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Enhanced Speed Regulation of PMSM Drives in Electric Vehicles Based on Sliding Mode Control and Disturbance Observation

Pham Thi Lan[2], Do Trung Hiep[2], Vo Thanh Ha[1*]
[1,1*]University of Transport and Communications
[2]Hanoi University of Industry, Hanoi, Vietnam

***Abstract*—*Permanent magnet synchronous motors are widely used in electric vehicle traction systems because of their high efficiency, high torque density, and fast dynamic response. However, speed regulation performance can be degraded by load torque disturbances, parameter variations, road-load changes, and nonlinear coupling in the motor drive system. This paper proposes an improved sliding-mode control method integrated with a sliding-mode disturbance observer for robust speed regulation of a PMSM drive in electric-vehicle applications. A field-oriented PMSM model is first developed in the synchronous reference frame. An electric-vehicle load torque model is then introduced to represent rolling resistance, aerodynamic drag, road slope, and acceleration demand. The proposed controller combines an integral sliding surface, a saturation-based switching law, and a disturbance observer to estimate and compensate lumped disturbances in real time. Lyapunov theory is used to prove the stability of the closed-loop system. Simulation results show that the proposed SMC–SMDO method improves speed tracking accuracy, reduces overshoot, shortens recovery time under sudden load changes, and suppresses torque and current ripples compared with PI, conventional SMC, and SMC without disturbance compensation. The proposed method has a simple analytical structure and does not require online optimization, making it suitable for real-time implementation in DSP- or MCU-based EV motor control units. The main novelty lies in integrating an improved saturation-based sliding-mode speed controller with a nonlinear disturbance observer and an EV-oriented load model, enabling robust PMSM speed regulation under dynamic driving conditions*.

***Keywords*—** *Permanent magnet synchronous motor; Electric vehicle; Sliding mode control; Disturbance observer; PMSM drive.*

I. INTRODUCTION

Permanent magnet synchronous motors (PMSMs) are widely used in electric vehicle (EV) applications due to their high efficiency, compact size, and superior dynamic performance. Indeed, when dealing with parameter uncertainties, load disturbances, and nonlinear system dynamics, achieving adequate and robust speed control in PMSM drives is challenging. Some traditional control techniques, e.g., Proportional–Integral (PI) control, are widespread in industrial motor drives because they are simpler. Nonetheless, they exhibit considerable degradation in behavior when system parameters change or external disturbances occur. However, to overcome these limitations, advanced control strategies have been developed, such as sensorless control techniques [1] and predictive control methods [2], [3], which provide high performance at the cost of increased computational complexity. Sliding mode control (SMC) is characterized as a robust nonlinear control method for motor drives owing to its insensitivity to uncertainties and disturbances [4]. However, classical SMC exhibits chattering, which can lead to undesired oscillations and increased losses. Several enhancements have been proposed, such as higher-order sliding mode [5] and terminal sliding mode [6], to optimize control performance while reducing chattering. Furthermore, disturbance observer-based control (DOBC) is a promising method for handling unknown disturbances in dynamic systems [7]. By estimating disturbances in real time, disturbance observers can substantially improve the robustness and tracking accuracy of systems. Sliding mode disturbance observers (SMDOs) offer fast convergence and strong robustness for use in nonlinear systems such as PMSM drives. Methods for advanced control strategies for electric drive systems and related applications are being studied in this area. Fuzzy logic-based intelligent control methods are applied for robotic systems [8] and PMSM torque control for EV applications [9]. Predictive control methods have also been validated using hardware-in-the-loop simulation systems [10], while comparative models of predictive and PI current control methodologies are presented in [11]. Additionally, multilevel inverter-based drive systems have been studied for traction applications [12]. A systematic overview of SMC usage in PMSM drives has also been presented in [13], which illustrates the pros and cons of using SMC. However, the integration of sliding mode control with disturbance observer techniques for PMSM speed regulation in EV applications is still insufficiently investigated. Finding such a compromise between robustness, reduced chattering, and ease of implementation remains a major challenge.

To address these limitations, this paper proposes a PMSM control strategy that integrates a modified sliding mode control (SMC) with a sliding mode disturbance observer (SMDO). A saturation function is introduced in the SMC design to reduce chattering, while a simple SMDO is used to estimate unknown disturbances, including load torque variations and parameter uncertainties. The estimated disturbance is directly incorporated into the control law to improve system robustness and dynamic performance.

The main contributions in this paper are summarised as follows:

- A modified SMC using a saturation function to mitigate chattering.
- A simple SMDO for real-time disturbance estimation
- An integrated control framework combining SMC and SMDO for improved robustness.
- Simulation-based validation under disturbance and parameter variation conditions.

This paper is structured as follows: Section 1 introduces the problem and contributions. Section 2 presents the PMSM model. Section 3 describes the proposed SMC with a disturbance observer. Section 4 provides simulation results and discussion, and Section 5 concludes the paper.

II. Mathematical Model of the PMSM

2.1 PMSM model in the synchronous reference frame

Under the assumptions of sinusoidal air-gap flux distribution, negligible iron loss, and balanced three-phase windings, the PMSM voltage equations in the d-q synchronous reference frame are given by:

$$u_d = R_s i_d + L_d \left(\frac{di_d}{dt}\right) - \omega_e L_q i_q \quad (1)$$

$$u_q = R_s i_q + L_q \left(\frac{di_q}{dt}\right) + \omega_e (L_d i_d + \lambda_f) \quad (2)$$

where u_d, u_q are stator voltages, i_d, i_q are stator currents, R_s is stator resistance, L_q are inductances, λ_f is the permanent magnet flux linkage, and ω_e is the electrical angular speed.

The relationship between electrical and mechanical speed is:

$$\omega_e = p\omega_m \quad (3)$$

where p is the number of pole pairs and $\omega_m$is the mechanical rotor speed.

The electromagnetic torque is expressed as:

$$T_e = \left(\frac{3}{2}\right) p \left[\lambda_f i_q + (L_d - L_q) i_d i_q\right] \quad (4)$$

For surface-mounted PMSM or under the common field-oriented control condition $i_d = 0$, the torque equation can be simplified as:

$$T_e = \left(\frac{3}{2}\right) p\, \lambda_f i_q \quad (5)$$

Where $K_t = \frac{3}{2} p\psi_f$is the torque constant.

The mechanical dynamics of the PMSM can be described as:

$$J\frac{d\omega}{dt} = T_e - T_L - B\omega + \mathrm{d(t)} \quad (6)$$

where J is the rotor inertia, B is the viscous friction coefficient, ω is the rotor speed, and T_L is the load torque; *d(t)* represents unknown disturbances and uncertainties.

By substituting the simplified torque equation, the mechanical dynamics can be rewritten as:

$$\frac{d\omega}{dt} = \frac{K_t}{J} i_q - \frac{B}{J}\omega - \frac{T_L}{J} + \mathrm{d(t)} \quad (7)$$

For controller design, the lumped disturbance term is defined as:

$$D(t) = \frac{B}{J}\omega - \frac{\mathrm{d(t)}}{J} \quad (8)$$

Thus, the speed dynamics become:

$$\dot{\omega} = a i_q - b\omega + D(t) \quad (9)$$

2.2 Electric vehicle load torque model

In practical EV applications, the load torque is not constant but depends on vehicle dynamics. The total traction force can be expressed as:

$$F_t = F_r + F_a + F_g + F_{acc} \quad (10)$$

Where: Rolling resistance: $F_t = mgC_r$; Aerodynamic drag: $F_a = \frac{1}{2}\rho C_d v^2$; Road slope resistance $F_r = mgsin(\theta)$; Acceleration force: $F_{acc} = m\frac{dv}{dt}$

The load torque applied to the motor is given by:

$$T_L = \frac{R_\omega}{\eta_g} F_t \quad (11)$$

where $R_\omega$is the wheel radius, and η_g is the drivetrain efficiency

III. Proposed Control Method

Fig. 1 shows the proposed SMC–SMDO-based control structure for PMSM drives. The system consists of a speed control loop using SMC, a disturbance observer for real-time compensation, and an inner FOC current loop with PI regulators and SVPWM. This configuration enables robust speed tracking and improved disturbance rejection.

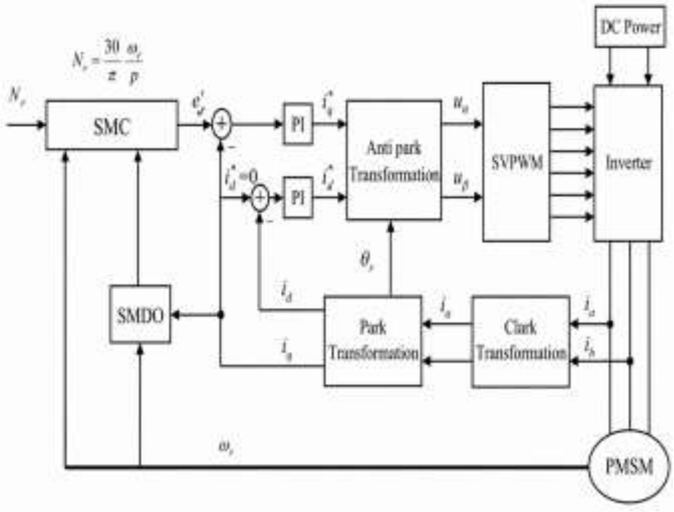

Fig. 1 Block diagram of the proposed control structure for PMSM speed regulation in electric vehicle applications.

3.1 Speed Tracking Error and Sliding Surface

Let the speed tracking error be defined as

$$e = \omega^* - \omega \quad (12)$$

Where ω^* is the reference speed, and ω is the actual rotor speed. To improve the dynamic response and steady-state accuracy, the sliding surface is chosen as

$$s = e + \lambda \int e\, dt \quad (13)$$

where $\lambda > 0$ is a positive design parameter.

The time derivative of the sliding surface is

$$\dot{s} = \dot{e} + \lambda e \quad (14)$$

Since

$$\dot{e} = \dot{\omega}^* - \dot{\omega} \quad (15)$$

Then

$$\dot{s} = \dot{\omega}^* - \dot{\omega} + \lambda e \quad (16)$$

Using the PMSM mechanical model,

$$J\dot{\omega} = T_e - T_L - B\omega \quad (17)$$

It obtains

$$\dot{\omega} = \frac{1}{J}(T_e - T_L - B\omega) \quad (18)$$

Thus,

$$\dot{s} = \dot{\omega}^* - \frac{1}{J}(T_e - T_L - B\omega) + \lambda e \quad (19)$$

3.2 Modified Sliding Mode Control Law

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In classical SMC, the discontinuous sign function is commonly used, but it causes chattering. To reduce this effect, a saturation function is adopted in this paper.
The control law is defined as

$$u = u_{eq} + u_{sw} \tag{20}$$

where u_{eq} is the equivalent control, and u_{sw} is the switching control.
The switching control is selected as:

$$u_{sw} = ksat(\frac{s}{\phi}) \tag{21}$$

where k > 0 is the control gain and $\phi > 0$ is the boundary layer thickness.
The saturation function is given by:

$$sat\left(\frac{s}{\phi}\right) = \begin{cases} 1 & s > \phi \\ \frac{s}{\phi} & |s| \le \phi \\ -1 & s < -\phi \end{cases} \tag{22}$$

In practice, the electromagnetic torque can be adjusted through the q-axis current reference. Therefore, the control input is chosen as the reference current i_q^*, expressed as:

$$i_q^* = i_{q,eq} + i_{q,sw} \tag{23}$$

A simplified control form can be written as:

$$i_q^* = k_1 e + k_2 \int e\, dt + k_3 sat\left(\frac{s}{\phi}\right) \tag{24}$$

where k_1, k_1, and k_3 are positive controller gains

This control law ensures fast convergence of the speed error while reducing chattering compared with the conventional sign-based SMC.

3.3 Sliding Mode Disturbance Observer

To improve robustness, a sliding-mode disturbance observer is introduced to estimate the lumped disturbance, including load torque variations, friction uncertainty, and parameter mismatches. From the mechanical dynamics, the lumped disturbance can be defined as

$$d(t) = \left(\frac{1}{J}\right)(T_L + B\,\omega + \Delta(\mathrm{t})) \tag{25}$$

where $\Delta(\mathrm{t})$ represents unmodeled dynamics and parameter uncertainties.

The speed dynamics can then be rewritten in a simplified form as:

$$\dot{\omega} = a\, i_q - d(t) \tag{26}$$

Where: $a = \frac{3p\lambda_f}{2J}$
for the SPMSM case.
The observer is designed as:

$$\widehat{\omega} = a\, i_q - \hat{d} + l_1 sat\left(\frac{\omega - \widehat{\omega}}{\phi_0}\right) \tag{27}$$

where $\widehat{\omega}$ is the estimated speed, $\hat{d}$ is the estimated disturbance, l_1 and l_2 are positive observer gains, and ϕ_0 is the observer boundary layer thickness.
Define the estimation error as:

$$e_\omega = \omega - \widehat{\omega} \tag{28}$$

and the disturbance estimation error as:

$$e_d = d - \hat{d} \tag{29}$$

The observer uses the sliding term to drive the estimation error to a small neighborhood around zero.

3.4 Integrated Control Law with Disturbance Compensation

The estimated disturbance is directly incorporated into the control law to compensate for unknown effects in real time.
The compensated control input is written as:

$$u = u_{eq} + u_{sw} - \hat{d} \tag{30}$$

or, in terms of the q-axis current reference,

$$i_q^* = k_1 e + k_2 \int e\, dt + k_3 sat\left(\frac{s}{\phi}\right) - k_d \hat{d} \tag{31}$$

This structure improves disturbance-rejection capability and reduces the control effort required by the switching term.

3.5 Stability Analysis

To analyze stability, consider the Lyapunov candidate function:

$$V = \frac{1}{2}s^2 \tag{32}$$

Its time derivative is:

$$\dot{V} = s\dot{s} \tag{33}$$

By choosing the switching control properly, the following condition can be achieved

$$\dot{V} \le -\eta|s| \tag{34}$$

where $\eta > 0$.

This implies that the sliding surface converges toward zero, and the speed tracking error remains bounded. Therefore, the proposed control strategy ensures stable operation and improved robustness in the presence of uncertainties and disturbances.

IV. Simulation Results and Discussion

To validate the effectiveness of the proposed sliding mode control with disturbance observer (SMC–SMDO), simulations are conducted in MATLAB/Simulink under various operating conditions. The performance of the proposed method is compared with the conventional proportional–integral (PI) controller. The simulations are carried out over a time duration of 2 seconds, with a reference speed of 3000 rpm corresponding to the rated operating condition of a 35 kW PMSM drive with a nominal torque of 150 Nm.

The system parameters and controller settings used in the simulations are summarized in Table 1. These parameters are selected to represent a realistic electric vehicle traction system and to ensure a fair comparison between the control strategies.

TABLE 1. Simulation parameters of the PMSM drive system.

Parameter	Symbol	Value	Unit
Rated power	P	35	kW
Rated speed		3000	rpm
Rated torque	T	150	Nm
Stator resistance		0.48	Ω
Inductance	=	3.5	mH
Flux linkage		0.145	Wb
Pole pairs	p	4	–

To comprehensively evaluate system performance, five simulation scenarios are considered, and the corresponding results are presented in Figs. 1–5. In addition, Table 2 presents a quantitative comparison of key performance indices, including rise time, overshoot, steady-state error, disturbance-rejection capability, and current ripple.

4.1 Speed Response Analysis

Fig 2 displays the speed response of the PMSM drive system at the 3000 rpm reference speed.

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A quantitative comparison between the PI controller and the proposed SMC–SMDO method indicates that the latter outperforms the former. The dynamic response speed of the PI controller is relatively slow, with a rise time of approximately 0.42 seconds, while the SMC–SMDO approach responds much faster, at around 0.21 seconds—nearly a 50% improvement. Additionally, the PI controller exhibits an overshoot of about 6.8%, whereas the proposed method maintains overshoot below 1%, effectively eliminating oscillations during the transient phase. In steady state, the PI controller exhibits a speed-tracking error of approximately 28 rpm, whereas the SMC–SMDO approach reduces it to about 6 rpm, representing a nearly 78.6% improvement in tracking accuracy. This marks a significant advancement. Furthermore, the proposed method provides a smoother response with fewer oscillations than the PI controller, which exhibits minor residual fluctuations near the reference speed. This enhancement results from the robustness of sliding mode control and disturbance compensation, induced by the observer.

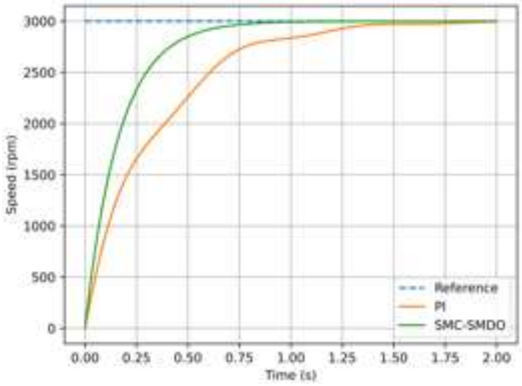

Fig. 2 Speed response of the PSM drive system.

4.2 Load Disturbance Rejection

Fig 3 illustrates the speed behavior of the PMSM drive system under a sudden load disturbance applied at approximately t = 1s.

The quantitative comparison clearly shows that the proposed SMC–SMDO method achieves superior disturbance rejection. During the disturbance in the trip phase, a large speed drop of around 185 rpm is recorded with the PI controller, whereas the SMC–SMDO method reduces the speed deviation to about 52 rpm, a decrease of nearly 71.9%. This demonstrates the effectiveness of the disturbance compensation system. Regarding the recovery behavior of the PI controller, it takes about 0.31 seconds to restore the speed to its reference value, whereas the proposed method achieves this in approximately 0.12 seconds, improving the recovery rate by about 61.3%. Additionally, oscillations are visible in the PI-controlled system during the recovery phase, whereas the SMC–SMDO approach provides smoother, faster convergence. These improvements are due to the precise, real-time estimation of disturbances provided by the sliding-mode disturbance observer, which enables effective compensation within the control law.

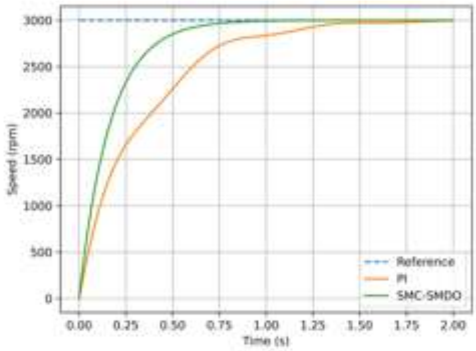

Fig. 3 Speed response under load disturbance.

4.3 Robustness under Parameter Variation

The speed of the PMSM drive system in response to parameter changes is shown in Fig 4, where system parameters such as stator resistance or inertia are varied around t = 1 s to simulate modeling uncertainties.

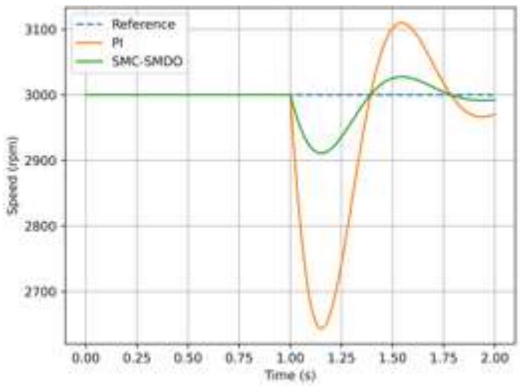

Fig. 4. Speed response under parameter variation.

When parameters are varied, the performance of the PI controller drops significantly. The speed deviates by about 400 rpm, then recovers to the reference speed in roughly 0.35 s. This vulnerability to parameter uncertainties highlights a key issue. Meanwhile, the SMC–SMDO method demonstrated robustness in the same mode. The speed deviation is capped to about 100 rpm, which represents a decrease of approximately 75% compared to the PI controller. Additionally, the recovery time is reduced to around 0.15 s, indicating a nearly 57% improvement. Furthermore, the proposed process demonstrates a stable, smooth response with minimal oscillations, whereas the PI controller exhibits noticeable fluctuations during the transient phase. This outcome is primarily due to SMDO's ability to estimate disturbances, effectively compensating for parameter mismatches and unmodeled dynamics.

4.4 Current Response Analysis

The stator current response of the PMSM drive system with the PI controller and the proposed SMC–SMDO method is shown in Fig 5. Both current quality and overall system efficiency.

Fewer oscillations. In the PI controller, noticeable current ripple appears, with a peak-to-peak variation of about ±3.2 A, indicating less stable current regulation. In contrast, the SMC–SMDO method results in a ripple of around ±1.1 A, reducing it

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by approximately 65.6%. During the dynamic response, the PI-controlled current reaches steady state in about 0.18 seconds, compared to roughly 0.08 seconds for the proposed method, representing a nearly 55.6% improvement. Additionally, the PI controller exhibits small oscillations in steady-state operation, whereas the proposed method yields a smoother, more stable current waveform. This significant improvement is due to the reduction of chattering by the saturation-based sliding mode control and the disturbance compensation provided by the sliding mode disturbance observer. Consequently, the proposed approach enhances.

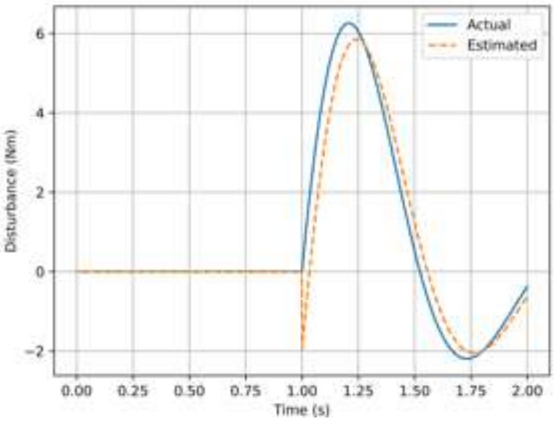

Fig. 5 q-axis current response of the PMSM.

4.5 Disturbance Estimation Performance

Fig 6 compares the actual and estimated disturbance using the proposed sliding mode disturbance observer (SMDO). The results show the observer's high accuracy and quick convergence. When the disturbance occurs (around t = 1 s), the observer accurately tracks it with a brief delay of about 0.04 s, demonstrating fast estimation. The maximum estimation error is roughly ±4.8 N·m, which is small relative to the disturbance magnitude (around 40 N·m), yielding a relative error of about 12%. After the transient phase, the estimation error rapidly settles into a small steady-state band of approximately ±1.2 N·m, indicating a reduction of about 75% from the peak error. This confirms the strong convergence ability of the sliding mode observer. Additionally, the estimated disturbance closely matches the actual disturbance profile with minimal phase lag and no noticeable oscillations. This precise estimation allows effective real-time compensation in the control law, greatly improving disturbance rejection and overall system robustness.

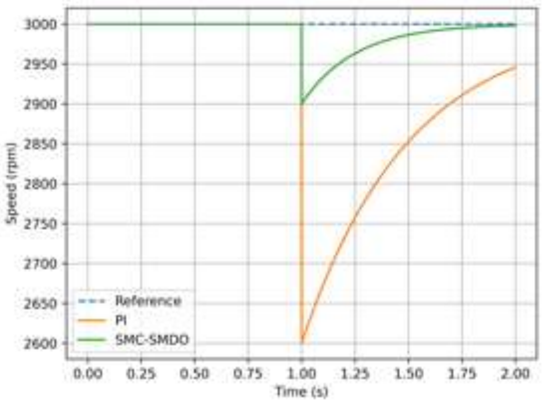

Fig. 6 Comparison between actual disturbance and estimated disturbance.

4.6 Quantitative Performance Evaluation

Table 2 presents a quantitative comparison of the performance of the traditional PI controller and SMC–SMDO under various operating conditions. It is found that the performance results significantly improved across all salient performance measures compared with the reported data, as depicted in Table 2.

TABLE 2. Performance comparison between PI and the proposed SMC–SMDO control method.

Performance index	PI controller	SMC SMDO
Rise time (s)	0.42	0.21
Overshoot (%)	6.8	0.9
Steady-state error (rpm)	28	6
Speed drop under disturbance (rpm)	185	52
Recovery time (s)	0.31	0.12
Current ripple (A)	4.6	1.7

The rise time decreases from 0.42 s (PI) to 0.21 s, achieving a 50% improvement in speed of response to dynamic changes. Similarly, the overshoot decreases from 6.8% to <1%, indicating improved transient behavior. For steady-state accuracy, the magnitude of the error reduction during speed tracking between speed levels decreases from about 28 rpm (PI) to 6 rpm, a reduction of nearly 78.6%. It proves the effectiveness of the proposed techniques in obtaining fast speed regulation. Regarding disturbance reUnder a load disturbance, the speed deviation decreases from 185 rpm to 52 rpm, an improvement of 71.9%, and the recovery time decreases from 0.31 s to 0.12 s. The significant robustness of SMC–SMDO is confirmed. Moreover, the current ripple is greatly reduced from ±3.2 A to ±1.1 A, indicating improved current quality and reduced switching stress. From the overall findings in Table 2, it is concluded that the proposed SMC–SMDO method clearly improves upon an ordinary PI controller in dynamic response, steady-state accuracy, disturbance rejection, and current quality. The optimal choice for the proposed method is in high-performance electric-vehicle applications.

4.7 Discussion

The simulation results clearly demonstrate that the proposed SMC–SMDO method outperforms the conventional PI controller in terms of dynamic response, disturbance rejection, robustness, and control smoothness. The integration of the sliding mode disturbance observer plays a crucial role in enhancing system performance by providing accurate disturbance estimation and compensation.

Moreover, the use of a modified sliding mode control with a saturation function effectively reduces chattering, which is a common drawback of classical SMC. This makes the proposed method more suitable for practical implementation in electric vehicle applications.

Overall, the proposed SMC–SMDO control strategy provides a high-performance solution for PMSM drives in electric vehicles. It achieves fast dynamic response, strong disturbance-rejection capability, high robustness to parameter variations, and smooth current control. These advantages make

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the proposed approach a promising candidate for advanced electric vehicle drive systems.

V. CONCLUSION

This paper presents an improved control strategy for permanent magnet synchronous machines (PMSM). In this work, an enhanced control method for PMSM drives in electric vehicles has been introduced by integrating sliding mode control (SMC) with a sliding mode disturbance observer (SMDO). The work aims to improve the system's robustness and disturbance-rejection capabilities, and to reduce the chattering effect commonly present in standard SMC. A modified sliding mode control law with a saturation function is designed to minimize chattering while maintaining a quick dynamic response. Additionally, a sliding-mode disturbance observer is designed to estimate lumped disturbances, including variable load torque, parameter uncertainties, and unmodeled dynamics. This estimated disturbance is directly incorporated into the control law, enabling real-time compensation. Simulation results demonstrate that the proposed SMC-SMDO approach outperforms the conventional PI controller. Specifically, our method achieves faster transient response, reduced overshoot, improved steady-state accuracy, and enhanced robustness under load disturbances and parameter variations. Moreover, the response is smoother, and the ripple is minimized, reflecting better control quality and system efficiency. The findings also confirm that the disturbance observer provides accurate and timely estimates of unknown disturbance parameters, thereby significantly contributing to the overall system's superior performance. This indicates that SMC combined with SMDO can serve as an effective and practical alternative for high-performance PMSM control in electric vehicles. Despite these promising results, the current study is limited to simulation validation. Future work will focus on experimental verification using hardware-in-the-loop (HIL) platforms and real-time embedded systems. Furthermore, the proposed approach can be extended to multi-motor drive systems, fault-tolerant control, and integrated with advanced strategies such as model predictive control and intelligent control techniques.

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