Adaptive Convergence Second Order Sliding Mode Speed Controller for PMSM with a Disturbance Observer Based on a Novel Sliding Mode Reaching Law

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Abstract – Permanent magnet synchronous motors (PMSMs) have attracted extensive attention owing to their high-power density, efficiency, and excellent dynamic performance. Sliding mode control (SMC) is widely used to enhance PMSM speed regulation. However, chattering and implementation difficulties often make conventional SMC less effective and harder to deploy in practice than proportional–integral–derivative (PID) control. This paper proposed an improved adaptive convergence second-order sliding mode control (I-SOSMC) based on PID type sliding mode surface, which exhibits improved dynamic performance, reduced chattering, and simple implementation. To further improve disturbance rejection, an improved sliding mode disturbance observer (I-SMDO) based on a novel sliding mode reaching law (SMRL) is integrated with the I-SOSMC to enhance the disturbance rejection in the PMSM drive. Moreover, the adaptive convergence mechanism in the I-SOSMC adjusts the convergence parameter online according to the estimated disturbance level, thereby strengthening disturbance rejection while further suppressing chattering. Preliminary simulations show that the proposed I-SOSMC reduces settling time from 56.39 ms to 1.41 ms and limits the maximum speed drop from 11.32% to 0.46%, corresponding to about 97.5% faster settling and 96% smaller speed sag. These results indicate that the proposed I-SOSMC achieves faster convergence, smaller speed fluctuations, and superior disturbance rejection, making it a promising solution for high-performance PMSM drives.

Keywords: Permanent magnet synchronous motor (PMSM), Second-order sliding mode control (SOSMC), PID sliding surface, Sliding mode disturbance observer (SMDO).

1. Introduction

With the rapid tightening of carbon-emission targets worldwide, electric propulsion systems are increasingly replacing conventional internal combustion engines in various applications, such as electric vehicles [1-3], hybrid vehicles [4-6] and electric aircraft [7-9]. In addition, they are also extended for renewable power generation [10-12]. Permanent magnet (PM) machines have been identified to be highly promising for electric propulsion, including the PM synchronous motors (PMSMs) [13-15], PM vernier motors [16-18], stator-PM motors [19-21] and flux-switching PM motors [22-24]. Among them, the PMSMs have gained extensive attention and have been widely employed in high performance control applications due to their superior power density and excellent dynamic performance [25-34]. Among various control methods, sliding mode control (SMC) is widely employed in PMSMs drives due to its robustness against model uncertainties and nonlinearities, as well as its low dependence on an accurate system model [35], [36].

However, conventional SMC suffers from the chattering problem, which limits its practical application [37]. To address this issue, high-order SMC (HOSMC) has been extensively investigated [38]. Compared with conventional SMC, HOSMC achieves smoother control, lower chattering, and higher convergence accuracy while retaining the robustness of SMC [39]. As a result, HOSMC receives considerable attention in recent years [40-42].

Nevertheless, HOSMC still suffers from two main limitations: difficult parameter tuning and increased control complexity, both of which restrict its wider application [43], [44]. To address these issues, a second-order SMC (SOSMC) strategy based on a PID sliding surface is introduced in [45] to improve the practical applicability of SMC. By combining the chattering suppression capability of HOSMC, the robustness of conventional SMC, and the ease of tuning associated with PID controllers, this method shows strong potential for practical applications [46].

In addition to HOSMC, observer-based methods have also been widely adopted to mitigate chattering. By estimating and compensating for external disturbances and model uncertainties, these methods can effectively improve system robustness while alleviating chattering, and have therefore attracted considerable research attention [47]. In [48], an improved sliding mode disturbance observer (SMDO)-based speed controller is developed to enhance the estimation accuracy of lumped disturbances and improve the robustness of the PMSM drive system. In [49], a SMDO is proposed to estimate both the future current and the lumped disturbances caused by parameter mismatches as well as computation and sampling delays in the PMSM system. In [50], a model-free predictive current control strategy with an adaptive SMDO

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is presented to accelerate convergence and further suppress chattering.

This paper proposed an improved adaptive convergence second-order sliding mode control (I-SOSMC) based on PID type sliding mode surface, which exhibits improved dynamic performance, reduced chattering, and simple implementation. Moreover, the adaptive convergence mechanism adjusts the convergence parameter in the I-SOSMC online according to the estimated disturbance level. In addition, an improved SMDO based on a novel sliding mode reaching law (SMRL) is integrated with the I-SOSMC to enhance the disturbance rejection in the PMSMs drive system.

2. Preliminaries

2.1 A Second Order Sliding Mode Dynamic

Consider a single-input second-order nonlinear system described by:

$$\ddot{y}_m(t) = -A_n\dot{y}_m(t) - B_n y_m(t) + C_n u(t) + D(t) \tag{1}$$

where $y_m(t)$ is the system output, $u(t)$ is the control input, $u(t) \in \Re$, A_n, B_n, and C_n are nonzero model parameters. $D(t)$ denotes the uncertain external disturbance, and $D_{max} \geq 0$ is assumed to be its upper bound, $|D(t)| \leq D_{max}$. The tracking error is defined as $e_y(t) = y_r - y_m$, where y_r is the reference input. In the preliminaries, an SOSMC with a PID-type sliding surface is introduced. The PID-type sliding surface is defined as [45]:

$$\dot{s}(t) + \beta s(t) = k_p e_y(t) + k_i\int_0^t e_y(\tau)d\tau + k_d\dot{e}_y(t) \tag{2}$$

where $s(t) \in \Re$ denotes the sliding variable. k_p, k_i and k_d are independent positive constants, representing the proportional, integral, and derivative gains, respectively, with $k_p, k_i, k_d \in \Re^+$. These parameters are selected such that the characteristic polynomial associated with $(k_i e(t)+k_p\dot{e}(t)+k_p\ddot{e}(t))$, satisfies the Hurwitz condition. In addition, $\beta > 0$ with $\beta \in \Re$ denotes the convergence parameter of the PID-type sliding surface, which determines convergence rate of $s(t)$. By differentiating (2) and substituting (1) into the result, one obtains:

$$\begin{aligned}\ddot{s}(t) + \beta\dot{s}(t) &= k_i e_y(t) + k_p\dot{e}_y(t)\\ &+ k_d\left(\ddot{y}_r(t) + A_n\dot{y}_m(t) + B_n y_m(t) - C_n u(t) - D(t)\right)\end{aligned} \tag{3}$$

Therefore, an appropriate control law can be designed to ensure that the system satisfies the above second-order sliding mode dynamics.

2.2 Mathematical Model of the PMSM

The dynamic model of the surface-mounted PMSMs can be expressed as:

$$\begin{cases}\dfrac{di_d}{dt} = \dfrac{1}{L_d}\left(u_d - R_s i_d + L_q n_p \omega i_q\right)\\ \dfrac{di_q}{dt} = \dfrac{1}{L_q}\left(u_q - R_s i_q - L_d n_p \omega i_d - n_p \omega \psi_f\right)\\ \dfrac{d\omega}{dt} = \dfrac{1}{J}\left(1.5 n_p \psi_f i_q - B\omega - T_L\right)\end{cases} \tag{4}$$

where n_p is the number of pole pairs, ψ_f is 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 stator voltages and currents in d-q reference frame; and R_s and L_s are the stator resistance and inductance, respectively.

3. Design of the Proposed SOSMC and SMDO

3.1 Design of the Adaptive Convergence SOSMC

Defined the speed tracking error $e(t) = \omega_{ref} - \omega$, where ω_{ref} and ω denote the reference motor speed and the actual motor speed, respectively. To facilitate the subsequent derivation, an intermediate variable $e_1(t)$, is introduced and defined as in (5), where θ_{temp} is an intermediate variable with the same dimension as the position signal, and θ denotes the actual motor position.

$$\begin{cases} e(t) = \omega_{ref} - \omega(t) = \dot{e}_1(t)\\ e_1(t) = \theta_{temp} - \theta(t)\end{cases} \tag{5}$$

According to (4), we can obtain (6), where K_t represents $(3n_p\psi_f)/2$ and $u(t)$ is the control input:

$$\ddot{e}_1 = \dot{\omega}_{ref} - \dot{\omega} = \dot{\omega}_{ref} - \frac{K_t}{J}u(t) + \frac{B}{J}\omega + \frac{1}{J}T_L \tag{6}$$

Consider (2) and (3), then substitute into (6) to obtain:

$$\ddot{s} + \beta\dot{s} = k_i e_1 + k_p\dot{e}_1 + k_d\left(\dot{\omega}_{ref} - \frac{K_t}{J}u(t) + \frac{B}{J}\omega + \frac{1}{J}T_L\right) \tag{7}$$

The adaptive convergence parameter $\beta(t)$ in the I-SOSMC is designed as follows:

$$\beta(t) = \beta_{base} - \Delta\beta + \left(\frac{\Delta\beta}{1+\gamma\left|\hat{d}(t)\right|}\right) \tag{8}$$

where β_{base} and $\Delta\beta$ denote the nominal value of β and its variation range, γ is the disturbance gain coefficient, and $\hat{d}(t)$ represents the online disturbance estimate.

Based on the above expression, and consider (7), the final output expression for the proposed improved SOSMC is designed as (9) with $\lambda_1 > 0$:

$$\begin{aligned} u_{I-SOSMC} &= \lambda_1 s + k_{sI}\, sigmoid(\dot{s}) +\\ &\frac{J}{k_d K_t}\left[k_i e_1 + k_p\dot{e}_1 + k_d\left(\dot{\omega}_{ref} + \frac{B}{J}\omega\right) - \beta\dot{s}\right]\end{aligned} \tag{9}$$

The switching gain term is designed as k_{sI} (S), which is a variable gain function dependent on the sliding-mode state vector. The expression of k_{sI} (S) is designed as (10) with $k_s \in \Re^+$ and $r > 0$.

$$k_{sI}(S) = \begin{cases}\left(\dfrac{\|S\|}{r}\right)k_s, & \|S\| > r\\ k_s, & \|S\| \leq r\end{cases} \tag{10}$$

Here, $S(t)$ is the $n\times1$ sliding-mode state vector of the system, where n=2 for the SOSMC. The $S(t)$ satisfies $S_1(t) = s(t)$, and $\|S\|$ is defined as the Euclidean norm of $S(t)$.

$$\|S\| = \sqrt{\sum_{i=1}^{n} S_i(t)^2} = \sqrt{s(t)^2 + \dot{s}(t)^2 + \cdots s^{(n-1)}(t)^2} \tag{11}$$

In this expression, the parameter r denotes the radius of a generalized convergence region within the allowable error range. Within this region, the switching gain. k_{sI} (S) is maintained at a level that allows the system to converge globally. Outside this radius, the size of the gain is determined by $S(t)$. Specifically, when $\|S\|$ exceeds r, $k_{sI}(S)$ increases gradually with $\|S\|$. When the system is subjected to a sudden disturbance, the $S(t)$ usually changes abruptly, causing the system state to deviate significantly from the equilibrium point. In this case, the increase in $\|S\|$ leads to a corresponding increase in k_{sI} (S), thereby enhancing the disturbance rejection capability. The sigmoid function is adopted as follows, ρ is an adjustable constant.

$$sigmoid(\dot{s}) = \frac{2}{\exp(-\rho\dot{s})+1} - 1 \tag{12}$$

3.2 Stability Proof of the Proposed SOSMC

To verify the stability of proposed I-SOSMC by using Lyapunov method. The Lyapunov function is defined as:

$$V = \frac{1}{2}s^2(t) + \frac{1}{2}\dot{s}^2(t) \tag{13}$$

Taking the time derivative of (13) and substituting (7) and (9), the Lyapunov function can be further expressed as:

$$\begin{aligned}\dot{V}(t) &= s(t)\dot{s}(t) + \dot{s}(t)\ddot{s}(t)\\ &= s(t)\dot{s}(t) + \dot{s}(t)\left(k_i e_1 + k_p \dot{e}_1 + k_d \ddot{e}_1 - \beta(s,\dot{s})\dot{s}(t)\right)\\ &= \dot{s}(t)\left(s(t) - k_d K_t J^{-1}\lambda_1 s(t) + k_d T_L J^{-1} - k_d K_t J^{-1} k_{sI}\, sigmoid(\dot{s})\right)\\ &= (1 - k_d K_t J^{-1}\lambda_1)\dot{s}(t)s(t) + \dot{s}(t)k_d J^{-1}(T_L - K_t k_{sI}\, sigmoid(\dot{s}))\end{aligned} \tag{14}$$

According to the system characteristics, four specific cases can be considered:

$$\begin{aligned}&\text{If } \dot{V}(t) < 0, \text{then:}\\ &case1: s(t)>0, \dot{s}(t)>0 \Rightarrow (1-k_d K_t J^{-1}\lambda_1) \le 0, K_t k_{sI} > |D_{\max}|\\ &case2: s(t)>0, \dot{s}(t)<0 \Rightarrow (1-k_d K_t J^{-1}\lambda_1) \ge 0, K_t k_{sI} > |D_{\max}|\\ &case3: s(t)<0, \dot{s}(t)<0 \Rightarrow (1-k_d K_t J^{-1}\lambda_1) \le 0, K_t k_{sI} > |D_{\max}|\\ &case4: s(t)<0, \dot{s}(t)>0 \Rightarrow (1-k_d K_t J^{-1}\lambda_1) \ge 0, K_t k_{sI} > |D_{\max}|\end{aligned} \tag{15}$$

where $D_{\max}$ represents maximum value of the disturbance. Since $V(0) = 0$ and $V(t) > 0$ for $s(t) \neq 0$, $\dot{s}(t) \neq 0$, the Lyapunov stability condition can be analyzed accordingly. Considering the condition $\lambda_1 = J/(k_d K_t)$, which represents the most stringent constraint for λ_1, and assuming $k_{sI} > |D_{\max}|/K_t$, the condition for λ_1 can be derived as (16).

$$\frac{J}{k_d K_t} - \frac{\zeta}{|s_{\max}|K_t} < \lambda_1 < \frac{J}{k_d K_t} + \frac{\zeta}{|s_{\max}|K_t}, \zeta = \left|K_t k_{sI} - |D_{\max}|\right| \tag{16}$$

where $|s_{\max}|$ is the maximum value of $s(t)$ during the control process, and ζ is given by (16). Under these conditions, the Lyapunov stability condition is satisfied. Therefore, the system state variables converge to zero within a finite time.

3.3 Design of the Sliding Mode Disturbance Observer

In this section, the I-SMDO is designed to estimate the lump disturbance $d(t)$. The estimated disturbance is then used as feedback in the I-SOSMC controller. The extended state-space model of the system can be written as (17):

$$\begin{bmatrix}\dot{\omega}\\ \dot{d}\end{bmatrix} = \begin{bmatrix}-\frac{B}{J} & -\frac{1}{J}\\ 0 & 0\end{bmatrix}\begin{bmatrix}\omega\\ d\end{bmatrix} + \begin{bmatrix}\frac{3n_p}{2J}\psi_f\\ 0\end{bmatrix} i_q \tag{17}$$

According to (4), the state-space equations of I-SMDO can be expressed as (18):

$$\begin{bmatrix}\dot{\hat{\omega}}\\ \dot{\hat{d}}\end{bmatrix} = \begin{bmatrix}-\frac{B}{J} & -\frac{1}{J}\\ 0 & 0\end{bmatrix}\begin{bmatrix}\hat{\omega}\\ \hat{d}\end{bmatrix} + \begin{bmatrix}\frac{3n_p}{2J}\psi_f\\ 0\end{bmatrix} i_q + \begin{bmatrix}1\\ l\end{bmatrix} u_{smo}(e_m) \tag{18}$$

where $\hat{\omega}$ and $\hat{d}(t)$ are the estimate values of ω and $d(t)$, respectively. Define $e_m = \omega - \hat{\omega}$ and $e_f = d(t) - \hat{d}(t)$. Subtracting (18) from (17) yields the observer error dynamics as:

$$\begin{cases}\dot{e}_m = -\frac{B}{J}e_m - \frac{1}{J}e_f - u_{smo}(e_m)\\ \dot{e}_f = -l u_{smo}(e_m)\end{cases} \tag{19}$$

where l indicates the observer gain. The sliding mode surface is selected as [48] with $c_m > 0$:

$$s_1 = e_m + c_m \int_0^t e_m dt \tag{20}$$

Therefore, the control law of I-SMDO is designed as follows:

$$u_{smo}(e_m) = \left(c_m - \frac{B}{J}\right)e_m + \text{SMRL}(s_1) \tag{21}$$

The novel SMRL is given by (22), with $k_0 > 0$, $k_1 > 0$ and $b > 0$, and "e" denotes the base of the natural logarithm.

$$\text{SMRL}(s) = -\xi\,\text{sgn}(s) - k_0 s - k_1(\mathrm{e}^{b|s|} - 1)\,\text{sgn}(s)\cdot\chi \tag{22}$$

Moreover, ξ is designed to satisfy $\xi_2 > \xi_1 > 0$ and $a > 0$, which is expressed as (23), where χ denotes a judgement condition of SMRL to indicate the value of s_1.

$$\xi = \begin{cases}\xi_2\left(\frac{|s_1|}{|s_1| + a}\right), & \xi \ge \xi_1\\ \xi_1, & \xi < \xi_1\end{cases};\ \chi = \begin{cases}1, & |s_1| \ge a\\ 0, & \text{else}\end{cases} \tag{23}$$

3.4 Stability Proof of the Proposed SMDO

To prove the stability of the I-SMDO, the Lyapunov function is selected as follows:

$$V_1 = \frac{1}{2}s_1^2(t) \tag{24}$$

According to (20)-(22) and differentiate (24), we can get

$$\begin{aligned}\dot{V}_1 = s_1\dot{s}_1 &= s_1\left[-\frac{1}{J}e_f + \text{SMRL}(s_1)\right]\\ &= s_1\left[-\frac{1}{J}e_f - \xi\,\text{sgn}(s_1)\right] + f(s_1)\\ &\le s_1\left[-\frac{1}{J}e_f - \xi\,\text{sgn}(s_1)\right] < -\xi_0|s_1| < 0\end{aligned} \tag{25}$$

The expression for $f(s_1)$ is as follows:

$$f(s_1) = -k_0 s_1^2 - k_1(\mathrm{e}^{b|s_1|} - 1)|s_1|\cdot\chi \le 0 \tag{26}$$

To satisfy the finite-time Lyapunov stability theory, the value range of ξ must be satisfied as follows:

$$\xi - \frac{|e_f|}{J} \ge \xi_1 - \frac{|e_f|}{J} > \xi_0 > 0 \tag{27}$$

The parameter ξ_0 represents the lower limit of ($\xi - |e_f|$), and ξ_0, ξ_1 satisfy the above equation, where $\xi_2>\xi_1>\xi_0$. Under the control law u_{smo} (21), the state variables of the system would converge to zero within finite time.

4. Simulation Verification

To verify the effectiveness of the proposed I-SOSMC method, simulations are carried out and the results are compared with those of a PI controller, conventional SMC, and the SOSMC in [45]. The control structure of the PMSM speed regulation system based on the proposed method is shown in Fig.1. The PMSM parameters used in the simulations are listed in [46]. According to the analysis in the previous section, the controller parameters are selected as follows: for the I-SOSMC: β_{base}=160, $\Delta\beta$=80, γ=10, k_s=0.5, λ_1=1000, r=0.03, k_p=19.5, k_i=0.05 and k_d=0.45. The SOSMC adopts the same parameters whenever applicable. The disturbance observer is designed with ξ_1=100, ξ_2=500, k_0=3000, k_1=5000, a=0.8, b=5, c_m=500 and l=800. In the simulation, the reference speed steps from 0 r/min to 1000 r/min. At 0.3s, a sudden load disturbance of 2 N·m is applied and maintained for 0.4, and then removed at 0.7s.

The simulation results in Fig. 2 show that all four methods can track the reference speed. The PI controller and SOSMC exhibit noticeable overshoot, whereas the conventional SMC and the proposed I-SOSMC achieve reference speed without overshoot. Fig. 3 illustrates the online adjustment process of the convergence parameter according to the estimated disturbance level. It can be observed that when the disturbance is small, $\beta(t)$ remains almost unchanged at its nominal value. Once the disturbance is applied, however, $\beta(t)$ decreases rapidly to nearly 50% of its original value. This adaptive variation is beneficial for suppressing disturbance-induced fluctuations and improving the disturbance rejection capability of the proposed controller [46].

Under sudden load disturbance, the proposed I-SOSMC decreases the settling time from 56.39 ms to 1.41 ms and reduces the maximum speed drop from 113.2 r/min (11.32%) to 4.56 r/min (0.46%). This corresponds to a 97.5% reduction in settling time and a 96.0% reduction in speed sag. The comparisons for Fig. 2 (a) are summarized in Table I. It is evident that the proposed method offers improved tracking performance and enhanced disturbance rejection capability for PMSM drive applications.

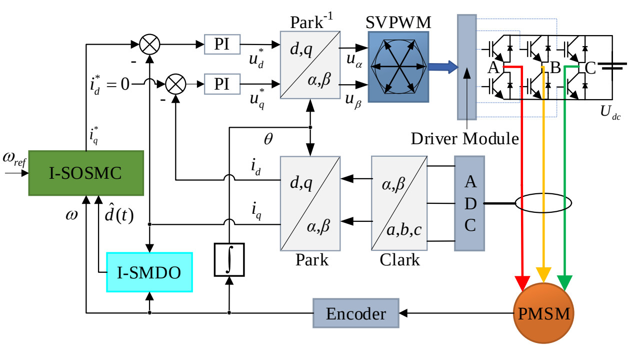

Fig. 1. Block diagram of the PMSM speed regulation system

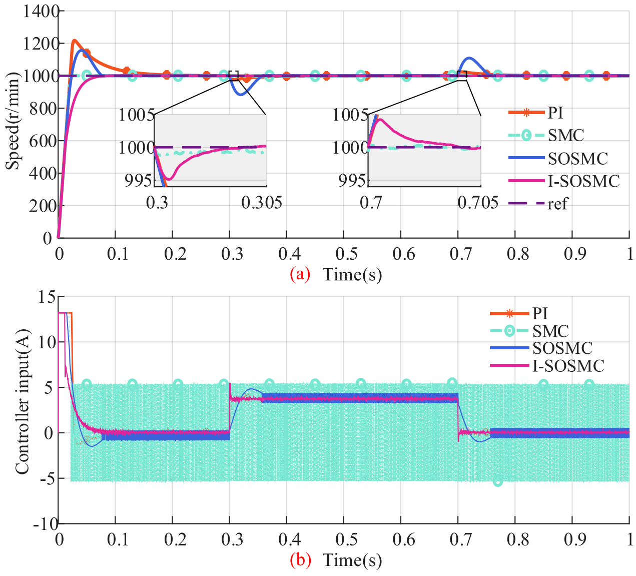

Fig. 2. The speed response and control input under different controllers: (a) speed curves, (b) control input.

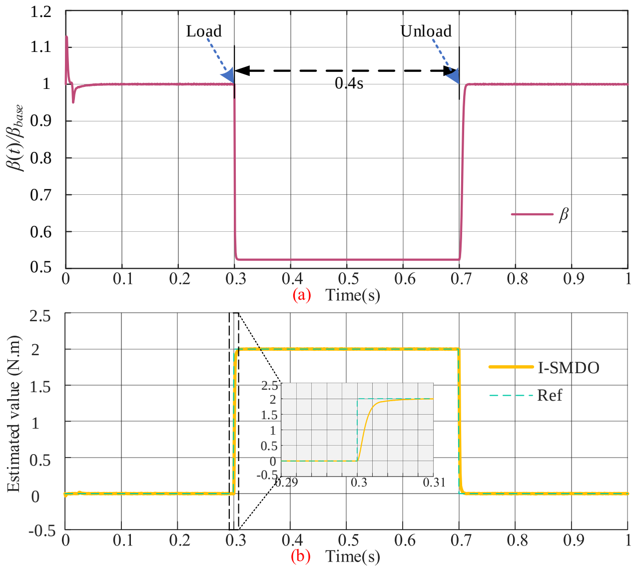

Fig. 3. Curves of the adaptive convergence mechanism: (a) curves of $\beta(t)/\beta_{base}$, (b) estimated values of I-SMDO.

TABLE I
PERFORMANCE COMPARISONS OF CONTROLLERS

Controller	Overshoot (%)	Speed Drop (r/min)	Settling Time (ms)
PI	21.78	24.35	118.30
SMC	0.03	0.94	N/A
SOSMC	15.61	113.20	56.39
I-SOSMC	0.10	4.56	1.41

From the quantitative comparisons in Table I indicate that, although conventional SMC also performs good disturbance rejection capability, the control input shown in Fig. 2 suffers from pronounced chattering, which is detrimental to practical PMSM drive systems. In contrast, the proposed I-SOSMC significantly alleviates the chattering phenomenon while preserving strong disturbance rejection.

5. Conclusion

This paper proposes an improved adaptive convergence second-order sliding mode control (I-SOSMC) scheme based on a PID-type sliding mode surface for PMSM drives. To further improve disturbance rejection, an improved sliding mode disturbance observer (I-SMDO) based on a novel sliding mode reaching law (SMRL) is integrated into the proposed scheme. Moreover, an adaptive convergence mechanism is introduced to adjust the convergence parameter online according to the estimated disturbance level, thereby enhancing disturbance rejection and suppressing chattering simultaneously. Simulation results show that the proposed method reduces the settling time from 56.39 ms to 1.41 ms and decreases the maximum speed drop from 11.32% to 0.46%. Therefore, the proposed method achieves fast dynamic response, strong disturbance rejection, and reduced chattering, which demonstrates its potential for high-performance PMSM drive systems.

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