Novel Fast Terminal Reaching Law Based Composite Speed Control of PMSM Drive System

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This work was supported by the Deputyship for Research and Innovation, Ministry of Education, Saudi Arabia, under Project 1289.

ABSTRACT In this paper, a novel fast terminal sliding mode reaching law (FTSMRL) based sliding mode control (SMC) is proposed to improve the speed dynamic performance of the permanent magnet synchronous motor (PMSM) and drive. The proposed FTSMRL contains two power terms, which can take the leading role in the SMC process, when sliding state is near or far from the selected sliding trajectory. The proposed SMC based FTSMRL can not only suppress the chattering phenomenon effectively, but also improve the reaching velocity of the sliding state variable. In order to further improve the system disturbance rejection ability of the control system, an extended state observer (ESO) is also developed in this work. The proposed observer estimates the disturbances and inputs the signal to a feed-forward compensation controller considering the chattering phenomenon caused by the high switching gain. The proposed method has been fully confirmed by mathematical stability check, numerical analysis and experiments, separately.

INDEX TERMS Sliding mode control (SMC), permanent magnet synchronous motor (PMSM), extended state observer (ESO), fast terminal sliding mode reaching law (FTSMRL), Lyapunov stability.

I. INTRODUCTION

Due to simple structure, high power density and high efficiency, the permanent magnet synchronous motor (PMSM) is widely used in many industrial applications, such as high precision computer numerical control (CNC) machines tool, aerospace, robotics, and other engineering fields [1]–[4]. The drive system design is very important to achieve the excellent performance for the current scenario of the drive applications [5]. Many linear control methods are implemented in the speed of the drive systems due to simplicity of their design and implementation, one of which is the proportional integral control. However, the control system of PMSM can be easily affected by the parameter variations, load disturbance and nonlinear dynamics during operation [6]–[8]. Though the internal disturbances would be minimized through the feedback control system and the outside disturbances is unavoidable factor, which induces the variations in the speed signal of the PMSM. The traditional proportional integral (PI) method can be affected by the external disturbances of the system, which deteriorates the speed control performances in terms of speed fluctuations. These fluctuations could not be ignored in high control performance, like electric vehicles (EVs) and CNC machines. In order to solve the problem of the traditional PI control methods, various nonlinear control methods have been developed till now, including fuzzy control method [9], predictive control method [10], neural network control method [11], disturbance rejection control.
methods [12–14], sliding mode control (SMC) methods, and so on. Among those, the SMC has received significant attention because it is inherently robust to the parameter uncertainties, non-linear external disturbances [15–20]. Up to now, for the strong robustness and fast response, the SMC has been successfully implemented on the motor drive systems [16], [21]–[23]. The SMC with fuzzy or neural network control methods can improve the speed response for the PMSM drive systems.

However, the SMC method is not flawless control method, which can be severely affected by the inherited traits, chattering phenomenon. The time delay in the high switching of the control law leads to the high frequency switching chattering. Hence, different methods are implemented to alleviate the chattering of the SMC, such as higher order SMC [24], non-singular terminal SMC [25], fast terminal SMC [26], fractional-orders [27], and different control laws based on SMC [28]. Normally, the switching gains of the control law in the SMC should be set as highly sufficient to minimize the system disturbances for the stable and robust performance. Although it is not easy to determine the higher bound limit of the disturbances, but the proper selection of control law gains can minimize the inherent problem of the chattering in the SMC system.

Thereof, the control law is directly proportional to the reaching velocity of the sliding mode state and the reaching velocity is dependent on the gain values of the control law. Hence, the reaching velocity can go up by increasing the switching gains of the control law and vice versa, so that the chattering is directly proportional to the gain values of the control law. In [29], the saturation function is used instead of sigmoid function to reduce the chattering. In [30], the exponential reaching law (ERL) is adopted to improve the reaching velocity of the sliding state and reduce the chattering from the SMC method, but the ERL has drawback of convergence, when tracking error is away from the sliding trajectory. Meanwhile, in [31], the terminal sliding mode reaching law (TSMRL) is implemented to further improve the reaching velocity and alleviate the chattering phenomenon from the SMC system effectively. In the TSMRL, a single power term is used rather than exponential term of the ERL. But, the TSMRL can only improve the reaching velocity of the sliding state, when sliding state is away from the sliding trajectory. When the sliding state is near to sliding trajectory, the TSMRL would become slowly. Therefore, in this paper, a novel fast TSMRL (FTSMRL) is proposed to enhance the reaching velocity of the sliding state when the whole system sliding state is near or far from the sliding trajectory.

The proposed FTSMLR in this paper can effectively reduce the chattering phenomenon of the control system. It has two terms used as power terms rather than exponential term and switching term of the ERL and TSMRL, respectively. Moreover, the disturbances rejection ability of the SMC can be improved by the control gains of the reaching law. Therefore, in order to further improve the robustness against the load disturbances of the speed controller, the composite controller can be developed, and the ESO is adopted to observe the system disturbances. Subsequently, the estimated value of the disturbances can be subtracted from the output of the speed loop known as composite speed controller, which can improve anti-disturbances rejection capacity of the speed controller for the PMSM drive system.

II. DESIGN AND ANALYSIS OF THE FTSMRL

A. CONVENTIONAL REACHING LAWS

The SMC is a variable structured control system, which consists of sliding trajectory and control law. The control law is responsible to ensure that the state trajectory can reach the designed sliding trajectory and converge along the sliding trajectory. The control law can ensure the velocity of the sliding state in the SMC systems. Meanwhile, the sliding state can get faster by choosing suitable control law, when the tracking error is near or far from the developed sliding trajectory. The reaching velocity of the sliding state would decrease to the zero to ensure that the sliding state could stay at sliding trajectory. It is not easy that the sliding state would stay with zero error on the sliding trajectory, but the sliding state would traverse on both sides of sliding trajectory.

Fig.1 demonstrates the reaching mechanism of the sliding state towards the sliding trajectory.

![Figure 1. The phase trajectory motion in the SMC process.](image)

The conventional reaching law (CRL) is only based on the constant rate term, which can be expressed as [29]

\[
\dot{s} = -k \text{sign}(s) \quad k > 0
\]

where \(k\) represents a constant rate and the CRL is simple in design. If the value of \(\varepsilon\) is too small, then the reaching time of sliding state would be larger. On other hand, if the value of \(\varepsilon\) is large, it would cause the severe chattering in the SMC systems.

Afterwards, ERL is proposed in [30], which can be illustrated as

\[
\dot{s} = -k_1 \text{sign}(s) - k_2 s \quad k_1 > 0, \ k_2 > 0
\]

where \(\dot{s} = -k_2 s\) is an exponential term. Obviously, by adding the exponential rate term \(-k_2 s\), which can force the sliding state to reach the sliding trajectory, so that the ERL is faster than the CRL. The ERL can ensure the quick convergence, when the sliding state is near to zero, then \(\dot{s} = -k_1 \text{sign}(s)\).
would play its role in the whole SMC process. The ERL is faster in reaching time and smaller chattering than those of the CRL because of the exponential term, but the ERL is still slow and has the chattering, when the sliding state is far from the sliding trajectory. Furthermore, TSMRL is designed by adding the power rate term rather than the exponential term of ERL [30], so that the TSMRL [31] can be written as

$$\dot{s} = -k_1 \text{sign}(s) - k_2 |s|^{\alpha_2}$$  \hspace{0.5cm} (3)

where $0 < \alpha_2 < 1$, the TSMRL [31] can guarantee faster convergence than that of the CRL [29] and ERL [30], respectively. The TSMRL [31] can increase the reaching speed of the sliding state, when the sliding state is far from the sliding trajectory. The TSMRL [31] would become slow when the sliding state is close to the sliding trajectory.

Therefore, the FTSMRL is designed to further enhance the dynamic quality and reaching time of the SMC controller, when the sliding state is near or far from the sliding trajectory, and can eliminate the chattering phenomenon successfully.

B. DESIGN OF THE FTSMRL

The FTSMRL is proposed in this paper, which has faster convergence, stronger robustness against external disturbances, better tracking, and smaller chattering than those of the conventional CRL [29], ERL [30], and existing TSMRL [31]. The FTSMRL can be described as

$$\dot{s} = -k_1 |s|^{\alpha_1} \text{sign}(s) - k_2 |s|^{\alpha_2} \text{sign}(s)$$  \hspace{0.5cm} (4)

where $k_1 > 0$, $k_2 > 0$, $0 < \alpha_1 < 1$, and $\alpha_2 > 1$. The $\dot{s} = -k_2 |s|^{\alpha_2} \text{sign}(s)$ term of FTSMRL plays leading role in the SMC, when tracking error is away from the sliding trajectory, ($|s| > 1$). When the tracking error gets near to the sliding trajectory, the term of FTSMRL, $\dot{s} = -k_1 |s|^{\alpha_1} \text{sign}(s)$, would dominate gradually. When $s$ is approaching to zero, $\dot{s}$ would become zero finally, in which the sliding state would reach the sliding trajectory with zero error. In this condition, the SMC can realize the smooth operation, and greatly weaken the chattering phenomenon.

C. NUMERICAL ANALYSIS OF THE FTSMRL

The performances of the ERL [30], TSMRL [31], and FTSMRL can be fully compared by the numerical analysis method. A motor model is firstly established by

$$\partial \ddot{\phi}(t) = \mu(t) + w(t)$$  \hspace{0.5cm} (5)

where $\partial$ is inertia, $\phi$ represents position, $\mu(t)$ is the input control signal, and $w(t)$ the disturbances of the system. The $\phi(t)$ is considered as a state variable of the motor, then the system with respect to $\phi(t)$ can be illustrated as

$$\ddot{\phi}(t) = f(\dot{\phi}, t) + q\mu(t) + w(t)$$  \hspace{0.5cm} (6)

where $f(t) = 25\dot{\phi}(t)$, $q = 135$, and $w(t)$ is selected as $10 \sin \pi t$. The tracking error of the position $\phi(t)$ and its derivative can be written as

$$\begin{align*}
e &= \phi_i - \phi \\
\dot{e} &= \dot{\phi}_i - \dot{\phi}
\end{align*}$$  \hspace{0.5cm} (7)

The $s$-function of the MATLAB is used to simulate the motor model for the ERL [30], TSMRL [31], and FTSMRL, respectively. The parameters are set as $g = 15$, $e = 20$, $k = 40$, $k_1 = 20$, $k_2 = 40$, $\alpha = 10$, $\alpha_1 = 0.9$ $\alpha_2 = 1.5$, $q = 135$, $f(\phi, t) = -25\dot{\phi}w(t) = 10\sin(\pi t)$, and $\phi_i = \sin(t)$. The initial state is set as $[e, \dot{e}] = [-2, -2]$, and the controlled object as $e(t)$. Fig. 2 shows the numerical analysis performance among the ERL [30], TSMRL [31], and FTSMRL, and full comparison is made with each other. Fig. 2(a) exhibits that the FTSMRL has stronger tracking ability for differential error than those of ERL [30] and TSMRL [31], separately.
Furthermore, Fig. 2(a) and Fig. 2(b) show that the FTSMRL has quicker tracking response and smaller chattering than those of the ERL [30] and TSMRL [31], respectively.

Therefore, it can be concluded from Fig.2 that the FTSMRL has faster reaching ability, smaller chattering and better tracking ability than those of the existing ERL [30] and TSMRL [31], respectively.

III. DESIGN OF SLIDING MODE CONTROL OF THE PMSM BASED ON THE FTSMRL

This section will present the mathematical model of the PMSM and the sliding mode speed control of the PMSM based on the FTSMRL.

A. DYNAMIC MODEL OF THE PMSM

The mathematical model of the PMSM for the speed and dq-axis currents under synchronous reference frame can be written as

\[
\begin{align*}
J \frac{d\omega}{dt} &= X_i i_q - B \omega - n_p T_L \\
L_s \frac{di_d}{dt} &= -R i_d + L_d n_p i_q + u_d \\
L_s \frac{di_q}{dt} &= -R i_q + L_d n_p i_d - n_p \omega \psi_f + u_q
\end{align*}
\]

where \( X_i = 3/2 n_p^2 \psi_f, n_p \) is the number of pole pairs, \( \psi_f \) the permanent magnet flux linkage, \( J, T_L \) and \( B \) are the moment of inertia, load torque and damping coefficient, \( u_d, u_q, i_d \) and \( i_q \) are the d- and q- axis stator voltages and currents, and \( R_s \) and \( L_s \) the stator resistance and inductance, respectively.

B. SLIDING MODE SPEED CONTROL OF THE PMSM BASED ON THE FTSMRL

The sliding mode speed control of the PMSM is designed based on the FTSMRL. The main equation for speed control loop with disturbances can be illustrated as

\[
\dot{\omega} = \frac{X_i}{J} i_q + D(t)
\]

where \( D(t) \) is the total disturbances, as illustrated by

\[
D(t) = -\frac{n_p T_L}{J} - \frac{B}{J} \omega
\]

The speed of the PMSM is selected as main variable for the design of SMC with FTSMRL based on the speed controller of the PMSM, and the tracking error of the speed is expressed as

\[
\varepsilon = \omega^* - \omega
\]

where \( \omega^* \) and \( \omega \) are the reference and actual speeds, respectively. Taking derivatives of (16) and substituting into (14), it will get

\[
\dot{\varepsilon} = \dot{\omega}^* - \frac{X_i}{J} i_q - D(t)
\]

Generally, Sliding mode control laws consist of equivalent control and reaching law, which are described in Eqs. (8) and (4), separately.

The final output of the speed control \( i_q^* \) based on FTSMRL can be obtained through the state variable (16), which must reach to zero \( (s = 0) \). The current \( i_q^* \) can be derived by (4), (8) and (16), which can be written as

\[
i_q^* = \frac{J}{X_i} (\Omega_{eq} + \Omega_b - D(t))
\]

\[
\Omega_{eq} = \dot{\omega}_r + g \varepsilon
\]

\[
\Omega_b = \int_0^t -k_1 |s|^{\alpha_1} \text{sign}(s) - k_2 |s|^{\alpha_2} \text{sign}(s) dt
\]

The simplified block diagram of the final SMC based speed control with new FTSMRL is shown in Fig. 3.

![Fig. 3. The SMC speed controller based on the FTSMRL method.](image)

C. STABILITY PROOF

The stability of the system can be verified by using the Lyapunov function, which can be illustrated as

\[
V = 1/2s^2
\]

Assumption 1: Suppose \( \dot{D}(t) \) is bounded, and there exists \( \xi_{D(t)} > 0 \) such that \( |\dot{D}(t)| \leq \xi_{D(t)} \), where \( D(t) \) is the total disturbances of the system. According to the assumption (1), the (4) and (8) in the Lyapunov function can be written as

\[
\dot{V} = \dot{s}s = -k_1(s)^{\alpha_1+1} - k_2 |s|^{\alpha_2+1} - \dot{D}(t)s
\]

\[
\leq -k_1(s)^{\alpha_1+1} - k_2 |s|^{\alpha_2+1} - |\dot{D}(t)| |s|
\]

\[
\leq -k_1(s)^{\alpha_1+1} - \left[ k_2 + \frac{|\dot{D}(t)|}{|s|^\alpha_1} \right] |s|^{\alpha_2+1}
\]

\[
= -2 \frac{\alpha_1 + 1}{\alpha_2 + 1} \tau_1 V - 2 \frac{\alpha_1 + 1}{\alpha_2 + 1} \tau_2 V
\]

where \( \tau_1 \) and \( \tau_2 \) are the positive constants. According to the stability analysis by using Lyapunov function on (22) is satisfied \( k_2 > \xi_{\dot{D}(t)} \). Then, the speed error of the PMSM will reach to the sliding mode surface \( s = 0 \) within the finite time to converge the zero in an asymptotic manner. Moreover, the reaching time \( t_i \) can be obtained by integrating the (4), from \( s_i = s_{i0} \) to \( s_i = 0 \) yields

\[
t_i = \frac{1}{1 - \alpha_1} s_{i0} (1 - \alpha_1) + \frac{1}{1 - \alpha_2} s_{i0} (1 - \alpha_2)
\]

\[
i = 1 \text{ to } m
\]
IV. ESO DESIGN FOR THE ANTI-DISTURBANCES OF THE SPEED CONTROLLER

Generally, a mathematical model of the system with first-order can be described as

\[
\begin{align*}
    z_1(t) &= \Pi(z_1) + \Omega u(t) \\
    y(t) &= z_1(t)
\end{align*}
\]  

(24)

where \( \Pi(z_1) \) is the perturbation, \( \Omega \) a fixed gain value, and \( u(t) \) the control input of the first-order based on (28). The expansion variable can be described by selection of the \( z_2(t) \), which is defined as \( \dot{z}_2(t) = Q(t) \). Therefore, the expanded version of (24) is written as

\[
\begin{align*}
    \dot{z}_1(t) &= z_2(t) + \Omega u(t) \\
    \dot{z}_2(t) &= Q(t) \\
    y(t) &= z_1(t)
\end{align*}
\]  

(25)

Under the assumption that \( u(t) = \dot{i}_q^* \) and \( z_1(t) = \omega \) by combining (11), (24), and (25), the ESO can be designed. Afterwards, \( \dot{v}_2(t) \) of the ESO with compensation for speed loop can be illustrated as

\[
\begin{align*}
    \varepsilon_1(t) &= v_1(t) - \omega \\
    \vdot{v}_1(t) &= v_2(t) + m_i \eta_1 \varepsilon_1(t) \\
    \vdot{v}_2(t) &= -\eta_2 \varepsilon_1(t)
\end{align*}
\]  

(26)

where \( \eta_1 \) and \( \eta_2 \) are two positive constant coefficients. \( v_1(t) \) and \( v_2(t) \) are the feedback speed signal and disturbance responses of the PMSM, separately. Then, the composite speed controller is developed, which would work on the feed forward compensation technique. The final anti-disturbance FTSMRL with the ESO scheme for speed regulation is shown in Fig.4.

V. EXPERIMENTAL AND ANALYSIS

One prototype of the PMSM drive system is developed for the validation of the proposed method, as shown in Fig. 5. An incremental encoder and two Hall current sensors are assembled to calculate the rotating speed and the phase currents, separately. The overall structure of the proposed control method with whole drive system of the PMSM is given out in Fig. 6, and the different control algorithms have been executed in a digital signal processor (DSP) controller, TMS32028335. The PMSM parameters are summarized in Table 1.

Furthermore, detailed control parameters of PI, TSMRL, FTSMRL and FTSMRL+ESO are listed in Table 2, which have been optimized by Trial-and-Error method. It can be seen from Table 2 that \( k_1 \) and \( k_2 \) variables of the ERL, TSMRL and FTSMRL have the same gain value for the fair comparison, respectively. The all gains values of the ERL, TSMRL and FTSMRL used in above equations are optimized by the

FIGURE 4. The FTSMRL based speed controller with ESO scheme for the speed regulation.

FIGURE 5. The experimental platform.

FIGURE 6. Diagram of the proposed control algorithm.

TABLE 1. The PMSM parameters.

| Symbol | Name                  | Value and unit |
|--------|-----------------------|----------------|
| \( p \) | Rated power           | 3.0 kW         |
| \( R_s \) | Stator resistance     | 0.8 Ohm        |
| \( \psi_f \) | Rotor flux linkage    | 0.35Wb         |
| \( L_r \) | dq-axis inductances   | 0.005H         |
| \( J \) | Inertia               | 3.78\times10^{-4} kg m^2 |

TABLE 2. Controller specifications on five control methods.

| Name                                      | Value and unit |
|-------------------------------------------|----------------|
| The optimized speed control gains of the PI controller | 150 and 60     |
| The optimized current gains of the PI controller | 60 and 30      |
| The optimized current control gains under ERL [30], TSMRL [31], and FTSMRL | 0.6 and 400    |
| The gains of ERL [30] \( g=1000, k_1=100000, \) and \( k_2=100000 \) | \( k_1=100000, \) and \( k_2=9000 \) |
| The gains of TSMRL [31] \( g=1000, k_1=100000, \) and \( k_2=100000 \) | \( k_1=100000, \) and \( k_2=9000, \alpha=1.5, \) and \( \alpha=0.9 \) |
| The gains of FTSMRL \( g=1000, k_1=100000, \) and \( k_2=100000 \) | \( g=1000, k_1=100000, \) and \( k_2=100000, \alpha=1.5, \) and \( \alpha=0.9 \) |
| The gains of FTSMRL+ESO \( g=1000, k_1=100000, \) and \( k_2=100000, \alpha=1.5, \) and \( \alpha=0.9, \) and \( \Omega=120. \) |
A. K. Junejo et al.: Novel Fast Terminal Reaching Law Based Composite Speed Control of PMSM Drive System

FIGURE 7. The optimal selection of PI gains for fair comparison with proposed SMC method through Trial-and-Error method under fixed integral gain (I): (a) speed and (b) q-axis current.

FIGURE 8. The optimal selection of PI gains for fair comparison with proposed SMC method through Trial-and-Error method under fixed proportional gain (P): (a) speed and (b) q-axis current.

A. OPTIMAL SELECTION OF GAINS FOR PI AND FTSMRL METHODS

It can be noted that the SMC control method has not an overshoot inherently, whereas the PI controller has so that the optimal selection of the gains for PI controller are important for the fair comparison. The PI controller has different responses under different conditions, which has large overshoots for the fast response or small with the slow. If the gain value of $P$ is chosen as smaller in the PI controller, then the disturbances rejection capability of the PI controller would be compromised.

In this paper, the FTSMRL is adopted with conventional sliding trajectory for the speed controller, which is faster and more robust against load disturbances than the conventional ERL [30] and existing TSMRL [31] methods, separately. The design of different gains of ERL, TSMRL and FTSMRL is very important for the SMC based speed controller. By full comparison, the gain of the FTSMRL is different than that of the TSMRL in term of $|s|^{\alpha_1}$, thereof, the optimal selection of the $\alpha_1$ is very important in this study. Hence, the tuning process of the $\alpha_1$ is done through the Try and Error method, which is shown in Fig. 9. It is decided from Fig. 9 that the optimal value of $\alpha_1$ is 1.5 in terms of the faster convergence, smaller steady state error, smaller chattering, and lower q-axis current ripple, respectively.

FIGURE 9. The optimal selection of FTSMRL gains for fair comparison with conventional PI, ERL [30] and existing TSMRL [31] algorithms through Trial-and-Error method under the fixed proportional gain $P$: (a) speed and (b) q-axis current.

B. STARTUP RESPONSE OF THE PMSM

The startup transient and steady-state dynamic speed performances of the PMSM drive system under the PI, ERL [30], TSMRL [31], FTSMRL, and FTSMRL+ESO are compared in details, in which three reference speed values are set as 1000, 1500, and 1800 rpm, separately. Fig. 10 shows the dynamic transient and steady state speed behaviors under the PI, ERL [30], TSMRL [31], FTSMRL, and FTSMRL+ESO with the reference speed of 1000 rpm. Fig. 10 (a) shows that...
the conventional PI method has a larger recovery time than the ERL [30] with smaller overshoot. The recovery time of the PI, ERL [30], TSMRL [31], FTSMRL, and FTSMRL+ESO is 350, 172, 162, 106, and 81 ms, respectively, and the steady-state error in the FTSMRL is smaller than those of the PI and ERL [30]. Moreover, it is seen that the chattering phenomenon is one inherited issue of the SMC controller, which adversely affects the system performance to some extent. Therefore, in order to minimize the chattering phenomenon of the SMC control system effectively, one FTSMRL is proposed in this paper, as shown in Fig. 10. It can be observed from Fig. 10 (b) that the FTSMRL has strong ability to minimize the chattering and current ripple from the \( q \)-axis current response. Moreover, it is known that the FTSMRL has superior dynamic performance than the PI, ERL, [30] and TSMRL [31], respectively.

In addition, Fig. 11 shows the dynamic startup and steady-state speed responses under the PI, ERL [30], TSMRL [31], FTSMRL, and FTSMRL+ESO under the speed of 1500 rpm. Fig. 11 (a) has demonstrated that the PI method has a smaller overshoot with larger recovery time than the ERL [30]. The recovery time of the PI, ERL [30], TSMRL [31], FTSMRL, and FTSMRL+ESO is 366, 191, 177, 143, and 134 ms, individually. Hereafter, it is determined that the proposed (FTSMRL+ESO) technique has quicker speed response with smaller speed fluctuation over PI, ERL [30], TSMRL [31], FTSMRL, separately. It is also known from Fig. 11 (b) that the FTSMRL has excellent ability to minimize the chattering and current ripple in the input of the current controller. Meanwhile, it is also seen from this figure that the FTSMRL has superior dynamic performance than PI, ERL [30] and TSMRL [31], separately.

Moreover, Fig. 12 (a) demonstrate that the PI method has an overshoot and other four methods have not any overshoot with a reference speed of 1800 rpm. The recovery time of the

**TABLE 3.** Start-up transient indexes of PI, ERL, TSMRL, FTSMRL and FTSMRL+ESO.

| Control method | Recovery time (ms) | Steady-state error (+ rpm) |
|----------------|--------------------|---------------------------|
| PI             | 350                | 366                       |
| ERL [30]       | 172                | 191                       |
| TSMRL [31]     | 162                | 177                       |
| FTSMRL         | 106                | 143                       |
| FTSMRL+ESO     | 81                 | 134                       |
FIGURE 12. The speed and q-axis responses of PI, ERL [30], TSMRL [31], and FTSMRL and FTSMRL+ESO methods under no-load @ 1800 rpm.

PI, ERL [30], TSMRL [31], FTSMRL and FTSMRL+ESO is 347, 204, 201, 167, and 137 ms, separately. It can be also observed from Fig.12 (b) that the FTSMRL has strong ability to minimize the chattering and current ripple from the q-axis current response. Meanwhile, Fig.12 (b) determine that the FTSMRL has superior dynamic performance than PI, ERL [30], and TSMRL [31], separately.

Furthermore, the performance indexes of the PI, ERL [30], TSMRL [31], FTSMRL and FTSMRL+ESO in terms of startup and steady-state are listed for the speed of 1000, 1500 and 1800 rpm, individually, as shown in Table 3.

**C. EVALUATION OF ROBUSTNESS TO THE LOAD DISTURBANCES**

The robustness against load disturbances of the PI, ERL [30], TSMRL [31], FTSMRL and FTSMRL+ESO methods has been compared at 5Nm, 8 Nm and 10 Nm with speed of 1000 rpm, 1500 rpm and 1800 rpm, separately. Figs. 13 to 15 show the speed and q-axis current performances with the 5 Nm, 8 Nm and 10 Nm loading torque under the PI, ERL [30], TSMRL [31], FTSMRL and FTSMRL+ESO, separately. Moreover, Fig. 13 (a) that speed dip and recovery time under the PI, ERL [30], TSMRL [31], FTSMRL and FTSMRL+ESO are (210 rpm, 415 ms), (239 rpm, 117 ms), (190 rpm, 85 ms), (134 rpm, 65 ms) and (70 rpm, 37 ms), respectively, when 5 Nm load is added. It can be observed from the Fig.13 (b) that the chattering and q-axis current ripple can be suppressed through FTSMRL effectively. Furthermore, it is known, by careful comparison, that the FTSMRL has the strongest robustness against external load and the fastest response under transient condition, which can effectively reduce the chattering phenomenon.

Furthermore, Fig. 14 has demonstrated the speed and q-axis performances under the PI, ERL [30], TSMRL [31], FTSMRL and FTSMRL+ESO with 8 Nm loading torque at

**TABLE 4. Load disturbance indexes of the PI, ERL [30], TSMRL [31], FTSMRL, and FTSMRL+ESO methods.**

| Control technique | Speed decrease (rpm) and recovery time (ms) with 5 Nm load | Speed decrease (rpm) and recovery time (ms) with 8 Nm load | Speed decrease (rpm) and recovery time (ms) with 10 Nm load |
|-------------------|----------------------------------------------------------|----------------------------------------------------------|----------------------------------------------------------|
| PI [30]           | 210 415                                                  | 450 435                                                  | 480 440                                                  |
| ERL [30]          | 239 117                                                  | 450 224                                                  | 520 520                                                  |
| TSMRL [31]        | 190 85                                                   | 350 166                                                  | 450 450                                                  |
| FTSMRL            | 134 65                                                   | 330 110                                                  | 435 435                                                  |
| FTSMRL+ESO        | 70 37                                                    | 260 104                                                  | 418 210                                                  |
reference speed of 1500 rpm, respectively. It can be seen from Fig. 14 (a) that the speed drop and recovery time under the PI, ERL [30], TSMRL [31], FTSMRL and FTSMRL+ESO are (450 rpm, 435 ms), (450 rpm, 224 ms), (350 rpm, 166 ms), (330 rpm, 110 ms) and (260 rpm, 104 ms), respectively, when 8 Nm load is added.

Moreover, Fig. 15 shows the speed and q-axis performances under the PI, ERL [30], TSMRL [31], FTSMRL and FTSMRL+ESO with 10 Nm loading torque at reference speed of 1800 rpm. It can be observed from Fig. 15 (a) that the speed dip and recovery time under the PI, ERL [30], TSMRL [31], FTSMRL and FTSMRL+ESO are (440 rpm, 480 ms), (520 rpm, 420 ms), (450 rpm, 276 ms), (435 rpm, 226 ms) and (418 rpm, 210 ms), respectively, when 10 Nm load is added. It is also noted from Fig.15 (a) that speed fluctuation under FTSMRL is smaller than PI, ERL [30], and TSMRL [31], separately. Moreover, it is observed from Fig.15 (b) that the FTSMRL has outstanding ability to minimize the chattering and current ripple from the q-axis current response, and the FTSMRL has superior dynamic performance than PI, ERL [30], and TSMRL [31], separately.

The external load disturbances ability indexes of the PI, ERL [30], TSMRL [31], FTSMRL and FTSMRL+ESO under the reference speed of 1000, 1500 and 1800 rpm are presented in Table 4. As realized from this table, the FTSMRL has faster and stronger anti-disturbance ability at load transient than those of PI, ERL [30] and TSMRL [31], separately. Similarly, the ESO is firstly designed to estimate the disturbances of the system, and then the estimated disturbance term is compensated with feed-forward compensation method, which can further enhance the anti-disturbance rejection ability of the speed controller based on the FTSMRL.

Therefore, it can be concluded from the Table 4 that the proposed (FTSMRL+ESO) method has improved performance against external disturbances and faster transient response over PI, ERL [30], TSMRL [31] and FTSMRL, respectively.

VI. CONCLUSION
In this paper, a new control law, FTSMRL, based SMC is proposed for the speed regulation of the PMSM drive system.
The FTSMRl is introduced to enhance the reaching velocity, reduce the chattering, and improve the anti-disturbance ability of the speed controller. The major contributions in this work are summarized as follows:

1. One novel FTSMRl is proposed to suppress the chattering phenomenon effectively, ensure the fast convergence, smooth the steady state performance, and improve the disturbances rejection ability of speed controller for the PMSM drive system;

2. An ESO is designed to estimate the disturbances and then the estimated disturbance term is used for the feed-forward compensation method; and

3. A composite speed control method is established, which combines the FTSMRl control law based SMC and ESO to further enhance the anti-disturbances capability, reduce steady state speed fluctuation, and decrease the chattering efficiently.

The proposed FTSMRl+ESO algorithm is fully compared with the PI, ERL [30], TSMRL [31] and FTSMRl methods on loaded and no-loading conditions, which has fully verified the anti-disturbance ability of the proposed method in this work. Moreover, the close loop stability is checked by Lyapunov theory, and the superiority of the proposed FTSMRl+ESO algorithm is verified by simulation and experimental results.

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