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Higher Order Predefined-time Sliding Mode Control for PMSM With Uncertain Disturbance

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Abstract: Permanent magnet synchronous motors (PMSM) offer several inherent advantages, such as higher power density, greater efficiency and reliability, more precise and rapid torque control, higher power factor, and longer bearing and insulation lifespans. As a result, they have been widely used in adjustable-speed traction motor drives. However, during operation, these motors are often subject to external load disturbances and parameter variations, which severely affect the robustness of the control system. To address this, an adaptive predefined-time disturbance observer (APTDO) is designed to track the disturbances in real-time and feed them back into the controller for disturbance compensation. Furthermore, to improve the control performance, a higher order predefined-time sliding mode controller (HO-PTSMC) is designed for the PMSM control system. Compared to traditional super-twisting sliding mode control (STSMC) methods, the field-oriented sliding mode control approach proposed in this paper significantly improves dynamic torque and speed responses and enhances the system's robustness under uncertain disturbances. The new sliding mode algorithm, being a fully continuous smooth function, effectively suppresses the chattering phenomenon inherent in traditional sliding mode algorithms, thereby significantly improving the steady-state performance of the system. Finally, simulations are conducted on the MATLAB Simulink platform, which validate the superiority of the proposed algorithm.

Keywords: Permanent Magnet Synchronous Motors (PMSM); Predefined-Time Sliding Mode Control; Field-oriented Control.

1. Introduction

Permanent Magnet Synchronous Motors (PMSM) are widely used in applications such as electric vehicles, rail transportation, and marine propulsion, owing to their high efficiency, high power density, excellent overload capability, and outstanding performance[1]. However, the dynamic model of a PMSM is a highly coupled, multivariable, and nonlinear complex system. Under practical operating conditions, the performance of the control system is highly susceptible to significant disturbances such as parameter variations, external disturbances, and unmodeled dynamics[2]. To achieve robust speed control performance, various nonlinear algorithms have been proposed, including Model Predictive Control [3], Fuzzy Control [4], Finite-Time Control [5], Robust Control [6], and Sliding Mode Control (SMC) [7].

Among various control methods, Sliding Mode Control (SMC) is considered one of the most effective approaches for handling system uncertainties. Due to its fast response, high accuracy, and strong robustness, it has been widely applied in motor control fields. In [8], a novel Higher-Order Super Twisting Sliding Mode Control (HO-STSMC) was proposed to achieve speed control of the Permanent Magnet Synchronous Motor (PMSM) with finite-time convergence. However, the upper bound of the settling time depends on the system's initial conditions, which limits its applicability for improving productivity in practical applications. To achieve better convergence performance, [9] designed an improved Second-Order Fixed-Time Sliding Mode Control (FTSMC) to ensure global fixed-time stability of the closed-loop system, where the settling time is bounded and independent of the initial conditions. In [10], a composite control strategy was proposed, combining an enhanced Non-Singular Fast Terminal Sliding Mode Control (NFTSMC) with a disturbance observer. This method aims to ensure fixed-time convergence while enhancing the system's disturbance rejection capabilities.

However, the Fixed-Time Sliding Mode Control (FTSMC) algorithm has two main issues: first, the estimation of the convergence time is conservative, and second, there is no clear relationship between the convergence time and the adjustable parameters of the controller. To address these issues, the application and development of predefined-time control methods are necessary [11-12]. Compared to fixed-time control, predefined-time control effectively resolves these problems. Firstly, the adjustable parameters of the controller determine the upper bound of the predefined settling time, avoiding the overestimation of the convergence time. Secondly, the predefined stable convergence time is bounded by the controller's adjustable parameters, facilitating the design of controllers that meet specific requirements. In [13], a novel predefined-time sliding mode control scheme was proposed for chaotic systems. Simulation results show that this method has a faster convergence rate compared to traditional finite-time SMC and fixed-time SMC, which is particularly suitable for systems like Permanent Magnet Synchronous Motors (PMSM) that require high dynamic performance. However, the introduction of the sign function on the sliding surface may lead to undesirable chattering phenomena. In [14], an adaptive practical predefined-time sliding mode control strategy was proposed for second-order MAS systems under uncertain disturbances, effectively addressing the issues of chattering and singularity. By introducing a tanh function, the strategy suppressed the chattering effect and improved the system's steady-state performance. These controllers, due to their excellent performance, are particularly suitable for complex nonlinear control systems such as PMSM. Currently, the application of predefined-time sliding mode control algorithms in PMSM control systems holds great promise.

On the other hand, in practical drive systems with high utilization, Permanent Magnet Synchronous Motors (PMSM) experience nonlinear effects such as rapidly changing external loads, inaccurate measurement of nominal parameters, and parameter perturbations. In such cases, the presence of uncertain disturbances significantly reduces the performance and stability of the system, becoming a major weakness in PMSM drives. To address these issues, disturbance observers have attracted significant attention from researchers, leading to many interesting results, such as nonlinear disturbance observers [15], fuzzy disturbance observers [16], and extended state observers [17]. However, the convergence of the disturbance observation errors in these approaches is typically achieved over an infinite time span. To obtain precise disturbance estimation, finite-time and fixed-time control techniques have been employed to design disturbance observers. In [18], a finite-time sliding mode disturbance observer was designed, where the observation error converges to zero within a finite time. However, these observers use discontinuous sign functions, which can lead to chattering phenomena. In [19], a novel nonlinear fixed-time disturbance observer (FTDO) was proposed, which improves convergence speed while avoiding the use of discontinuous functions like the sign function, thereby reducing chattering and improving observation accuracy. Subsequently, research on predefined-time sliding mode disturbance observers has gained attention. In [20], a predefined-time attitude stabilization strategy based on a disturbance observer was proposed for rigid spacecraft with external disturbances and inertial uncertainties. The method achieves disturbance suppression by constructing a predefined-time nonlinear disturbance observer (PTNDO) and ensures the rapid and accurate convergence of the disturbance estimation error. It is important to note that the aforementioned observers assume an upper bound for disturbances, which is not suitable for PMSM drive systems, as the motor load disturbances can vary greatly in practical applications. Using a large upper bound as a parameter for the observer can cause chattering, which negatively impacts control accuracy. Adaptive strategies can effectively resolve this issue.

Inspired by the above studies, this paper proposes a high-order predefined-time sliding mode control (HO-PTSMC) method based on an adaptive predefined-time disturbance observer (APTDO) for PMSM drive systems. Simulation results demonstrate that the new control method effectively enhances the anti-disturbance performance of PMSMs under uncertain disturbances. The highlights of this work are as follows:

1. The APTDO is designed to track the uncertain disturbances present in the motor, ensuring that disturbances converge within a predefined time. Moreover, this method adopts an adaptive control strategy that does not require prior knowledge of the disturbance upper bound. The adaptive gain varies with the system state, preventing overestimation.

2. The HO-PTSMC is designed to track the speed and current loop errors of the PMSM. This controller demonstrates a better convergence speed and anti-disturbance performance. Compared to traditional sliding mode algorithms, it uses a fully continuous smooth function, effectively suppressing the chattering effect of sliding mode algorithms and improving the steady-state performance of the system.

3. Both HO-PTSMC and APTDO employ a novel practical predefined-time sliding mode algorithm. This algorithm treats time as an explicit design parameter, allowing more precise determination of the sliding surface and switching control timing during system design. As a result, the design process is simplified, and the design becomes more controllable and adjustable.

2. SPMSM Mathematical Model

2.1. Conventional Model Description

The dynamical model of a PMSM in synchronous reference frame is given by the following:

$$\begin{cases} J\dot{\omega}_r = T_e - B\omega_r - T_L \\ T_e = 1.5P_n\left(\psi_f + (L_d - L_q)\right)i_q \end{cases} \tag{1}$$

$$\dot{i}_d = -\frac{R}{L_d}i_d + \frac{L_q}{L_d}P_n\omega_r i_q + \frac{1}{L_d}u_d \tag{2}$$

$$\dot{i}_q = -\frac{R}{L_q}i_q - \frac{L_d}{L_q}p\omega_r i_d - \frac{\psi_f}{L_q}p\omega_r + \frac{1}{L_q}u_q \tag{3}$$

Surface-mounted PMSM(SPMSM) meets $L = L_d = L_q, T_e = \frac{3}{2}P_n\psi_f i_q$, it can be rewritten as:

$$J\dot{\omega}_r = 1.5P_n\psi_f i_q - B\omega_r - T_L \tag{4}$$

$$\dot{i}_d = -\frac{R}{L}i_d + P_n\omega_r i_q + \frac{1}{L}u_d \tag{5}$$

$$\dot{i}_q = -\frac{R}{L}i_q - p\omega_r i_d - \frac{\psi_f}{L}p\omega_r + \frac{1}{L}u_q \tag{6}$$

Here, ω_r is the mechanical angular velocity, ψ_f is the magnetic chain, P_n is the number of pole pairs, L_d, L_q is the shaft stator inductance, B is the damping friction coefficient, i_q is the q-axis stator current, T_L is the load torque, and J is the moment of inertia.

2.2. Improved Model Description with Uncertain Disturbance

In practical systems, measurement inaccuracies always lead to discrepancies between nominal and actual parameters. Moreover, during motor operation, the parameters of the motor may change. These factors result in models that may not accurately reflect the actual behavior of the system, and under certain operating conditions, the model may differ from the system's actual response. Therefore, the control system designed must exhibit robustness in the presence of parameter uncertainties. To address these uncertainties, the model takes into full account the uncertainties in parameters such as flux linkage, stator inductance, moment of inertia, damping friction coefficient, and stator resistance.

The improved model, considering parameter uncertainties, is expressed as follows:

$$\left(J + \Delta J\right)\dot{\omega}_r = 1.5P_n\left(\psi_f + \Delta\psi_f\right)i_q - \left(B + \Delta B\right)\omega_r - T_L \tag{7}$$

The improved model, considering parameter uncertainties, is expressed as follows:

$$\begin{cases} \dot{\omega}_r = \rho i_q^* + G \\ G = a(i_q - i_q^*) - \dfrac{1}{J}\left(\left(B + \Delta B\right)\omega_r + T_L - 1.5P_n\Delta\psi_f i_q + \Delta J\dot{\omega}_r\right) \end{cases} \tag{8}$$

Here, $\rho = 1.5P_n\psi_f / J$, G is the total uncertain disturbance, which is influenced by motor speed, external load, current errors, and unmatched parameters that are limited by the rated values of SPMSM.

3. Controller Design

This section first introduces an adaptive predefined-time disturbance observer (APTDO) to capture the uncertain disturbances during the motor operation, employing an adaptive control strategy that does not require knowledge of the upper bound of the disturbances. Subsequently, a higher order predefined-time sliding mode controller (HO-PTSMC) is proposed for controlling the motor's speed and current loops, with the disturbance estimate from the observer fed back to the controller. This approach enables precise speed control of the motor in the presence of uncertain disturbances. Fig. (1) presents the block diagram of the novel PMSM system.

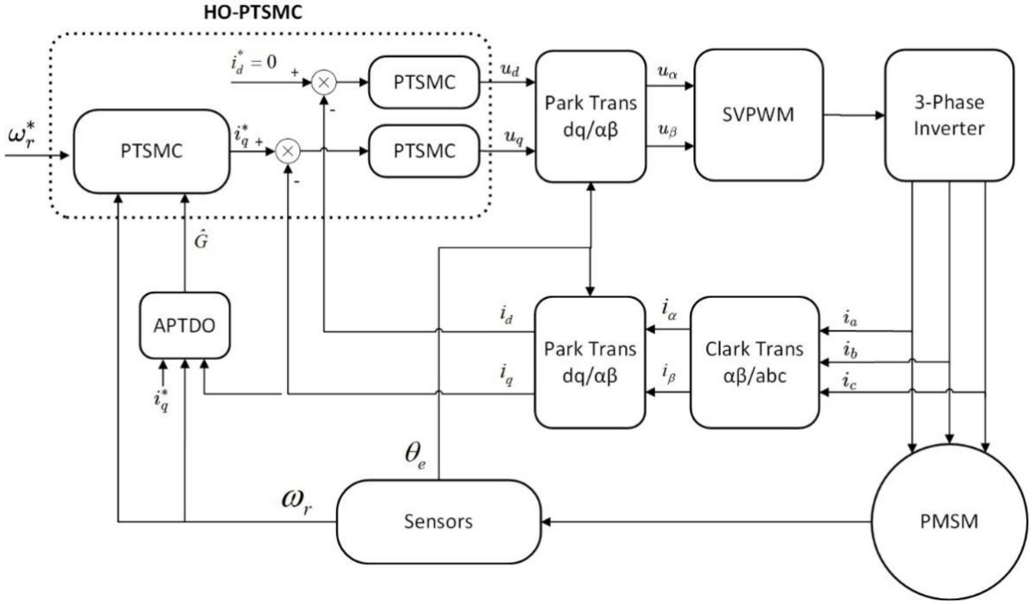

Fig 1. the block diagram of the novel PMSM system

3.1. Design of Adaptive Predefined-time Disturbance Observer

We define a speed estimation error as the sliding mode surface: $s_o = \omega_r - \hat{\omega}_r$, through equation (4), we design APTDO as follows:

$$\begin{cases} \dfrac{d\hat{\omega}_r}{dt} = \rho i_q^* + \hat{G} \\ \hat{G} = a_1 sig^{1-\gamma}\left(s_o\right) + a_2 sig^{1+\gamma}\left(s_o\right) + \hat{a}_3 \tanh\left(\dfrac{s_o}{\epsilon_1}\right) \end{cases} \tag{9}$$

Here, $sig^{\varpi}(\cdot) = |\cdot|^{\varpi} sign(\cdot)$, $0 < \gamma < 1, a_1 = \dfrac{1}{T_o}\dfrac{\pi}{\gamma}\left(\dfrac{1}{2}\right)^{1-\frac{\gamma}{2}}, a_2 = \dfrac{1}{T_o}\dfrac{\pi}{\gamma}\left(\dfrac{1}{2}\right)^{1+\frac{\gamma}{2}}$, ϵ_1 is a small positive constant. The adaptive parameter $\hat{a}_3$ is designed as follows:

$$\dot{\hat{a}}_3 = \mu(|s_o| - \varepsilon\hat{a}_3) \tag{10}$$

Here, $\varepsilon = \max\left\{2a_1 / \mu^{1-\gamma/2}, 2a_2 / \mu^{1+\gamma/2}\right\}$, μ is a positive constant.

According to [19], we can obtain that there exists a positive constant such that $\hat{a}_3 \le \bar{a}_3$ and $a_3 \le \bar{a}_3$. Considering the non-linear dynamical system in equation (4), if the disturbance observer is designed as equation (5,6), the estimated speed error s_ω will converge to a narrow region Δ_d around zero within the predefined-time T_o , Δ_d is expressed as follows:

$$\Delta_d = \sqrt{2\min\left\{\left(\frac{2\gamma T_d\vartheta_d}{\pi}\right)^{\frac{2}{2-\gamma}}, \left(\frac{2\gamma T_d\vartheta_d}{\pi}\right)^{\frac{2}{2+\gamma}}\right\}^{\frac{2}{2+\gamma}}} \tag{11}$$

Here, $\vartheta_d = \frac{1}{2}\varepsilon\left(\overline{a}_3^{2+\gamma} + \overline{a}_3^2 + \zeta_d\right) + \overline{a}_3\epsilon\Omega$, $\zeta_d = (1-\gamma/2)^{(1-\gamma/2)/(\gamma/2)} + (1-\gamma/2)^{1/(\gamma/2)}$, $\Omega = 0.2785$.

When $t > T_o$, $\tilde{G} = G - \hat{G}$ will exist an upper bound $\ddot{G}$ which can be expressed as follows:

$$\ddot{G} = \left| \hat{a}_3 - a_1 sig^{1-\gamma}(\Delta_d) - a_2 sig^{1+\gamma}(\Delta_d) - \hat{a}_3 \tanh(\frac{\Delta_d}{\epsilon_1}) \right| \tag{12}$$

So, we can conclude that the novel disturbance observer can quickly track the uncertain disturbance of the PMSM in a predefined-time period T_o.

3.2. Design of Higher Order Predefined-time Sliding Mode Controller

The sliding manifold $s(x,t) = (s_d, s_q, s_\omega)^T$ of the field-oriented sliding mode control is governed by:

$$s_d = i_d - i_d^* \tag{13}$$

$$s_q = i_q - i_q^* \tag{14}$$

$$s_\omega = \omega_r - \omega_r^* \tag{15}$$

The effect of uncertain disturbance is considered in First-Order Velocity Control and not in Higher-Order Current Control.

3.2.1. First-Order Velocity Control

We define the q-axis velocity control law as

$$i_q^* = i_{q,eq}^* + i_{q,N}^* \tag{16}$$

Here, i_q^* is the quadrature-axis stator current, $i_{q,eq}^*$ is the equivalent control and $i_{q,N}^*$ is the switching control.

From the sliding surface s_ω, $\dot{s}_\omega$ is found to be

$$\dot{s}_\omega = \rho i_q^* + G - \dot{\omega}_r^* \tag{17}$$

The equivalent control becomes:

$$i_{q,eq}^* = \frac{1}{\rho}\left(\dot{\omega}_r^* - G\right) \tag{18}$$

Substituting the estimated term $\hat{G}$ by the above designed disturbance observer, equation (18) becomes:

$$i_{q,eq}^* = \frac{1}{\rho}\left(\dot{\omega}_r^* - \hat{G}\right) \tag{19}$$

By applying a predefined time sliding mode algorithm, switch control becomes:

$$i_{q,N}^* = \frac{1}{\rho}\left(b_1 sig^{1-\alpha}(s_\omega) + b_2 sig^{1+\alpha}(s_\omega) + b_3 \tanh\left(\frac{s_\omega}{\epsilon_2}\right)\right) \tag{20}$$

Here, $0 < \alpha < 1, b_1 = \frac{1}{T_{c1}}\frac{\pi}{\alpha}\left(\frac{1}{2}\right)^{1-\frac{\alpha}{2}}, b_2 = \frac{1}{T_{c1}}\frac{\pi}{\alpha}\left(\frac{1}{2}\right)^{1+\frac{\alpha}{2}}$, ϵ_2 is a small positive constant.

The output of q-axis velocity control i_q^* serves as the input to q-axis current sliding mode control in next Section.

3.2.2. Higher-Order Current Control

We define the qd-axis current control law as

$$u_q = u_{q,eq} + u_{q,N} \tag{21}$$

$$u_d = u_{d,eq} + u_{d,N} \tag{22}$$

Here, u_q, u_d is the qd-axis stator voltage, $u_{q,eq}, u_{d,eq}$ is the equivalent control and $u_{q,N}, u_{d,N}$ is the switching control.

From the sliding surface s_q, s_d, $\dot{s}_q, \dot{s}_d$ is found to be

$$\begin{aligned} \dot{s}_q &= -\frac{R}{L}i_q - P_n\omega_r i_d - \frac{\psi_f}{L}P_n\omega_r + \frac{1}{L}u_q - \dot{i}_q^* \\ \dot{s}_d &= -\frac{R}{L}i_d + P_n\omega_r i_q + \frac{1}{L}u_d - \dot{i}_d^* \end{aligned} \tag{23}$$

The equivalent control becomes:

$$\begin{aligned} u_{q,eq} &= L\dot{i}_q^* + Ri_q + LP_n\omega_r i_d + \psi_f P_n\omega_r - \frac{\psi_f}{L}p\omega_r \\ u_{d,eq} &= L\dot{i}_d^* + Ri_d - LP_n\omega_r i_q \end{aligned} \tag{24}$$

By applying a predefined time sliding mode algorithm, switch control becomes:

$$u_{qd,N} = L\left(c_1 sig^{1-\beta}(s_{d,q}) + c_2 sig^{1+\beta}(s_{d,q}) + c_3 \tanh\left(\frac{s_{d,q}}{\epsilon_3}\right)\right) \tag{25}$$

Here, $0 < \beta < 1, c_1 = \frac{1}{T_{c2}}\frac{\pi}{\beta}\left(\frac{1}{2}\right)^{1-\frac{\beta}{2}}, c_2 = \frac{1}{T_{c2}}\frac{\pi}{\beta}\left(\frac{1}{2}\right)^{1+\frac{\beta}{2}}$, ϵ_3 is a small positive constant.

The output of qd-axis voltage control $u_{q,eq}, u_{d,eq}$ serves as the input to SVPWM module to complete the convergence of current. Finally, we can calculate the total convergence time of the speed tracking error as $T_c = T_{c1} + T_{c2}$.

4. Simulation Experiment

In this section, the proposed control method for the PMSM will be validated through real-time experiments to demonstrate its effectiveness and advantages. The PMSM parameters of the simulation model are shown by Table 1. The sampling frequency of simulation is set to 100 kHz, and the initial states of the PMSM are specified as follows:

$$\left[i_q, i_d, \omega_r, \theta_e\right]^T = \left[0, 0, 0, 0\right]^T \tag{26}$$

The indicator RMSE and MAXE used in the experiment are defined by the following:

$$\begin{aligned} MAXE\left(e_\xi\right) &= max\left(\left|e_\xi(i)\right|\right) \\ RMSE\left(e_\xi\right) &= \sqrt{\sum_{i=1}^{N} \frac{e_\xi^2(i)}{N}} \end{aligned} \tag{27}$$

Here, N is the number of the sampled tracking error, $e_\xi(i)$ is the speed tracking error of the i-th sampling time. Meanwhile, the settling time and maximum speed drop are considered to evaluate the dynamic performance of the proposed method.

Table 1. Parameters of PMSM

Parameter	*Units*	*Values*
Stator resistance R	Ω	2.875
Stator inductance L_d, L_q	mH	8.5
Rotational inertia J	$kg \cdot m^2$	0.003
Flux of permanent magnet ψ_f	Wb	0.175
Viscous damping B	$N \cdot m \cdot s$	0.008
Pole pairs P_n		4

4.1. Comparison of the APTDO

In this experiment to verify the effectiveness of the proposed APTDO, three types of loads are considered: step disturbance, time-varying disturbance, and high-frequency noise disturbance. From the Fig. (2), it can be seen that the APTDO designed in this paper can track these three types of disturbance quickly with good special effects.

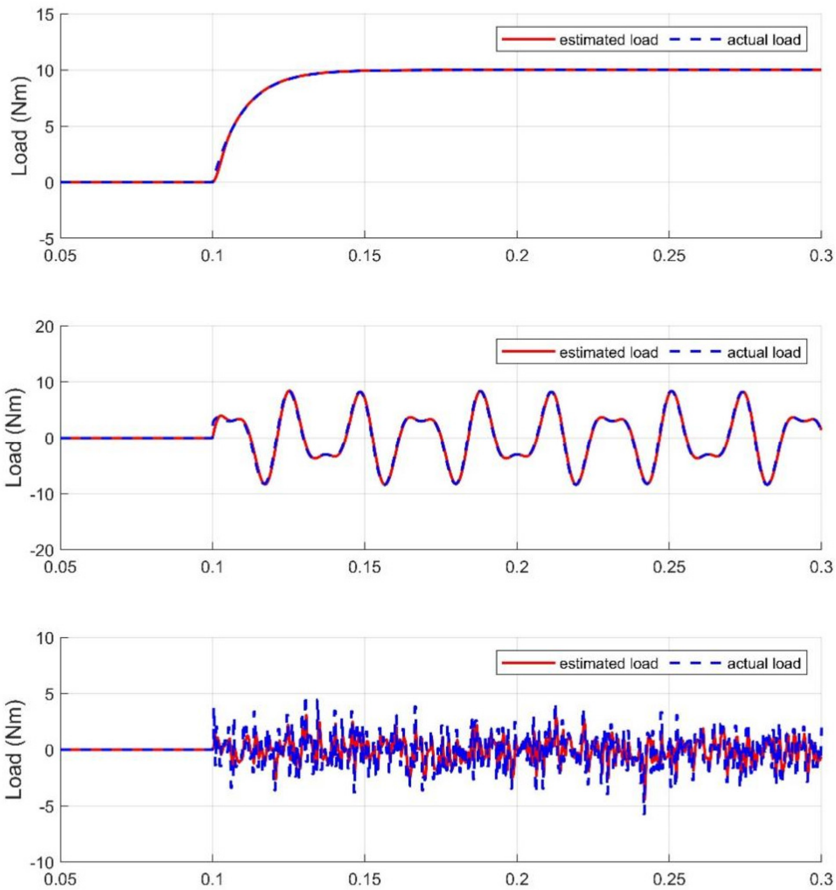

Fig 2. The disturbance estimation performance of APTDO

4.2. Comparison of the HO-PTSMC

The effect of the proposed HO-PTSMC is verified in this experiment and compared with the HO-STSMC proposed in paper [8]. As can be seen from Fig. (3-4), the novel proposed algorithm has better dynamic performance at both step and time-varying reference speed, and is able to complete speed tracking quickly. The data in Table 2 further validate the above conclusion, as the new algorithm adopts the fully continuous smooth function, it can effectively suppress the jitter oscillations and thus achieve a smaller RMSE effect, which indicates that the new algorithm also has a significant improvement in the steady state performance.

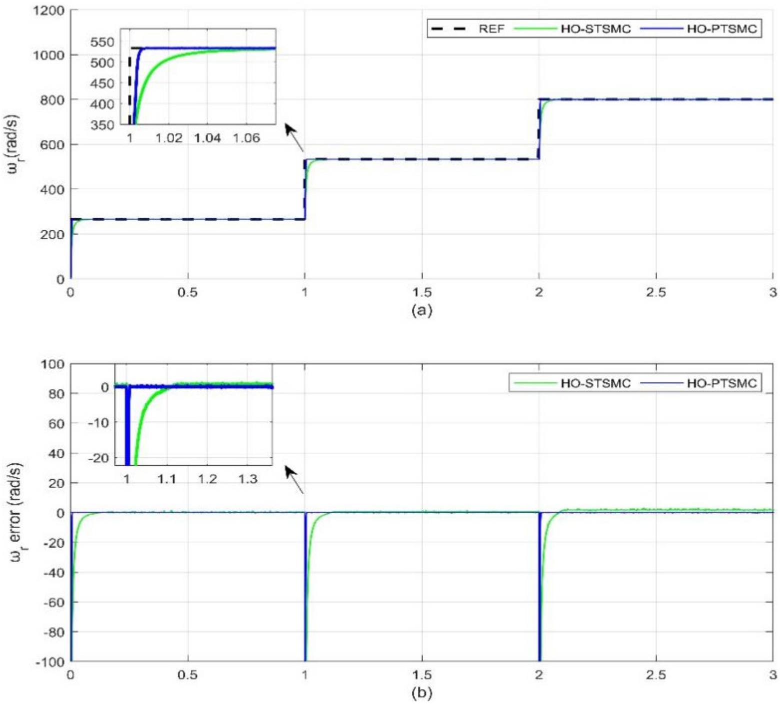

Fig 3. the dynamic performance comparison of step speed

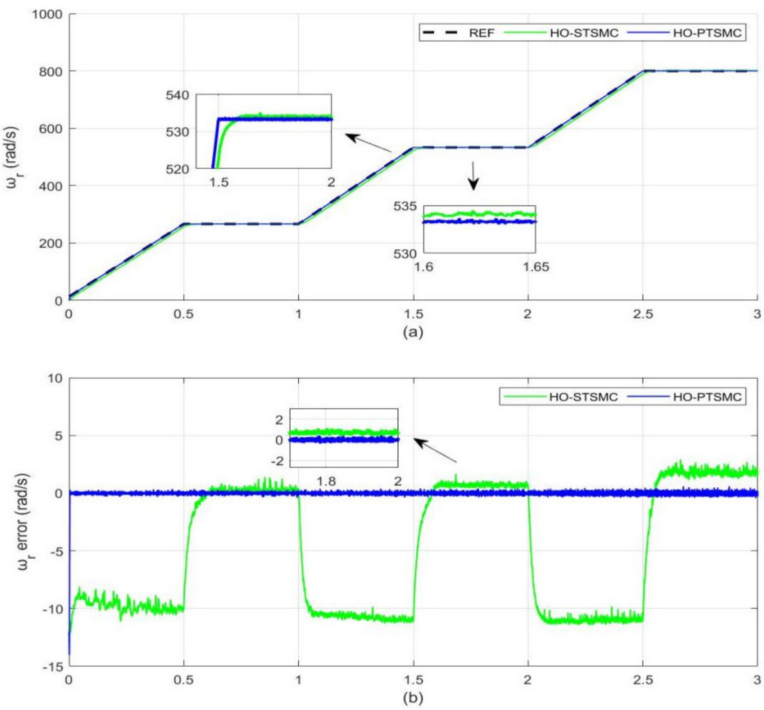

Fig 4. the dynamic performance comparison of time-varying speed

Table 2. Parameters of PMSM

Controller method	Step speed		Time-varying speed	
	RMSE	MAXE	RMSE	MAXE
HO-STSMC	0.2498	2.3671	0.3594	4.4399
HO-PTSMC	0.0781	0.6352	0.0698	0.5468

4.3. Comparison of the HO-PTSMC+APTDO Feedback

The effect of the proposed HO-PTSMC with or without perturbation feedback is compared in this experiment. In considering the three-disturbance proposed above, it can be found from Fig. (5) that the control system with the addition of APTDO feedback has a huge improvement in the anti-perturbation capability, which verifies the effectiveness of the perturbation observer.

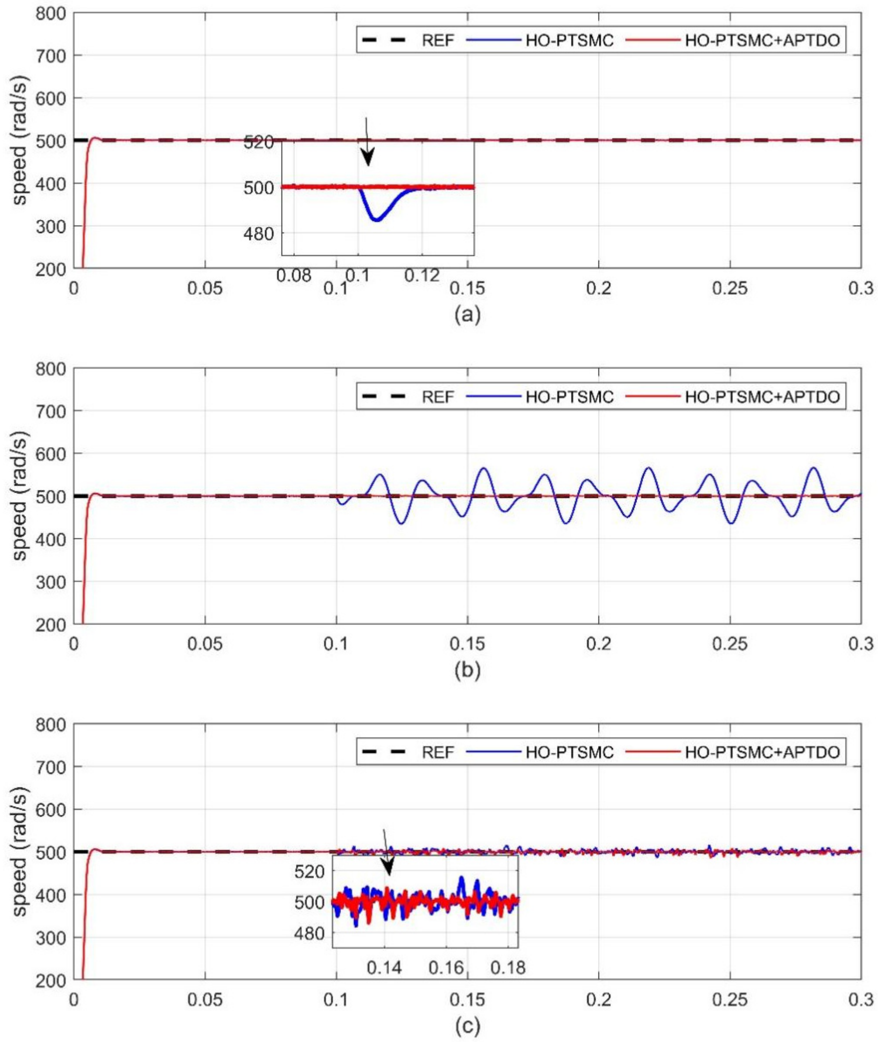

Fig 5. the dynamic performance comparison of disturbance feedback

5. Summary

This paper develops an improved sliding mode control scheme using APTDO and HO-PTSMC techniques for permanent magnet synchronous motor (PMSM) control, aiming to enhance disturbance rejection and achieve speed tracking convergence within a predefined time. An adaptive strategy is employed in APTDO, enabling dynamic adjustment to adapt to varying uncertain disturbances. Subsequently, an HO-PTSMC is proposed to ensure predefined time convergence and robustness of the speed control. Real-time experimental results effectively validate the excellent speed estimation performance of HO-PTSMC and the superior speed control performance of the proposed method. Future work will focus on the DSP hardware validation of the PMSM system.

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