



RESEARCH ARTICLE

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AN ADAPTIVE SLIDING MODE OBSERVER WITH PLL-BASED ESTIMATION FOR SENSORLESS PMSM DRIVES

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ABSTRACT

Permanent magnet synchronous motors (PMSMs) are widely used in high-performance drive systems because of their high efficiency, high torque density, and rapid dynamic response. Field-oriented control (FOC) is the dominant control strategy for such drives, but its performance depends critically on accurate rotor position and speed information. In sensorless PMSM drives, sliding mode observers (SMOs) are attractive because of their robustness and modest computational demand. However, conventional SMOs still exhibit an inherent trade-off between fast convergence and chattering suppression, while direct extraction of rotor position and speed from the estimated back-electromotive-force (back-EMF) signals remains vulnerable to noise and filtering delay. This paper presents a sensorless PMSM drive based on closed-loop FOC and an improved SMO-based estimation scheme. The PMSM is modeled in the synchronous dq reference frame, whereas the observer is constructed in the stationary reference frame from stator current dynamics and back-EMF reconstruction. To improve estimation performance, an adaptive sliding-mode injection gain is introduced to regulate the observer correction level according to the current estimation error, and a smooth switching law is employed to reduce chattering. In addition, a phase-locked loop (PLL) is incorporated to reconstruct the rotor electrical angle and speed from the estimated back-EMF components, thereby improving estimation smoothness and noise immunity. Simulation results obtained in MATLAB/Simulink under start-up, acceleration, steady-state, and load disturbance conditions demonstrate stable drive operation, accurate speed tracking, and improved estimation behavior compared with the conventional SMO. The results confirm that the proposed observer enhances convergence and reduces steady-state oscillations while preserving the simplicity and practical applicability of SMO-based sensorless control for PMSM drives.



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I. INTRODUCTION

Permanent magnet synchronous motors (PMSMs) have become increasingly prevalent in high-performance motion control systems owing to their high efficiency, high torque density, compact structure, and excellent dynamic characteristics [1-3]. Unlike induction motors, PMSMs do not require rotor current excitation, which eliminates rotor copper losses and contributes to higher overall energy efficiency [4]. These characteristics make PMSMs particularly suitable for demanding applications such as robotics, machine tools, electric vehicles, and servo drives, where precise torque control and rapid dynamic response are required [5]. To fully exploit the advantages of PMSMs, advanced control strategies are necessary. Among them, field-oriented control (FOC) has become the dominant approach for high-performance PMSM drives [6] [7]. By transforming the stator currents into a rotor-oriented synchronous reference frame, FOC enables independent regulation of the torque-producing and flux-related current components [2], [8]. For surface-mounted PMSMs, where magnetic saliency is negligible, the electromagnetic torque becomes directly proportional to the q-axis current, while the d-axis current can be regulated to zero [9] [10].

This decoupled control structure simplifies torque control and enables fast dynamic response with high steady-state accuracy. Furthermore, the cascaded architecture of FOC, consisting of an outer speed control loop and inner current control loops, provides a systematic framework for controller design and facilitates integration with pulse-width modulation (PWM) techniques and coordinate transformations [11-13]. Despite the maturity and effectiveness of FOC, its practical implementation generally requires accurate rotor position or speed information [14]. In conventional drive systems, such information is obtained using mechanical sensors such as encoders or resolvers. However, the use of mechanical sensors increases system cost and hardware complexity, introduces additional wiring and installation requirements, and may reduce system reliability in harsh operating environments characterized by high temperature, vibration, or contamination [15-17]. These limitations have motivated extensive research on sensorless control strategies for PMSM drives, in which rotor position and speed are estimated from measured electrical signals together with mathematical models of the machine [18] [19]. Among the various sensorless estimation techniques proposed for PMSMs, sliding mode observers (SMOs) have attracted considerable attention due to their inherent robustness against parameter variations and external disturbances [20-22]. SMO-based estimators employ a discontinuous correction mechanism that forces the estimation error to converge toward a predefined sliding surface, thereby providing strong robustness properties and fast error convergence. In PMSM applications, SMOs are commonly formulated in the stationary reference frame to estimate the back electromotive force (back-EMF) components using measured stator voltages and currents [23-24].

Because the back-EMF inherently carries rotor position information, the rotor electrical angle can subsequently be reconstructed using a phase-locked loop (PLL) or an arctangent-based computation [25]. Compared with other observer-based techniques, such as extended Kalman filters or model reference adaptive systems, SMOs provide an attractive compromise between estimation accuracy, computational complexity, and robustness [26]. In addition, their relatively simple structure facilitates real-time implementation in digital controllers and provides good immunity to parameter uncertainties, particularly variations in stator resistance [27]. Consequently, SMO-based sensorless control has been widely adopted in industrial PMSM drives operating in the medium-to-high speed region, where the back-EMF magnitude is sufficiently large to ensure a reliable signal-to-noise ratio [28]. Despite the robustness and practical simplicity of conventional SMOs, their estimation performance is still limited by the trade-off between fast convergence and chattering suppression. In addition, direct extraction of rotor position and speed from the estimated back-EMF signals remains sensitive to noise and filter-induced phase delay, which may deteriorate estimation smoothness and dynamic performance. Therefore, this paper develops an adaptive sliding-mode observer with a smooth switching law and PLL-based reconstruction for sensorless PMSM drives. The main contribution lies in integrating adaptive injection gain regulation, chattering-reduced switching action, and closed-loop angle/speed estimation into a unified SMO-based sensorless framework, aiming to improve convergence behavior, estimation smoothness, and robustness while preserving implementation simplicity.

II. MATHEMATICAL MODEL OF THE PERMANENT MAGNET SYNCHRONOUS MOTOR

The dynamic model of a three-phase PMSM can be conveniently formulated in the synchronously rotating dq reference frame. By transforming the stator variables into orthogonal direct and quadrature components that rotate synchronously with the rotor magnetic field, the resulting dq-axis quantities become constant under steady-state operating conditions. This representation provides a compact and physically intuitive description of PMSM dynamics and is particularly well suited for analysis and controller design within the framework of FOC. In the synchronous dq reference frame, the stator voltage equations of the PMSM are expressed as:

$$v_{sd} = R_s i_{sd} + \frac{d\psi_{sd}}{dt} - \omega_e \psi_{sq} \quad (1)$$

$$v_{sq} = R_s i_{sq} + \frac{d\psi_{sq}}{dt} + \omega_e \psi_{sd} \quad (2)$$

Where v_{sd} , v_{sq} are the stator voltage components, i_{sd} , i_{sq} are the stator current components, R_s is the stator resistance, ψ_{sd} , ψ_{sq} denote the stator flux linkages, and ω_e is the electrical angular speed of the synchronous reference frame. For a PMSM, the rotor magnetic field is produced by permanent magnets rather than rotor windings. As a result, no rotor voltage equations are involved, and the rotor flux is directly determined by the permanent magnet flux linkage. Accordingly, the stator flux linkages in the dq reference frame can be expressed as:

$$\psi_{sd} = L_d i_{sd} + \psi_f \quad (3)$$

$$\psi_{sq} = L_q i_{sq} \quad (4)$$

Where L_d and L_q are the stator inductances along the d-axis and q-axis, respectively, and ψ_f is the flux linkage produced by the permanent magnets. Substituting (3) and (4) into (1) and (2), the complete electrical model of the PMSM in the dq reference frame is obtained. The electromagnetic torque generated by the PMSM is given by

$$T_e = \frac{3}{2} p (\psi_f i_{sq} + (L_d - L_q) i_{sd} i_{sq}) \quad (5)$$

Where p denotes the number of pole pairs. For surface-mounted PMSMs, where magnetic saliency is negligible and $L_d \approx L_q$, the electromagnetic torque expression simplifies to

$$T_e = \frac{3}{2} p \psi_f i_{sq} \quad (6)$$

Which indicates that the electromagnetic torque is directly proportional to the q-axis current, while the d-axis current does not contribute to torque production. The mechanical dynamics of the PMSM are described by the rotor motion equation

$$J \frac{d\omega_m}{dt} = T_e - T_L - B\omega_m \quad (7)$$

Where J is the total moment of inertia, ω_m is the mechanical angular speed, T_L is the load torque, and B is the viscous friction coefficient. The relationship between electrical and mechanical speeds is given by

$$\omega_e = p \omega_m \quad (8)$$

Equations [1-8] collectively represent the complete mathematical model of the PMSM in the synchronously rotating dq reference frame and provide the foundation for the design and analysis of field-oriented control and sensorless control strategies. The overall closed-loop configuration of the considered PMSM drive is illustrated in Figure 1. In this study, the PMSM drive is operated under a conventional closed-loop field-oriented control (FOC) scheme, in which the measured three-phase stator quantities are transformed into a rotor-aligned synchronous reference frame to enable decoupled regulation of flux and torque components. The control structure adopts the standard cascaded configuration with an outer speed loop and inner current loops, allowing the torque-producing current to be generated from the speed error and the corresponding voltage references to be synthesized for application to the inverter through space-vector pulse-width modulation (SVPWM). Within this framework, a sliding mode observer (SMO) is incorporated for sensorless operation, using the measured stator voltage and current signals in the stationary reference frame to reconstruct the back-EMF components and, from them, estimate the rotor electrical angle and speed. The resulting FOC-based PMSM drive therefore provides the control platform on which the observer design is developed, as presented in the following section.

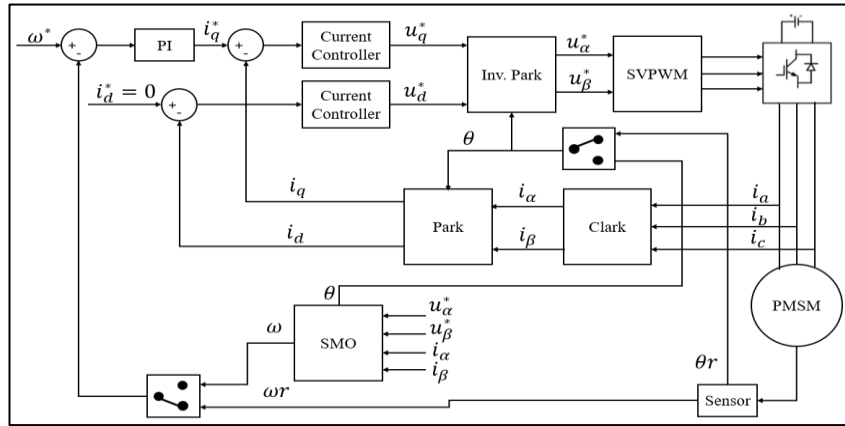


Figure 1: Overall block diagram of the closed-loop FOC PMSM drive with the proposed sliding-mode observer (SMO)-based speed estimation.

Source: Authors, (2026).

III. SLIDING MODE OBSERVER DESIGN

III.1 SLIDING-MODE OBSERVER FOR SENSORLESS SPEED ESTIMATION

In order to establish a baseline for the proposed estimation method, a conventional sliding mode observer (SMO) is first introduced within the FOC-based PMSM drive. The SMO employs the measured stator voltage and stator current signals to estimate the back-electromotive force (back-EMF), rotor electrical angle, and rotor speed. The estimated quantities are analyzed under various operating conditions to characterize the dynamic behavior and estimation capability of the observer within the PMSM drive system. The overall structure of the SMO is illustrated in Figure 2.

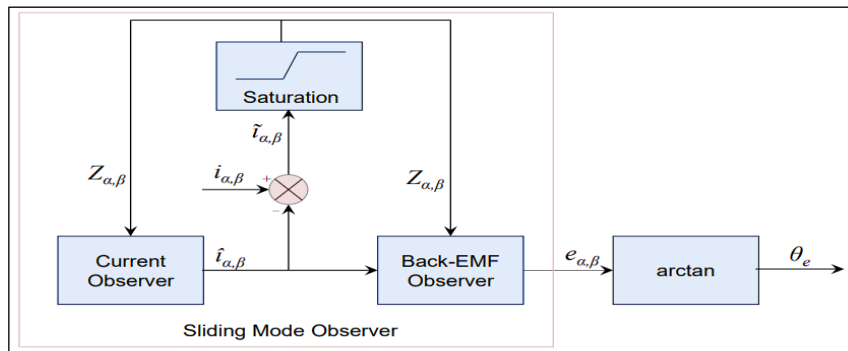


Figure 2: Overall block diagram of the sliding-mode observer –based speed estimation.

Source: Authors, (2026).

The stator phase voltages (u_a, u_b, u_c) are measured at the inverter output terminals and transformed into the stationary reference frame using the Clarke transformation, yielding the stationary voltage components (u_α, u_β). In a similar manner, the measured stator phase currents are converted into the corresponding stationary current components (i_α, i_β). These stationary-frame voltage and current signals constitute the inputs to the sliding mode observer. The sliding mode observer is derived from the stator current dynamics of the PMSM expressed in the stationary $\alpha\beta$ reference frame. Under the assumptions of balanced operation and negligible magnetic saturation, the stator current dynamics can be expressed as

$$\frac{di_\alpha}{dt} = -\frac{R_s}{L_s} i_\alpha + \frac{1}{L_s} u_\alpha - \frac{1}{L_s} e_\alpha \quad (9)$$

$$\frac{di_\beta}{dt} = -\frac{R_s}{L_s} i_\beta + \frac{1}{L_s} u_\beta - \frac{1}{L_s} e_\beta \quad (10)$$

Where R_s and L_s denote the stator resistance and stator inductance, respectively, and e_α, e_β are the back-EMF components in the stationary frame. Within the observer, an estimated current model is constructed using the estimated stator currents $\hat{i}_\alpha, \hat{i}_\beta$ and the estimated back-electromotive-force components $\hat{e}_\alpha, \hat{e}_\beta$. To enhance robustness against parameter uncertainties and external disturbances, the sliding mode observer incorporates a discontinuous correction term driven by the current estimation error. The resulting observer dynamics are expressed as

$$\frac{d\hat{i}_\alpha}{dt} = -\frac{R_s}{L_s} \hat{i}_\alpha + \frac{1}{L_s} u_\alpha - \frac{1}{L_s} v_\alpha \quad (11)$$

$$\frac{d\hat{i}_\beta}{dt} = -\frac{R_s}{L_s} \hat{i}_\beta + \frac{1}{L_s} u_\beta - \frac{1}{L_s} v_\beta \quad (12)$$

Where the discontinuous injection terms v_α and v_β are defined as

$$v_\alpha = K_{sw} \text{sat}(i_\alpha - \hat{i}_\alpha) \quad (13)$$

$$v_\beta = K_{sw} \text{sat}(i_\beta - \hat{i}_\beta) \quad (14)$$

Here, K_{sw} is the sliding-mode gain, and $\text{sat}(\cdot)$ denotes a saturation function introduced to reduce chattering effects compared to an ideal sign function. Under sliding-mode operation, the current estimation errors converge to zero, and the equivalent values of the discontinuous injection terms correspond to the back-electromotive-force components. To mitigate the high-frequency chattering introduced by the sliding-mode action, the signals v_α and v_β are processed through low-pass filters, yielding the estimated back-EMF components as

$$\hat{e}_\alpha = \text{LPF}(v_\alpha), \hat{e}_\beta = \text{LPF}(v_\beta) \quad (15)$$

The cutoff frequency of the low-pass filter is selected as a compromise between effective noise attenuation and acceptable dynamic response. At medium and high operating speeds, where the back-electromotive-force magnitude is sufficiently large, the filtered signals provide reliable information for position and speed estimation. The estimated back-EMF components are subsequently used to reconstruct the rotor electrical angle and rotor speed. The rotor electrical angle is obtained using an arctangent-based calculation given by

$$\hat{\theta}_e = \text{atan2}(\hat{e}_\beta, \hat{e}_\alpha) \quad (16)$$

The electrical angular speed can be obtained either by differentiating the estimated rotor electrical angle or by exploiting the proportional relationship between the back-electromotive-force magnitude and the electrical speed,

$$\hat{\omega}_e \propto \sqrt{\hat{e}_\alpha^2 + \hat{e}_\beta^2} \quad (17)$$

In practical implementations, appropriate scaling and filtering are applied to ensure a smooth and noise-robust speed estimate. The corresponding mechanical rotor speed is then calculated as

$$\hat{\omega}_r = \frac{1}{p} \hat{\omega}_e \quad (18)$$

Where p denotes the number of pole pairs. Despite its simplicity and satisfactory robustness, the conventional SMO still suffers from two inherent drawbacks in practical implementation. First, the use of a fixed switching gain leads to an unavoidable compromise between fast error convergence and chattering attenuation. Second, the direct extraction of rotor position and speed from the estimated back-EMF signals is susceptible to noise contamination and filter-induced phase delay, which may deteriorate estimation smoothness and dynamic performance. To overcome these shortcomings, an improved observer structure is developed in the following subsection by combining an adaptive sliding-mode injection mechanism with a PLL-based position and speed estimation stage.

III.2 PROPOSED ADAPTIVE SMO WITH PLL-BASED ESTIMATION

To address the drawbacks of the conventional sliding-mode observer, an adaptive SMO with PLL-based rotor position and speed reconstruction is developed. The proposed scheme consists of two main improvements. First, an online gain adaptation mechanism is introduced to adjust the observer injection gain according to the magnitude of the current estimation error, thereby improving the trade-off between fast transient convergence and chattering reduction. Second, instead of directly extracting rotor position and speed from the estimated back-EMF components, a phase-locked loop is employed to provide smoother and more noise-resilient estimation. As a result, the proposed observer achieves enhanced convergence behavior and improved robustness for sensorless PMSM drives. The current estimation errors are defined as

$$e_\alpha = i_\alpha - \hat{i}_\alpha \quad (19)$$

$$e_\beta = i_\beta - \hat{i}_\beta \quad (20)$$

The adaptive switching gain is defined as

$$K_{sw}(t) = K_0 + k_a \sqrt{e_\alpha^2 + e_\beta^2} \quad (21)$$

Where K_0 denotes the minimum switching gain required to guarantee sliding motion and k_a is a positive adaptive coefficient that determines the sensitivity of the gain adjustment. Using the adaptive gain, the discontinuous injection terms in the observer are reformulated as

$$v_\alpha = K_{sw}(t) \text{sat}(e_\alpha) \quad (22)$$

$$v_\beta = K_{sw}(t) \text{sat}(e_\beta) \quad (23)$$

This adaptive mechanism increases the injection strength when the estimation error becomes large and gradually reduces the gain when the error approaches zero. Consequently, the observer preserves strong robustness during transient conditions while significantly reducing steady-state chattering. In addition to the adaptive gain mechanism, the discontinuous switching function is replaced by a smooth hyperbolic tangent function to further mitigate chattering effects. The modified switching function is defined as

$$\text{sat}(e) = \tanh(\lambda e) \quad (24)$$

Where $\lambda > 0$ determines the slope of the switching function. Compared with the classical sign function, the hyperbolic tangent function provides a continuous transition around the sliding surface, which suppresses high-frequency oscillations without sacrificing convergence speed. Substituting [21-24] into the observer equations yields the improved current estimation dynamics

$$\frac{d\hat{i}_\alpha}{dt} = -\frac{R_s}{L_s} \hat{i}_\alpha + \frac{1}{L_s} u_\alpha - \frac{1}{L_s} K_{sw}(t) \tanh(\lambda e_\alpha) \quad (25)$$

$$\frac{d\hat{i}_\beta}{dt} = -\frac{R_s}{L_s} \hat{i}_\beta + \frac{1}{L_s} u_\beta - \frac{1}{L_s} K_{sw}(t) \tanh(\lambda e_\beta) \quad (26)$$

Under sliding-mode operation, the estimation errors e_α and e_β converge toward zero and the equivalent values of the injection signals correspond to the back-EMF components. The estimated back-EMF signals are obtained by applying low-pass filtering to the adaptive injection signals

$$\hat{e}_\alpha = \text{LPF}(v_\alpha) \quad (27)$$

$$\hat{e}_\beta = \text{LPF}(v_\beta) \quad (28)$$

The estimated back-EMF signals are then processed by the PLL-based reconstruction stage to obtain the rotor electrical angle and electrical speed. To analyze the convergence property of the observer, consider the Lyapunov candidate function

$$V = \frac{1}{2} (e_\alpha^2 + e_\beta^2) \quad (29)$$

The time derivative of the Lyapunov function is given by

$$\dot{V} = e_\alpha \dot{e}_\alpha + e_\beta \dot{e}_\beta \quad (30)$$

Substituting the observer error dynamics into (30) yields

$$\dot{V} = -\frac{K_{sw}(t)}{L_s} (e_\alpha \tanh(\lambda e_\alpha) + e_\beta \tanh(\lambda e_\beta)) \quad (31)$$

Since $K_{sw}(t) > 0$ and $e \tanh(\lambda e) \geq 0$ for all $e \neq 0$, it follows that

$$\dot{V} \leq 0 \quad (32)$$

Which indicates that the estimation errors are bounded and driven toward the sliding surface. Therefore, the proposed adaptive sliding mode observer preserves the inherent robustness of the classical SMO while reducing chattering and improving estimation smoothness. Rotor Position and Speed Reconstruction Using a Phase-Locked Loop Although the rotor electrical angle can be directly obtained from the estimated back-EMF components using an arctangent function, this approach is known to be sensitive to measurement noise and numerical differentiation. In particular, the direct differentiation of the estimated electrical angle may amplify high-frequency disturbances introduced by switching harmonics and inverter nonlinearities. These effects can degrade the stability of the speed estimation and lead to undesirable oscillations in the outer speed control loop. To improve the robustness of the sensorless estimation process, a phase-locked loop (PLL) is employed to reconstruct the rotor electrical angle and electrical speed from the estimated back-EMF signals. The PLL structure provides a closed-loop tracking mechanism that filters measurement noise while maintaining fast dynamic response. Let the estimated back-EMF vector be defined in the stationary reference frame as

$$\hat{e}_{\alpha,\beta} = \begin{bmatrix} \hat{e}_\alpha \\ \hat{e}_\beta \end{bmatrix} \quad (33)$$

For a surface-mounted PMSM operating under steady-state conditions, the back-EMF components can be expressed as

$$e_\alpha = -\omega_e \psi_f \sin(\theta_e) \quad (34)$$

$$e_\beta = \omega_e \psi_f \cos(\theta_e) \quad (35)$$

Which indicates that the back-EMF vector is orthogonal to the rotor flux vector and rotates synchronously with the electrical angular speed. Based on this property, the rotor position can be estimated by aligning the estimated back-EMF vector with the reference

frame generated by the PLL. Let the estimated rotor electrical angle generated by the PLL be denoted by $\hat{\theta}_e$. The corresponding unit vectors are defined as

$$\hat{\mathbf{u}}_d = \begin{bmatrix} \cos(\hat{\theta}_e) \\ \sin(\hat{\theta}_e) \end{bmatrix} \quad (36)$$

$$\hat{\mathbf{u}}_q = \begin{bmatrix} -\sin(\hat{\theta}_e) \\ \cos(\hat{\theta}_e) \end{bmatrix} \quad (37)$$

The PLL is designed to track the phase of the estimated back-EMF vector. To this end, the projection of the estimated back-EMF vector onto the estimated q-axis is used as a phase-related signal, which can be expressed as

$$e_q^{PLL} = -\hat{e}_\alpha \sin(\hat{\theta}_e) + \hat{e}_\beta \cos(\hat{\theta}_e) \quad (38)$$

This signal is then processed by a PI loop filter to generate the estimated electrical speed. The PLL control law for the electrical speed estimation is defined as

$$\hat{\omega}_e = K_{p,PLL} e_q^{PLL} + K_{i,PLL} \int e_q^{PLL} dt \quad (39)$$

Where $K_{p,PLL}$ and $K_{i,PLL}$ denote the proportional and integral gains of the PLL regulator. The estimated electrical angle is obtained by integrating the estimated electrical speed

$$\hat{\theta}_e = \int \hat{\omega}_e dt \quad (40)$$

The corresponding mechanical rotor speed is then calculated using the relationship

$$\hat{\omega}_r = \frac{\hat{\omega}_e}{p} \quad (41)$$

Where p is the number of pole pairs. Compared with the direct arctangent-based estimation approach, the PLL-based reconstruction offers several advantages. First, the closed-loop filtering effect of the PLL significantly attenuates measurement noise and switching harmonics present in the estimated back-EMF signals. Second, the integral action of the PLL improves steady-state accuracy and eliminates bias errors in the speed estimation. Finally, the PLL structure provides smooth and continuous rotor angle tracking, which enhances the stability of the field-oriented control system during dynamic operating conditions. The proposed sensorless estimation scheme integrates three complementary mechanisms: an adaptive sliding mode observer for back-EMF reconstruction, a smooth switching law for chattering suppression, and a PLL-based stage for rotor position and speed extraction. This combination addresses the main shortcomings of the conventional fixed-gain SMO. The adaptive observer modifies the injection gain according to the current estimation error. As a result, strong corrective action is retained during transients, whereas excessive switching activity is avoided as the estimation error decreases. This feature improves convergence behavior without imposing unnecessarily large observer gains in steady-state operation. The use of the hyperbolic tangent function in place of the discontinuous sign function further improves the observer behavior near the sliding surface. In particular, it reduces high-frequency oscillations in the estimated signals while maintaining the robustness properties associated with sliding-mode-based estimation. The back-EMF components reconstructed by the observer are then supplied to a phase-locked loop to obtain the rotor electrical angle and speed. Unlike direct angle differentiation, the PLL provides a closed-loop estimation process with improved noise rejection and smoother speed reconstruction, which is particularly beneficial under dynamic operating conditions. Taken together, these modifications yield a sensorless estimation structure with improved robustness, lower sensitivity to switching noise, and smoother steady-state behavior, while preserving a relatively simple implementation.

IV. RESULTS AND DISCUSSION

The system is implemented in MATLAB/Simulink and consists of a PMSM drive operating under a conventional closed-loop FOC scheme, augmented with a SMO for rotor speed and position estimation. The FOC controller governs the stator currents and rotor speed based on measured electrical quantities, providing stable and well-regulated drive operation over a wide range of operating conditions. Within the implemented framework, the SMO utilizes the stator voltage and current components expressed in the stationary $\alpha\beta$ reference frame to estimate the back-electromotive-force components. These estimated signals are subsequently used to reconstruct the rotor electrical angle and rotor speed. The behavior of the estimated quantities is examined during start-up, acceleration, steady-state operation, and load disturbance scenarios in order to characterize the dynamic response and estimation capability of the observer in the PMSM drive system. The complete MATLAB/Simulink implementation of the closed-loop FOC-based PMSM drive and the associated SMO-based estimation structure are illustrated in Figures 3 and 4, respectively. The presented simulation results provide insight into the interaction between the control system and the observer dynamics, as well as the overall performance of the PMSM drive under various operating conditions.

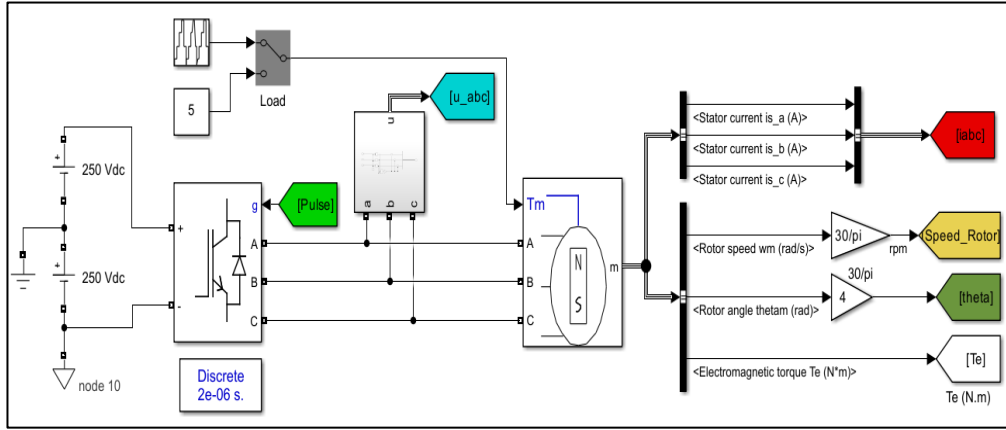


Figure 3: Power stage and PMSM model of the FOC drive.

Source: Authors, (2026).

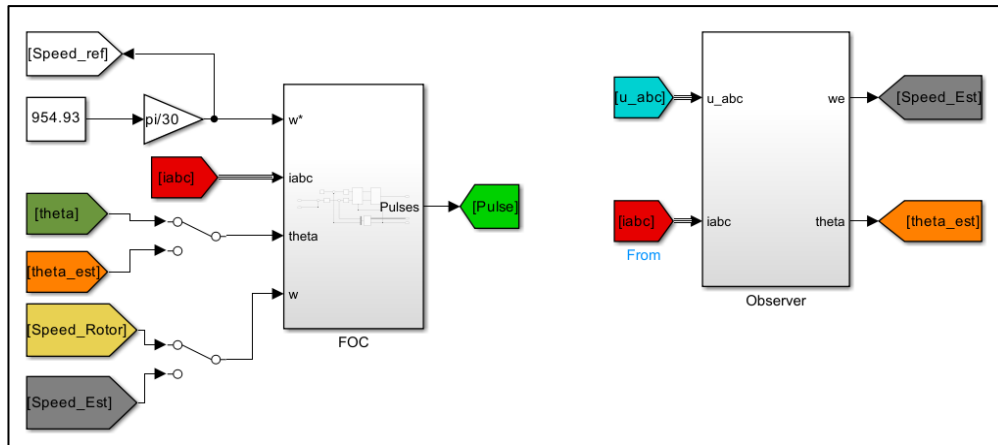


Figure 4: Block diagram of the FOC-controlled PMSM drive with the sliding mode observer.

Source: Authors, (2026).

The FOC-controlled PMSM drive incorporating a SMO is examined under four representative operating scenarios in order to characterize its dynamic behavior and robustness. The considered scenarios include: (i) operation with a varying load at a constant reference speed, which reflects the disturbance rejection capability and speed regulation performance; (ii) operation with a varying load combined with a time-varying reference speed, aimed at assessing robustness and tracking performance under simultaneous disturbances; (iii) operation with a constant load and constant reference speed, representing steady-state conditions; and (iv) operation with a constant load and a varying reference speed, which highlights the transient response and speed tracking characteristics of the drive system. Together, these scenarios provide a comprehensive view of the system behavior under both steady-state and dynamic operating conditions.

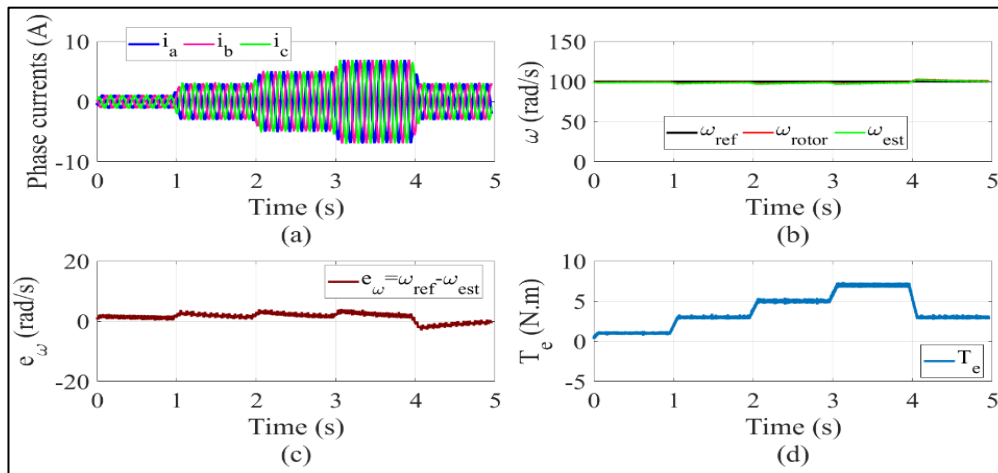


Figure 5: Dynamic responses of the FOC-controlled PMSM drive under varying load conditions at a constant reference speed. (a) Three-phase stator currents; (b) Rotor speed response; (c) Speed tracking error; (d) Electromagnetic torque.

Source: Authors, (2026).

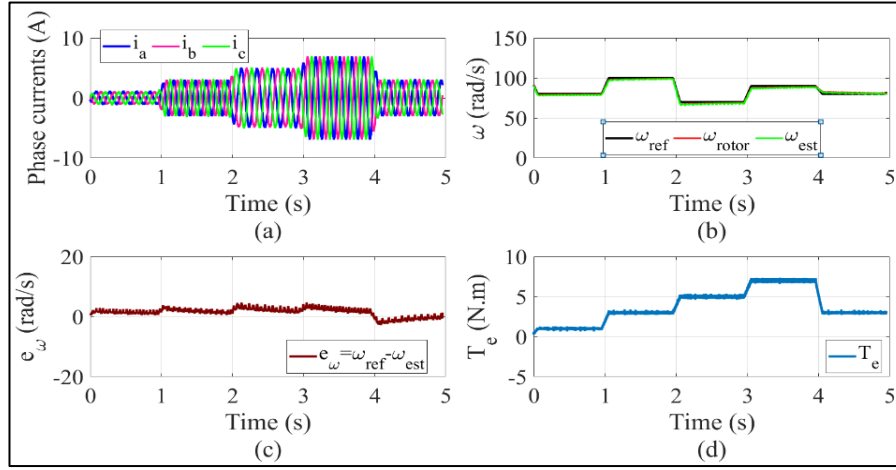


Figure 6: Dynamic responses of the PMSM drive under varying load and time-varying reference speed. (a) Three-phase stator currents; (b) Rotor speed response; (c) Speed tracking error; (d) Electromagnetic torque.

Source: Authors, (2026).

The dynamic responses of the FOC-controlled PMSM drive incorporating sliding mode observer-based estimation under four representative operating scenarios are presented in Figures 5–8. In all cases, the stator currents remain well balanced and nearly sinusoidal, confirming effective current regulation by the inner control loops. The rotor speed follows the reference trajectory smoothly during both steady-state operation and transient conditions, while the electromagnetic torque responds promptly to load variations with limited oscillations, indicating robust torque control and stable system behavior. During start-up and dynamic operating conditions, brief transient oscillations are observed in the stator currents and electromagnetic torque, after which the system rapidly converges to steady-state operation. The speed response exhibits negligible steady-state deviation and maintains consistent behavior under load disturbances and reference speed changes, demonstrating the effectiveness of the FOC structure in regulating the PMSM drive.

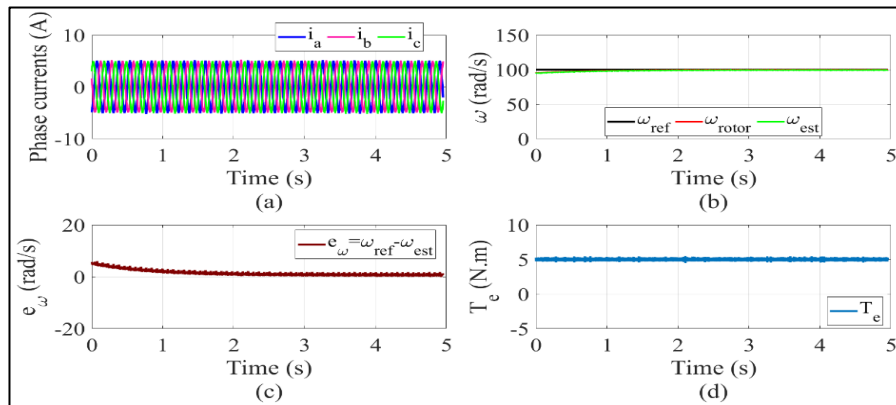


Figure 7: FOC-controlled PMSM drive under constant load and constant reference speed. (a) Three-phase stator currents; (b) Rotor speed response; (c) Speed tracking error; (d) Electromagnetic torque.

Source: Authors, (2026).

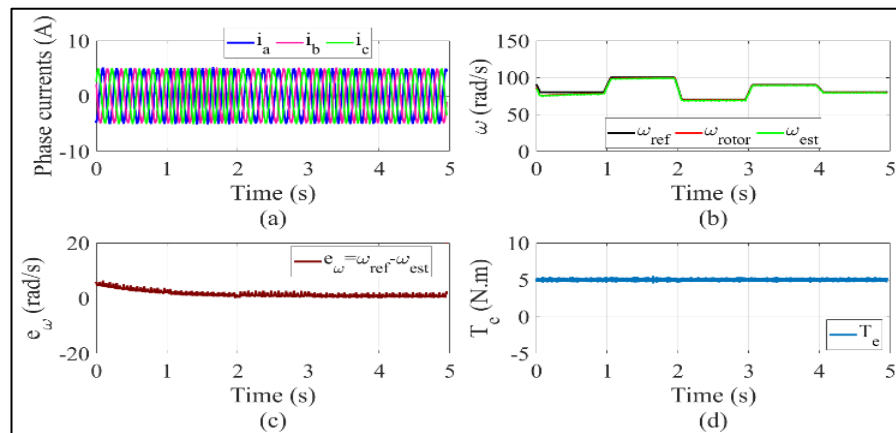


Figure 8: Dynamic responses of the FOC-controlled PMSM drive under constant load and varying reference speed. (a) Three-phase stator currents; (b) Rotor speed response; (c) Speed tracking error; (d) Electromagnetic torque.

Source: Authors, (2026).

The estimated speed and electrical angle display smooth waveforms with low ripple across all operating scenarios. Minor deviations may appear during the initial transient interval; however, the estimated quantities quickly settle as the system reaches steady operation and remain consistent with the drive dynamics thereafter. This behavior indicates effective suppression of chattering and noise effects and reflects the ability of the sliding mode observer to provide stable and reliable speed and position information under both steady-state and transient operating conditions.

V. CONCLUSION

A sensorless PMSM drive based on closed-loop field-oriented control and sliding-mode observation has been presented in this study. The PMSM model was established in the synchronous dq reference frame, while the observer was formulated in the stationary reference frame from stator current dynamics and back-electromotive-force reconstruction. To improve the estimation performance, an adaptive sliding-mode injection gain was introduced to regulate the observer correction strength according to the current estimation error, thereby alleviating the trade-off between fast convergence and chattering attenuation. A smooth switching law was further employed to suppress high-frequency oscillations in the observer signals, and a phase-locked loop was incorporated to reconstruct the rotor electrical angle and speed from the estimated back-EMF components. Together, these modifications improve the smoothness and robustness of the estimation process while preserving the structural simplicity of the conventional SMO framework. Simulation results obtained in MATLAB/Simulink under start-up, acceleration, steady-state, and load disturbance conditions confirmed stable drive operation and accurate speed tracking. Compared with the conventional SMO scheme, the proposed observer provided smoother estimation behavior, reduced steady-state oscillations, and more reliable rotor position and speed information. The proposed sensorless estimation scheme therefore constitutes a practical and computationally efficient solution for PMSM drives requiring robust rotor position and speed estimation.

VI. AUTHOR'S CONTRIBUTION

Conceptualization: Thanh Lam. Le.

Methodology: Thanh Lam. Le.

Investigation: Thanh Lam. Le.

Discussion of results: Thanh Lam. Le.

Writing – Original Draft: Thanh Lam. Le.

Writing – Review and Editing: Thanh Lam. Le.

Resources: Thanh Lam. Le.

Supervision: Thanh Lam. Le.

Approval of the final text: Thanh Lam. Le.

VII. REFERENCES

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