A novel hierarchical nonlinear proportional-integral fast terminal sliding mode control for PMSM drives

Peng Gao¹,² and Guangming Zhang¹

Abstract
This study proposes a novel hierarchical nonlinear proportional-integral fast terminal sliding mode (HNLPIFTSM) control for permanent magnet synchronous motor (PMSM) speed regulation system. A new type of sliding surface called HNLPIFTSM surface, which combines the benefits of a nonlinear proportional-integral (PI) sliding mode surface and a fast terminal sliding mode (FTSM) surface, is proposed to enhance the robustness and improved the dynamic response, whilst preserving the great property of the conventional hierarchical fast terminal sliding mode (HFTSM) control strategy. The proposed HNLPIFTSM surface uses the novel nonlinear PI sliding mode surface as its inner loop and uses the FTSM surface as its outer loop. Meanwhile, an extended state observer (ESO) is used to estimate the uncertain terms of the PMSM speed regulation system. Furthermore, the stability of the closed-loop control system under the ESO and the HNLPIFTSM control strategy is proved by the Lyapunov stability theorem. Finally, the simulations and experimental demonstrations verify the effectiveness and superiorities of our proposed HNLPIFTSM control strategy over the conventional HFTSM control strategy.

Keywords
Hierarchical nonlinear proportional-integral fast terminal sliding mode control, permanent magnet synchronous motor, nonlinear PI sliding mode surface, fast terminal sliding mode surface, extended state observer

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Introduction
Sliding mode (SM) control strategy is a common robust control method, which was proposed by former Soviet scholars in the 1950s. The sliding mode variable structure control system based on the SM control has strong robustness and anti-interference to uncertain system, and the control strategy is simple and easy to realize, which has been widely in practical applications.¹³

The inherent chattering problem of sliding mode variable structure seriously limits the application of SM control strategy in practical engineering. In the meantime, in the face of complex control problems, it is difficult to achieve efficient control effect by using traditional SM control strategy. Hence, compound SM control methods are effective measures for such requirements. In recent years, in order to improve the control effect of uncertain systems, many scholars have studied various composite SM control strategies, such as fractional order SM control,⁴,⁵ adaptive SM control,⁶–⁹ passivity-based SM control,¹⁰ mode-free SM control,¹¹,¹² fuzzy SM control,¹³,¹⁴ event-triggered SM

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fast terminal sliding mode (HNLPIFTSM) control strategy is proposed for the PMSM speed regulation system in the present work. A novel type of sliding mode surface called HNLPIFTSM surface, which combines the benefits of the nonlinear proportional-integral (PI) sliding mode surface and the FTSM surface, is proposed to enhance the robustness and improved the dynamic response. The proposed HNLPIFTSM surface uses the nonlinear PI sliding mode surface as its inner loop and uses the FTSM surface as its outer loop. Meanwhile, a linear ESO is used to estimate the uncertain terms of the PMSM speed regulation system. The stability of the closed-loop control system under the linear ESO and HNLPIFTSM control strategy is proved using the Lyapunov stability theory.

Through comparisons with the existing studies, our contributions of this article are further highlighted as follows.

1. In order to improve the dynamic response speed and anti-disturbance ability, a nonlinear PI sliding mode surface is designed.
2. The combination of the FTSM surface with the nonlinear PI sliding mode surface is used to design a novel HNLPIFTSM control strategy.
3. The effectiveness and superiorities of our ESO based the HNLPIFTSM control strategy are proved by the comparative simulations and experimental demonstrations.

The remaining parts of this paper are arranged as:

In Section 2, some important knowledge of the mathematical model of PMSM are briefly presented. Control strategies and stability analysis are given in Section 3, the simulations and experimental demonstrations are shown in Section 4. Finally, Section 5 concludes the study.

Problem description

The torque equation of PMSM is first described as follows:

\[
T_e = \frac{3}{2}p_n (\phi_p i_q(t) + (L_d - L_q)i_d(t)i_q(t)),
\]

where \(T_e\) is the electromagnetic torque; \(\phi_p\) presents the flux of permanent magnet; \(L_d, L_q, i_d(t)\) and \(i_q(t)\) present inductance components and current components of the dq-axes.

When \(L_d = L_q\) is satisfied, the motion equation of PMSM is given as:

\[
\begin{align*}
T_e - T_L &= J \frac{d\omega(t)}{dt} + B\omega(t), \\
T_e &= \frac{3}{2}p_n \phi_p i_q(t),
\end{align*}
\]
\[
\frac{d\omega(t)}{dt} = \frac{3p_w\phi_f}{2J} i_q(t) - \frac{B}{J} \omega(t) - \frac{1}{J} T_L, \tag{3}
\]

where \(\omega(t)\) is actual mechanical speed of PMSM; \(J\) implies rotational inertia; \(T_L\) is load torque; \(B\) presents friction coefficient of the rotor and load. To simplify analysis, the motion equation of PMSM can be rewritten as:

\[
\frac{d\omega(t)}{dt} = \frac{3p_w\phi_f}{2J} i_q(t) + \Delta d, \tag{4}
\]

where \(\Delta d\) is the total disturbance of the system, \(i_q(t)\) is the control input.

The error equation of the PMSM speed regulation system is given as:

\[
e(t) = \omega_r(t) - \omega(t), \tag{5}
\]

where \(\omega_r(t)\) is the reference mechanical speed; \(e(t)\) is the error of the mechanical speed.

**Control strategies and stability analysis**

**Control strategies designed**

The traditional linear sliding mode surface as the inner loop is selected as:

\[
s_1(t) = K_p e(t) + K_i \int e(t), \tag{6}
\]

where \(K_p > 0\) and \(K_i > 0\).

Based on the FTSM control strategy, the following FTSM surface as the outer loop is proposed as:

\[
s_2(t) = a_1 s_1^q(t) + a_2 s_1(t) + \frac{ds_1(t)}{dt}, \tag{7}
\]

where \(a_1 > 0\) and \(a_2 > 0\), \(p\) and \(q\) are positive odd integers, \(\frac{1}{2} < \frac{p}{q} < 1\).

In order to resist the occurrence of uncertain interference, the following reaching law is applied:

\[
\frac{ds_2(t)}{dt} = -\eta \text{sign}(s_2(t)), \tag{8}
\]

where \(\eta\) is positive constant, the symbolic function \(\text{sign}(s_2(t))\) is as follows.

\[
\text{sign}(s_2(t)) = \begin{cases} 
1 & \text{if } s_2(t) > 0 \\
0 & \text{if } s_2(t) = 0 \\
-1 & \text{if } s_2(t) < 0 
\end{cases} \tag{9}
\]

According to (7), (8), and (9), one can obtain:

\[
a_1 s_1^q(t) + a_2 s_1(t) + \frac{ds_1(t)}{dt} = -\eta \text{sign}(s_2(t)) \tag{10}
\]

By substituting (6) into (10), one has:

\[
a_1 s_1^q(t) + a_2 s_1(t) + K_p \frac{de(t)}{dt} + K_ie(t) = -\eta \text{sign}(s_2(t)) \tag{11}
\]

By substituting (4) and (5) into (11) gives:

\[
a_1 s_1^q(t) + a_2 s_1(t) + K_i e(t) + \eta \text{sign}(s_2(t)) + K_p \left(\frac{d\omega(t)}{dt} - \frac{3p_w\phi_f}{2J} i_q(t) - \Delta d\right) = 0 \tag{12}
\]

According to (12), the traditional HFTSM control input is defined as:

\[
i_q^*(t) = \frac{2J}{3p_w\phi_f^2} K_p \left( a_1 s_1^q(t) + a_2 s_1(t) + K_i e(t) + \eta \text{sign}(s_2(t)) \right)
+ \frac{2J}{3p_w\phi_f^2} \left( \frac{d\omega(t)}{dt} - \Delta d\right) \tag{13}
\]

In this paper, a nonlinear PI sliding mode surface as the inner loop is defined as:

\[
s_1(t) = K_p \text{sig}(e(t))^\alpha + K_i \int \text{sig}(e(t))^\alpha, \tag{14}
\]

where the nonlinear function \(\text{sig}(e(t))^\alpha\) is defined as:

\[
\text{sig}(e(t))^\alpha = |e(t)|^\alpha \text{sign}(e(t)), \tag{15}
\]

where \(0 < \alpha < 1\).

**Remark 1.** Compare the traditional linear sliding mode surface (6), the proposed nonlinear PI sliding mode surface (14) can effectively overcome the disadvantages of simple and rough signal processing of the traditional linear sliding mode surface.

Combining (7), (8), and (14), we have:

\[
a_1 s_1^q(t) + a_2 s_1(t) + K_p \frac{d\text{sig}(e(t))^\alpha}{dt} + K_i \text{sig}(e(t))^\alpha
+ \eta \text{sign}(s_2(t)) \tag{16}
\]

Substituting (4) and (5) into (16) yields:

\[
a_1 s_1^q(t) + a_2 s_1(t) + K_i \text{sig}(e(t))^\alpha + \eta \text{sign}(s_2(t))
+ K_p \alpha |e(t)|^{\alpha-1} \left( \frac{d\omega(t)}{dt} - \frac{3p_w\phi_f}{2J} i_q(t) - \Delta d\right) = 0 \tag{17}
\]
According to (17), the proposed HNLPIFTSM control input is designed as:

\[
\tilde{i}^{*}(t) = \frac{2J}{3p_{o}\phi_{f}K_{p}\phi_{f}|e(t)|^{\alpha-1}}
\left( a_{1}s_{1}^{\xi}(t) + a_{2}s_{1}(t) + K_{i}\text{sign}(e(t))\dot{a} \right)
+ \frac{2J}{3p_{o}\phi_{f}} (\frac{d\omega_{l}(t)}{dt} - \Delta d)
\]

(18)

In this subsection, the stability of the proposed HNLPIFTSM control strategy will be discussed. The Lyapunov function for the proposed HNLPIFTSM control strategy is selected:

\[
V = \frac{1}{2}s_{1}^{2}(t) > 0
\]

(19)

By substituting (14) into (7), we can get:

\[
s_{2}(t) = a_{1}s_{1}^{\xi}(t) + a_{2}s_{1}(t) + K_{i}\text{sign}(e(t))\dot{a}
+ K_{p}\text{sign}(e(t))\dot{a}^{-1}\left( \frac{d\omega_{l}(t)}{dt} - \frac{3p_{o}\phi_{f}}{2J} \tilde{i}^{*}(t) - \Delta d \right)
\]

(20)

Then, substituting the proposed HNLPIFTSM control input (18) into (20), the following equation can be obtained.

\[
s_{2}(t) = -\eta \int \text{sign}(s_{2}(t))
\]

(21)

According to (19) and (21), we can get:

\[
\frac{dV}{dt} = s_{2}(t) \frac{ds_{2}(t)}{dt}
= s_{2}(t)(-\eta \text{sign}(s_{2}(t)))
= -\eta |s_{2}(t)|
\]

(22)

According to the Lyapunov criterion, the FTSM surface as the outer loop can reach zero. Then, the FTSM surface satisfies the following condition.

\[
a_{1}s_{1}^{\xi}(t) + a_{2}s_{1}(t) + \frac{ds_{1}(t)}{dt} = 0
\]

(23)

When chosen p and q properly, we can get that the nonlinear PI sliding mode surface \(s_{1}(t)\) as the inner loop reach zero in finite time, which can be derived from the following expression:

\[
t = \frac{q}{a_{2}(q-p)} \left( \ln \left( a_{2}s_{1}(0)^{\frac{a_{2}}{a_{1}}} + a_{1} \right) - \ln a_{1} \right),
\]

(24)

where \(s_{1}(0) \neq 0\) is an initial state.

When the nonlinear PI sliding mode surface reach zero in finite time, the novel nonlinear PI sliding mode surface can be written as:

\[
K_{p}\text{sign}(e(t))\dot{a} + K_{i} \int \text{sign}(e(t))\dot{a} = 0
\]

(25)

Let \(R = |e(t)|^{\alpha} \text{sign}(e(t))\), equation (25) can be written as:

\[
R + \frac{K_{i}}{K_{p}} \int R = 0
\]

(26)

Then

\[
R = R_{0} e^{-\frac{K_{i}}{K_{p}t}},
\]

(27)

where \(R_{0}\) is the coefficient determined by the initial condition. According to (15) and (27), we know \(e(t) \rightarrow 0\) when \(t \rightarrow \infty\), the stability of the system (25) can be guaranteed. Consequently, the stability of the proposed HNLPIFTSM control strategy is proved.

**Linear ESO designed**

The motion equation of PMSM can be expressed as:

\[
\frac{dx_{1}}{dt} = x_{2} + b_{0}u,
\]

(28)

where \(x_{1} = \omega(t); x_{2} = \Delta d; u = \tilde{i}^{*}(t)\) and \(b_{0} = \frac{3p_{o}\phi_{f}}{2J} \).

Then, the linear ESO was designed as: \(^{29}\)

\[
\begin{align*}
\dot{e}(t) &= Z_{21} - y(t) \\
\frac{dZ_{21}}{dt} &= Z_{22} - \beta_{1}\dot{e}(t) + b_{0}u(t), \\
\frac{dZ_{22}}{dt} &= -\beta_{2}\dot{e}(t)
\end{align*}
\]

(29)

where \(\beta_{1}\) and \(\beta_{2}\) are positive constants; \(Z_{21}\) and \(Z_{22}\) are the estimated values of \(x_{1}\) and \(x_{2}\), respectively.

According to the previous studies, \(^{44}\) the stability of the linear ESO will be discussed.

The linear ESO (29) can be rewritten as:

\[
\begin{align*}
\frac{dZ_{21}}{dt} &= Z_{22} + \beta_{1}(x_{1} - Z_{21}) + b_{0}u(t) \\
\frac{dZ_{22}}{dt} &= \beta_{2}(x_{1} - Z_{21})
\end{align*}
\]

(30)

Equation (30) can be written as:

\[
\begin{bmatrix}
\frac{dZ_{21}}{dt} \\
\frac{dZ_{22}}{dt}
\end{bmatrix} = A \begin{bmatrix}
Z_{21} \\
Z_{22}
\end{bmatrix} + B \begin{bmatrix}
x_{1} \\
u(t)
\end{bmatrix},
\]

(31)

where

\[
A = \begin{bmatrix}
-\beta_{1} & 1 \\
-\beta_{2} & 0
\end{bmatrix}
\]

(32)
According to (31), (32), and (33), the stability of the system can be guaranteed. So, we can get:

\[
\begin{align*}
Z_{21} & \rightarrow x_1 \\
Z_{22} & \rightarrow x_2
\end{align*}
\]

Therefore, the linear ESO exhibits stability.

**Theorem 1:** By substituting (27) into (18), the proposed control input with the linear ESO is designed as:

\[
i^*(t) = \frac{2J}{3p_0\beta_f K_e \dot{\alpha} |e(t)|^{a-1}} \\
\left( a_1 \dot{s}_2(t) + a_2 s_1(t) + K_e \text{sign}(s_2(t)) \right) + \frac{2J}{3p_0\beta_f} \left( \int \dot{\omega}_r(t) dt - Z_{22} \right)
\]

By substituting (35) into (20), we can obtain:

\[
s_2(t) = - \eta \int \text{sign}(s_2(t)) + K \Delta D
\]

where \( K = K_e |e(t)|^{a-1} \) and \( \Delta D \) is the estimation error of the linear ESO.

Assumption 1: The following condition is assumed for analysis in the paper.

\[
\frac{d(K \Delta D)}{dt} \leq \Theta
\]

where \( \Theta \) is a constant parameter.

According to (39), we know that \( \frac{dV}{dt} < 0 \) can be guaranteed as long as \( \eta \Theta > 0 \). Consequently, the stability of the proposed HNLPIFTSM control strategy with the linear ESO is proved.

A novel field oriented control (FOC) of the PMSM speed regulation system based on the proposed HNLPIFTSM control strategy (18) with the linear ESO (29) is given in Figure 1.

**Comparative simulations and experimental demonstrations**

In order to verify the effectiveness and superiorities of our proposed HNLPIFTSM control strategy over the conventional HFTSM control strategy, the FOC of the
PMSM speed regulation system based on different control strategies are constructed in this paper. Table 1 shows the key parameters of the PMSM in the simulation. The selected parameters of the ESO are given as: $\beta_1 = 2000$ and $\beta_2 = 1000000$. The selected parameters of the traditional HFTSM control strategy and the proposed HNLPFTSM control strategy in the simulation are given in Tables 2 and 3, respectively. In particular, to better eliminate the effect of parameter setting on the comparison results, we set some same parameters in the traditional HFTSM control strategy and the proposed HNLPFTSM control strategy.

The dynamic response of rotational speed is first used for comparison in the simulation. Figures 2 to 5 show the rotational speed response curves under the different control strategies, respectively. To better compare the control performance of various controllers at different speeds, the reference speed is set to 30 and 60 rpm, respectively. Based on different control schemes, the actual speed response of the PMSM without load starting are compared in Figures 2 and 3, respectively. Based on different control schemes, the actual speed response of the PMSM with $1N\cdot m$ load starting are compared in Figures 4 and 5, respectively. Taking Figures 2 to 5 to analyse, the reaching time under the proposed algorithm HNLPFTSM control strategy is shorter than the reaching times under the conventional existing controller. The Figures show that the speed response curves based on the proposed HNLPFTSM control strategy are faster and better than the conventional existing controller. As a result, the proposed HNLPFTSM control strategy has better dynamic characteristics than the traditional control strategy.

### Table 1. Parameters of the PMSM.

| $L$ | $\phi_f$ | $J$ | $p_n$ | $B$ |
|-----|----------|-----|-------|-----|
| $8.5mH$ | $0.175Wb$ | $0.003kg\cdot m^2$ | 4 | $0.008N\cdot m\cdot s$ |

### Table 2. Parameters selected of the traditional HFTSM control strategy.

| $K_p$ | $K_i$ | $p$ | $q$ | $\eta$ | $a_1$ | $a_2$ |
|------|------|----|----|------|------|------|
| 3    | 15   | 7  | 9  | 10   | 1    | 1    |

### Table 3. Parameters selected of the proposed HNLPFTSM control strategy.

| $K_p$ | $K_i$ | $p$ | $q$ | $\eta$ | $\tilde{\alpha}$ | $a_1$ | $a_2$ |
|------|------|----|----|------|---------------|------|------|
| 3    | 15   | 7  | 9  | 10   | 0.25          | 1    | 1    |

Figure 2. (a) Actual speed response under the traditional HFTSM control strategy without load when the reference speed is set at 30 rpm and (b) actual speed response under the traditional HFTSM control strategy without load when the reference speed is set at 60 rpm.
Figure 3. (a) Actual speed response under the proposed HNLPIFTSM control strategy without load when the reference speed is set at 30 rpm and (b) actual speed response under the proposed HNLPIFTSM control strategy without load when the reference speed is set at 60 rpm.

Figure 4. (a) Actual speed response under the traditional HFTSM control strategy with 1 N·m load when the reference speed is set at 30 rpm and (b) actual speed response under the traditional HFTSM control strategy with 1 N·m load when the reference speed is set at 60 rpm.

Figure 5. (a) Actual speed response under the proposed HNLPIFTSM control strategy with 1 N·m load when the reference speed is set at 30 rpm and (b) speed response curves under the proposed HNLPIFTSM control strategy with 1 N·m load when the reference speed is set at 60 rpm.
In the following article, an external load with step change is used to demonstrate the anti-disturbance capability of the proposed HNLPIFTSM control strategy. The reference speed is set to 30 rpm. In Figures 6 and 8, the external load suddenly becomes $1 \text{N} \cdot \text{m}$ from $0 \text{N} \cdot \text{m}$ at 4.5 s under the traditional HFTSM control strategy and the proposed HNLPIFTSM control strategy, respectively. In Figures 7 and 9, the external load suddenly becomes $0 \text{N} \cdot \text{m}$ from $1 \text{N} \cdot \text{m}$ at 4.5 s under the traditional HFTSM control strategy and the proposed HNLPIFTSM control strategy, respectively. Table 4 gives the speed recovery time under the traditional HFTSM control strategy and the proposed HNLPIFTSM control strategy with the load changed suddenly. It can be seen from Figures 6 to 9 and Table 4 that the recovery time under the proposed HNLPIFTSM control strategy is smaller than that of the traditional HFTSM control strategy, which reveal the proposed HNLPIFTSM control strategy has better robustness than that of the conventional existing controller.

In this subsection, we will further validate the effectiveness and superiority of our proposed HNLPIFTSM control strategy. A PMSM speed control experimental platform based a cSPACE (Control signal process and control engineering) is used in this paper, which is shown in Figure 10. The cSPACE PMSM speed control experimental platform consists of a SM060R20B30M0AD PMSM, a MY1016 DC Generator, a diver experiment box with TI TMS320F28335 DSP and a Matlab/Simulink software. The key parameters of the proposed HNLPIFTSM control strategy in the experiment are given as: $\tilde{a} = 0.25$, $p = 7$, $q = 9$, $\eta = 1$. The selected parameters of the ESO in the experiment are given as: $\beta_1 = 200$ and $\beta_2 = 10000$.

When the reference speed is set to the same value, the performances of the traditional HFTSM control

| Control strategies                  | The external load suddenly increase at 4.5 s | The external load suddenly decrease at 4.5 s |
|------------------------------------|---------------------------------------------|---------------------------------------------|
| The traditional HFTSM control strategy | 0.31                                        | 0.25                                        |
| The proposed HNLPIFTSM control strategy | 0.08                                        | 0.07                                        |
Figure 7. (a) Actual speed response curve under the proposed HNLPIFTSM control strategy when sudden increases $1 \, N \cdot m$ load disturbance at 4.5 s, (b) detailed view of the diagram (a), and (c) iq current response curve under the proposed HNLPIFTSM control strategy when sudden increases $1 \, N \cdot m$ load disturbance at 4.5 s.

Figure 8. (a) Actual speed response curve under the traditional HFTSM control strategy when sudden decreases of $1 \, N \cdot m$ load disturbance at 4.5 s, (b) detailed view of the diagram (a), and (c) iq current response curve under the traditional HFTSM control strategy when sudden decreases of $1 \, N \cdot m$ load disturbance at 4.5 s.
strategy and the proposed HNLPIFTSM control strategy are showed in Figure 11. It can be seen from Figure 11 that the experimental demonstrations verify the excellent speed tracking performance of the proposed HNLPIFTSM control strategy.

When the reference speed is set to 100 rpm and the external load is changed from no load to load suddenly, the performances of the traditional HFTSM control strategy and the proposed HNLPIFTSM control strategy are showed in Figures 12(a) and 13(a), respectively. When the reference speed is set to 100 rpm and the external load is changed from load to no load suddenly, the performances of the traditional HFTSM control strategy and the proposed HNLPIFTSM control strategy are showed in Figures 12(b) and 13(b), respectively. Such Figures show that the proposed control strategy has the superior kinematics and strong anti-disturbance ability of load disturbance. In summary, the experimental demonstrations verify the excellent speed tracking performance and robustness of the proposed HNLPIFTSM control strategy.

Conclusions and future work

In this paper, we propose a novel ESO based the HNLPIFTSM control strategy to obtain high performance of the PMSM speed regulation system. Firstly, a novel HNLPIFTSM surface is designed, which combines the advantages of the nonlinear PI sliding mode surface and the FTSM surface, is proposed to improved the robustness and the dynamic response, while maintaining the good performance of traditional HFTSM
control strategy. The proposed HNLPIFTSM surface uses the nonlinear PI sliding mode surface as its inner loop and uses the FTSM surface as its outer loop. Meanwhile, an ESO is used to estimate the uncertain terms of the speed regulation system. Comparative simulations and experimental demonstrations verify the

Figure 11. (a) The experimental speed response under the traditional HFTSM control strategy and (b) the experimental speed response under the proposed HNLPIFTSM control strategy.

Figure 12. (a) The experimental speed response under the traditional HFTSM control strategy when the external load is changed from no load to load suddenly and (b) the experimental speed response under the traditional HFTSM control strategy when the external load is changed from load to no load suddenly.

Figure 13. (a) The experimental speed response under the proposed HNLPIFTSM control strategy when the external load is changed from no load to load suddenly and (b) the experimental speed response under the proposed HNLPIFTSM control strategy when the external load is changed from load to no load suddenly.
excellent speed tracking performance and robustness of the proposed strategy.

At present, we only use the control strategy in the middle and low speed control of PMSM. In the future work, we will further complete the application of the proposed HNLPIFTSM control strategy in the control of high speed motor.

Declaration of conflicting interests

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