i}_q - B J \hat{\omega} + w_o \]
\[ w_o = -\gamma o k^{1/3} |\hat{\omega} - \omega|^{2/3} \text{sign}(\hat{\omega} - \omega) + \hat{\omega}_m(t) \]
\[ \dot{\hat{\omega}}(t) = w_1 \]
\[ w_1 = -\gamma k^{1/2} |\hat{\omega}_m(t) - w_o|^{2/3} \text{sign}(\hat{\omega}_m(t) - w_o) + z_2 \]
\[ \dot{z}_2 = -\gamma k \text{sign}(z_2 - w_1) \]

where \( \hat{\omega}_m(t) \) and \( \hat{\omega} \) are the estimated disturbances and speed derivation, \( \gamma_0, \gamma_1 \) and \( \gamma_2 \) are the co-efficients of the FTSMO, \( w_o \), and \( w_1 \) are different variables in the disturbances estimation process.

Remark 2. It is noted from the FTSMO that the proper selection of \( \gamma_0, \gamma_1, \gamma_2 \) and are very important in practice. The tracking performance indexes of the system would be affected by the unmodeled dynamics, measuring noise, and limited control energy of the system. One reasonable switching gain can shorten the system convergence time effectively, while higher gain values of the FTSMO would result in the overshoot for the speed response. Therefore, it is required that the careful estimation on the total disturbances should be made for the compensation process.

Furthermore, it should be noted that the high gain values
of $\sigma_1$ and $\sigma_2$ can improve the convergence of the close loop control system, which can induce the high chattering in the control input at the same time. Furthermore, $\sigma_3$ should be chosen properly because it would appear on the rejection ability of the load disturbances and chattering of the system. Hence, it is drawn that the parameters of the FTSMO based on FTSMC would influence the robustness capability of the system.

### C. Stability Analysis of the FTSMO

In this work, it is supposed that the FTSMO has differential inputs, and $\omega$ and $\dot{\omega}$ have the Lipschitz constant $N>0$ for their derivatives. From (4) and (23), the error variables of the observer can be described as $\ell_o = \dot{\omega} - \omega$, $\ell_1 = \hat{\omega}_o(t) - y_o(t)$, and $\ell_2 = \hat{\omega}_o(t) - y_o(t)$. Therefore, the observer errors can be written as

\[
\ell_o = -\frac{B}{J} (\ell_o) - \gamma \frac{k^{1/3}}{\ell_o} |\ell_o|^{2/3} \text{sign}(\ell_o) + \ell_1
\]

\[
\ell_1 = -\gamma k^{1/2} |\ell_1|^{1/2} \text{sign}(\ell_1 - \ell_o) + \ell_2
\]

\[
\ell_2 = -\gamma k \text{sign}(\ell_2 - \ell_1) + [\gamma, \gamma]
\]

The Lyapunov function has been used to check the stability of the FTSMO, and hence the satisfied conditions are described as

\[
v_1 = \frac{1}{2} \ell_o^2, \quad v_1 = \ell_o, \dot{\ell}_o \leq 0
\]

\[
v_2 = \frac{1}{2} \ell_1^2, \quad v_2 = \ell_1, \dot{\ell}_1 \leq 0
\]

\[
v_3 = \frac{1}{2} \ell_2^2, \quad v_3 = \ell_2, \dot{\ell}_2 \leq 0
\]

The converging principle of the FTSMO can be expressed as $\ell_o \rightarrow 0$, $\hat{\omega}_o(t) \rightarrow y_o(t)$, and $z = \hat{\omega}_o(t) - y_o(t)$. By taking the derivative of $v_1$, which is the first Lyapunov function of (25), the derivative of $v_1$ can be described as

\[
\dot{v}_1 = v_1 \dot{\ell}_o = v_1 \left[ -\frac{B}{J} (\ell_o) - \gamma \frac{k^{1/3}}{\ell_o} |\ell_o|^{2/3} \text{sign}(\ell_o) + \ell_1 \right]
\]

\[
= \left[ -\frac{B}{J} (\ell_o) - \gamma \frac{k^{1/3}}{\ell_o} |\ell_o|^{2/3} + \ell_o, \ell_1 \right]
\]

It is seen that $v_1 \leq 0$ would satisfy the condition of Lyapunov function, when the proper selection of the $\gamma_o$ and $k$ has been achieved. Simultaneously, the $\dot{\ell}_o$ will converge to $\ell_1$ and the two errors of (24) can be combined together, as illustrated by

\[
\ell_1 - \dot{\ell}_o = \frac{B}{J} (\ell_o) + \gamma \frac{k^{1/3}}{\ell_o} |\ell_o|^{2/3} \text{sign}(\ell_o)
\]

\[
\ell_2 - \dot{\ell}_1 = \gamma k^{1/2} |\ell_1|^{1/2} \text{sign}(\ell_1 - \ell_o)
\]

\[

By taking the derivative of $\ell_2$, the upper bound of the derivative $\ell_2$ can be rewritten as $\ell_2 \leq \frac{B}{J} |\ell_o|^{1/3} \text{sign}(\ell_o)$.

Similarly, $v_2 = \ell_1, \dot{\ell}_1 \leq 0$ and $v_3 = \ell_2, \dot{\ell}_2 \leq 0$ would be satisfied by selecting the proper gains of $\gamma_o, \gamma_1, \gamma_2$ and $k$. In order to reach the requirement of (27), it should satisfy with the following condition by

\[
\ell_o k^{1/3} \geq \frac{B^2}{J^3} |\ell_o|^{1/3} + \frac{1}{\ell_o^{2/3}}
\]

\[
\ell_2, \ell_1, k \geq N
\]

Based on what mentioned above, it is concluded that the design procedure of the FTSMO and stability check have been successfully proved, and optimal parameters gain values are listed in Table II. The speed loop of the PMSM drive with total disturbance estimation based on the FTSMO is shown in Fig. 3.

**FIGURE 3.** Block diagram of the proposed control method for the speed loop.

The dynamic speed response of the PMSM can be improved by using the FTSMO. Furthermore, it is very important to make correct selection on $\ell$, otherwise, some chattering would occur in the drive system. The flow diagram of speed loop based on the FTSMO with FTSMC is depicted in Fig. 4.
D. Stability Check of the Proposed Sliding Trajectory

In this work, one second order system is considered by

\[ \dot{x}(t) = f(x, t) + bu(t) + y_d(t) \]  

(29)

where \( u(t) \) represents the control input, \( y_d(t) \) the disturbance, and b the known gain. Hence, \( f = -25\dot{x} \), \( b=133 \), \( y_d(t) = 10\sin(\pi t) \), and the signal \( x_0 = \sin t \) are chosen as the position reference with the initial state value [-1.5, 1.5].

The conventional sliding surface is chosen as

\[ s = x_2 + cx_1 \]  

(30)

where \( x_2 = \dot{x}_1 \), \( c \) is the co-efficient of the \( x_1 \), which must satisfy the Hurwitz condition \( c > 0 \), and \( x_1 \) and \( x_2 \) are the tracking error and derivative of the CSMC, respectively. The FTSMC surface is decided by

\[ s = x_2 + \lambda_1 |x_1|^\alpha + \lambda_2 |x_1|^\beta \]  

(30)

where \( \lambda_1 \) and \( \lambda_2 \) are the positive constants. In the Numerical Analysis Section, the parameter values of the sliding mode surface of CSMC and FTSMC for fair comparison are given in Table I, which can be obtained through the Trial and Error method.

| Parameters                               | Values and Units |
|------------------------------------------|------------------|
| The sliding mode surface and reaching law gains for CSMC | \( C = 15 \) |
| The sliding mode surface and reaching law gains for FTSMC | \( \lambda_1 = 60 \) and \( \lambda_2 = 15 \) |

Moreover, the selection in the surface gains of the sliding mode control are very important to this work. The gain values of the \( c \) and \( \lambda_2 \) for the CSMC and FTSMC are properly tuned through the Trial and Error method, which is finally tuned as 15, respectively. Thereof, if the gain values of \( c \) or \( \lambda_2 \) are increased than 15, the overshoot would come out in the response of the position and speed signals, and vice versa. Therefore, the gain of 15 is optimal value for the \( c \) or \( \lambda_2 \), respectively.

The stability checks on two sliding mode surfaces, CSMC and FTSMC, has been fully made by simulation, as illustrated in Figs. 5 and 6 respectively. Both Fig. 5 (a) and Fig. 5 (b) are considered to check the convergence rate and transient responses of the CSMC and FTSMC sliding surfaces.

FIGURE 5. The responses of sliding surface for CSMC and FTSMC. (a) Derivative of the error. (b) Error under CSMC and FTSMC. (c) System phase trajectory.

Moreover, Fig. 5 (a) shows the derivative of error responses under the CSMC and FTSMC. It is seen from this figure that the CSMC surface has greater steady state fluctuation, higher ripple, and bigger chattering than the FTSMC. Furthermore, it can be observed from Fig. 5(b) that the FTSMC response of sliding state is faster and smoother.
than that of CSMC. Fig. 6 shows the position and angular speed tracking responses under the CSMC and FTSMC. It is seen clearly from this figure that the FTSMC has stronger tracking capability than that of the CSMC, and the FTSMC has very small tracking error in the position, while the CSMC has 10% error in the position.

V. EXPERIMENTAL VALIDATION

In order to investigate the advantages of the FTSMO based on the FTSMC method, comprehensive experiments have been made in this section, which are fully compared with those of the conventional PI, CSMC and FTSMC, respectively. Main parameters for the control methods are given out in Table II. The conventional sliding mode manifold for the CSMC has been chosen as

$$\dot{\vartheta} = \dot{E} + \alpha E$$

(32)

Hence, the CSMC is designed as

$$i_q = F_i^*(\dot{\omega}^* + \alpha E + \int (\lambda_1 \vartheta + \lambda_2 |\vartheta|^b \text{sign}(\vartheta)) \, dt)$$

(33)

where $\alpha$, $\lambda_1$, and $\lambda_2$ are the control and switching gains of the CSMC, which are 4000, 0.001, and 20000, respectively.

| TABLE II NOMINAL PARAMETERS OF THE PMSM |
|-----------------------------------------|
| Symbol | Parameters | Value and Unit |
|--------|------------|----------------|
| $n_p$  | Pole pairs | 3              |
| $p$    | Rated power| 3.0 kW         |
| $R_s$  | Stator resistance | 0.8 Ω |
| $\psi_f$ | Flux linkage | 0.35 Wb |
| $L_s$  | Mutual inductance | 0.005 H |
| $J$    | Inertia    | $3.78 \times 10^{-4} \text{kg} \cdot \text{m}^2$ |
| $B$    | Viscous damping | $1.74 \times 10^{-3} \text{N} \cdot \text{m} \cdot \text{s} / \text{rad}$ |

In this work, one prototype for the PMSM drive system is built up, as illustrated in Fig. 7. An incremental encoder and a hall current sensor are used to measure the rotating speed and the primary current, respectively. The load is managed by another PMSM coupled to the shaft of the originally controlled motor.

![FIGURE 7. The test platform.](image)

Moreover, the whole PMSM drive system based on the proposed method is shown in Fig. 8. Comprehensive experiments are made and fully compared with conventional PI, CSMC and FTSMC in different working conditions, including no-load, loaded and speed reverse conditions, respectively.

| TABLE III SPECIFICATIONS OF THE CONTROLLER |
|-------------------------------------------|
| Parameters | Values and Units |
| PI gains for current controller | 1 and 350 |
| Sampling frequency | 10 kHz |
| The gains of CSMC | $\mu_1 = 4000$, $\lambda_1 = 0.001$, and $\lambda_2 = 200000$ |
| The gains of FTSMC | $\mu_1 = 4000$, $\mu_2 = 4000$, $\lambda_1 = 0.001$, and $\lambda_2 = 100000$ |
| The gains of FTSMC+FTSMO | $\mu_1 = 4000$, $\mu_2 = 4000$, $k_1 = 0.001$, $k_2 = 80000$, $k_3 = 120$, $\gamma_0 = 3$, $\gamma_1 = 1.5$, and $\gamma_2 = 1.2$ |

The full algorithm includes the SVPWM as implemented by the DSP-coding on the DSP (TMS32028335) controller. The control parameters for current and speed controllers of PI, CSMC, FTSMC, and FTSMO based FTSMC are designed, as listed in Table III.

Furthermore, the tuning of all variables for the CSMC, FTSMC and proposed FTSMO based FTSMC are dependent closely on the tuning process similar to the tuning of the PI controller. In this paper, these variables are obtained by adopting the Trial-and-Error Method so as to get better convergence, quicker tracking and stronger robustness against the load disturbances. The comparative tuned parameters have been already available in Table II.

Case-1: The Startup Transient and Steady State Performance under No-load Condition

In this case, the system performance is tested under no load. Simultaneously, the speed curves of the system under PI, CSMC, FTSMC, and FTSMO based FTSMC are shown in Fig. 9 (a) and (b), and Fig. 10 (a) and (b) with reference speed of 1000 rpm and 1600 rpm, respectively.
It is observed from these pictures that the actual speed response under the FTSMO based FTSMC can follow the desired speed very well in terms of the quickest response, which means the speed response under proposed method can reach the steady-state in much shorter time than PI, CSMC and FTSMC, separately. The settling times of speed response under PI, CSMC, FTSMC, and FTSMO based FTSMC with the reference speeds of 1000 rpm and 1600 rpm are (415 ms, 347 ms), (301 ms, 246 ms), (134 ms, 177 ms), and (75 ms, 102 ms), respectively. Because the SMC controller has the property of fast convergence, the CSMC, FTSMC, and FTSMO based FTSMC are observed faster in the startup transient than that of PI controller, respectively.

As seen from Figs. 9 and 10, it is known that the PI controller has an overshoot during the start-up process under no-load condition, which seldom occurs in the CSMC, FTSMC, and FTSMO based FTSMC due to the SMC excellent control ability.

| Control method | Settling time (ms) | Steady-state error (± rpm) |
|----------------|--------------------|---------------------------|
| PI             | 415                | 30                        |
| CSMC           | 301                | 20                        |
| FTSMC          | 134                | 18                        |
| FTSMC+FTSMO    | 75                 | 15                        |

Specifically, it is observed from Fig. 9 (a) and 10 (a) that the FTSMO based FTSMC has smaller speed fluctuations in the steady state condition than that of PI, CSMC, and FTSMC, respectively. Moreover, from Fig. 9 (b) and 10 (b), it is known that the q-axis current ripple and chattering under the FTSMO based FTSMC are smaller than PI, CSMC, and FTSMC during the start-up and steady states, separately.

Furthermore, the quantitative analysis has been added to make the paper very comprehensive for the readers under different indicators, which are listed in Tables III and IV, individually. The startup and steady-state performance...
indexes based on PI, CSMC, FTSMC and FTSMC+FTSMO are listed under the reference speed of 1000 rpm and 1600 rpm, respectively, as depicted in Table IV.

It can be noted from Table VI that the FTSMO based FTSMC is 82%, 75% and 44% quicker than those of PI, CSMC and FTSMC, respectively.

**Case-2: Anti-disturbance Performance of the Drive System**

In this study, the FTSMO based FTSMC method is verified under 1000 and 1600 rpm with 5 and 10 Nm load, as shown in Figs.11 and 12, respectively. In addition, it is observed from the same picture that the speed drop and settling time under PI, CSMC, FTSMC, and FTSMO based FTSMC with dynamic load of 5 Nm are (210rpm, 410ms), (192rpm, 190ms), (170rpm, 95ms) and (138 rpm, 43 ms), respectively. Furthermore, the q-axis current response is shown in Fig.11 (b) for the aforementioned control methods under loaded condition, as observed from the same picture that the FTSMO based FTSMC has smaller current ripple and chattering than PI, CSMC, and FTSMC, separately.

Again, the sudden 10 Nm load is added with the reference speed of 1600 rpm to validate the anti-disturbances property of the proposed method and fully compared with conventional PI, CSMC and FTSMC, respectively. It can be seen from Fig. 12 (b) that the FTSMO based FTSMC has quicker speed response than PI, CSMC and FTSMC, individually. The settling time is calculated as 450, 465, 253, 182 ms, and speed drop is observed as is 440, 530, 430, and 340 rpm under PI, CSMC, FTSMC, and FTSMO based FTSMC, individually. Furthermore, the q-axis current response is shown in Fig.12 (b) for the aforementioned control methods under the load of 10 Nm, where the FTSMO based FTSMC has smaller current ripple and chattering than PI, CSMC, and FTSMC, separately. It can be concluded that the proposed FTSMO based FTSMC has strong robust ability when the sliding state is near or far from the designed sliding mode surface.

Moreover, Table V has demonstrated much stronger robustness of the FTSMO based FTSMC against load disturbances than those of PI, CSMC and FTSMC under 5 Nm and 10 Nm, separately. Therefore, it is seen that Table IV has confirmed that the proposed (FTSMC+FTSMO) method has superior performance against load disturbances and quicker transient response over PI, CSMC and FTSMC, respectively.
Case-3: The Dynamics of the System under Speed Reversal Condition

In this case, the speed reversal dynamic performance of PMSM drive system has been checked and compared under PI, CSMC, FTSMC, and FTSMO based FTSMC. The speed reversal process has been taken from 1000 to -1000 rpm and then -1000 to 1000 rpm, as shown in Fig. 13. It can be observed from the same picture that the speed response has an overshoot under PI controller, and needs more time to settle on the steady state. At the same time, it is also seen from Fig.13 (a) that the speed under the FTSMO based FTSMC has faster response, stronger robust tracking ability, and smaller steady state error during the reversal operation than the PI, CSMC, and FTSMC, separately. As noted from Fig.13 (b) that current ripple inherent chattering phenomenon are smaller than the conventional PI, CSMC

TABLE V

| Control Method | Speed drop (rpm) and reaching time(ms) with 5 Nm load | Speed drop (rpm) and reaching time time(ms) with 10 Nm load |
|----------------|------------------------------------------------------|------------------------------------------------------|
| PI             | 210 410                                              | 440 450                                              |
| CSMC           | 192 190                                              | 530 465                                              |
| FTSMC          | 170 95                                               | 430 253                                              |
| FTSMC+FTSMO    | 138 43                                               | 340 182                                              |

VI. CONCLUSIONS

In this paper, the FTSMO based FTSMC has been implemented for the speed regulation of the PMSM drive system with load disturbance. Main contributions of this paper can be summarized as follows:

(1) One new FTSMC is introduced in this paper, which is designed and implemented to ensure the fast convergence in the finite time and alleviate the chattering effectively.

(2) One disturbance estimation strategy based on the FTSMO with the feed-forward compensation technique is proposed to eliminate the chattering phenomena effectively, which can enhance the whole drive system performance against the load disturbances.

(3) The Lyapunov theorem is employed to analyze the PMSM drive performance and stability of the FTSMC and FTSMO with FTSMC, respectively.

(4) The PMSM drive performance under FTSMO based FTSMC method has been fully compared with those of the conventional PI, CSMC and FTSMC, separately.

Both simulation and experimental results have fully demonstrated that the FTSMO based FTSMC method can get quicker dynamic response, stronger robustness under load and speed change, lower q-axis chattering in comparison to those of conventional PI, CSMC and FTSMC, individually.

Due to the excellent drive performance, the FTSMO based FTSMC in this work can be also employed for the PMSM current loops next step.

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