A Robust Control Strategy for Effective Field-Oriented Control of PMSMs

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ABSTRACT

Field-Oriented Control (FOC) is widely recognized as a standard framework for Permanent Magnet Synchronous Motor (PMSM) drives. Linear control techniques are commonly employed in designing controllers for this strategy. However, traditional control methods often exhibit performance limitations and reduced robustness, particularly under harsh operating conditions, which makes the FOC structure less appealing and less effective. To address and overcome these challenges, this study proposes a Second-order Non-singular Terminal Sliding (SNTS) mode approach to achieve fast, accurate, and robust tracking for the FOC control structure applied to PMSM drives. The SNTS method combines the benefits of non-singular terminal sliding mode and second-order control laws. This approach ensures rapid and precise tracking while minimizing steady-state errors by using a nonlinear terminal sliding mode surface instead of a linear one. Furthermore, the system state transitions smoothly along the sliding mode surface with continuous functions, which reduces chattering around the sliding surface. The second-order control law incorporated into this method helps mitigate chattering and achieve fast convergence. The Lyapunov stability theory is employed to verify the stability of the SNTS technique designed for the PMSM system. Simulation and experimental validation on a hardware platform confirm the effectiveness and superiority of the proposed SNTS method, demonstrating its capability to enhance the performance of speed controllers for PMSM drives.

Keywords-field-oriented control; robust control; PMSM system; motor drives; sliding mode control; PI control

I. INTRODUCTION

Nowadays, the emphasis on renewable energy sources, energy conservation, and efficient operation of systems has garnered considerable attention [1-2]. In this developmental trajectory, the research and application of advanced technologies for drive systems have also become a focal point for researchers. With the advancement of material technology and the trend towards efficient energy usage, Permanent Magnet Synchronous Motors (PMSMs) have garnered significant attention from researchers and industrial companies worldwide. This interest is driven by the superior characteristics and advantages that PMSMs offer. PMSMs are known for their high efficiency and compact size with a high power-to-weight ratio, lower noise levels, reduced rotor inertia, and effective heat dissipation [3]. Additionally, PMSMs provide high reliability for the systems in which they are integrated. Traditional motors typically utilize brushes and commutators to supply power. However, PMSMs eliminate the need for brushes and commutators, leading to reduced noise levels and minimized electromagnetic interference (EMI). The absence of brushes also eliminates the need for maintenance and replacement due to wear. Furthermore, using magnets instead of rotor windings helps reduce copper losses and allows for optimal use of radial space [4-6]. Advanced materials used in the design of PMSMs further enhance their performance. The careful selection of advanced magnets and soft magnetic materials can significantly reduce the motor's size while maintaining a very high torque-to-power density [7]. This explains the widespread application of PMSMs across various industrial and domestic fields, such as robotics, electric vehicles, aerospace applications, and integrated traction systems for renewable energy [8-10].

Despite their numerous advantages and widespread applications, PMSM systems also pose significant challenges. These challenges arise primarily because PMSMs are highly sensitive to variations in internal motor parameters, external disturbances such as load torque fluctuations, and unanticipated nonlinear dynamics during motor operation [11]. Such influencing factors can lead to serious issues [12]. This has driven researchers to focus on developing control strategies that employ advanced control techniques to attain accurate control and enhance PMSM performance. In recent years, significant research efforts have been devoted to exploring and developing control techniques for PMSMs. One of the most widely recognized techniques is vector control [13]. Among the various approaches to vector control, Field-Oriented Control (FOC) is considered the most popular and broadly accepted strategy for PMSM control. FOC is renowned for its high accuracy, which is essential for applications involving motion control. The harmonic distortion and current/torque ripple associated with FOC-based control are notably low, often significantly lower than those observed with other vector control techniques that rely on direct torque control [14, 15]. The core concept of FOC is to simplify the motor control system to resemble that of a DC motor through coordinate transformations. The standard configuration of FOC enables a hierarchical control structure, as detailed in [16]. Typically, linear control methods like Proportional-Integral (PI) control, are employed to design controllers for FOC strategies. Therefore, implementing a three-phase PMSM control system based on the FOC strategy requires multiple linear controllers, which directly impacts the performance of FOC. In industrial applications, systems must operate consistently in environments influenced by various external disturbances [17]. Consequently, conventional PI are often insufficient to address the complex dynamics of PMSM systems. Many studies are now focusing on nonlinear control theories for designing controllers of PMSM systems. Noteworthy nonlinear control theories include neural network control [18], hybrid control [19], and Sliding Mode Control (SMC) [20], stands out as particularly noteworthy [21]. SMC offers substantial advantages due to its relatively simple structure and robust performance against uncertainties and external disturbances [22]. Hence, this algorithm has gradually become a widely used method for the analysis and design of various nonlinear systems.

Researchers have extensively studied and widely published the application of SMC for managing systems integrated with PMSMs [23]. Despite its numerous advantages, SMC faces limitations due to the chattering phenomenon occurring around the chosen sliding surface. Numerous studies have been conducted to address this issue. To enhance the robustness of SMC within a system, a large switching gain is often employed [24]. This approach helps mitigate chattering issues and facilitates rapid convergence. However, it is important to note that if the system is exposed to unknown disturbances, this solution may inadvertently lead to increased chattering [25]. In the case of PMSM systems, the classical linear sliding mode surface, which is a linear function of the system state, has been commonly used [26]. This type of surface is designed for simplicity, convenience, and relatively easy parameterization [27]. However, it is insufficient when applied to the design of complex nonlinear systems [28]. Additionally, the primary controller is often designed based on discontinuous control laws [29]. The aforementioned approaches have not yet fully achieved comprehensive effectiveness, and each type still has its own drawbacks.

This paper introduces a robust control method termed SNTS (Second-order Non-singular Terminal Sliding) to enhance the performance of PMSM systems within the FOC framework. This method significantly improves existing control techniques by addressing key limitations associated with traditional linear controllers, such as PI controllers, which are commonly used in FOC-based PMSM systems. Linear control methods, though widely adopted, often suffer from reduced robustness, slower response times, and higher susceptibility to steady-state errors, particularly in dynamic and challenging operational environments. In contrast, the SNTS method provides enhanced speed regulation and achieves superior tracking performance. It offers rapid convergence and minimal steady-state error, ensuring more accurate control of PMSM systems under varying real-time conditions. By employing a non-singular sliding mode, the SNTS approach accelerates system convergence and minimizes steady-state error. Additionally, the incorporation of second-order control laws enhances the initial convergence of both the system state and the sliding mode surface, while avoiding the need for discontinuous switching functions. This design strategy effectively mitigates chattering phenomena, leading to smoother operation. As a result, PMSM systems governed by the SNTS method exhibit improved dynamic response, reduced oscillations, and faster tracking performance when compared to conventional linear control strategies. Simulation and experimental results validate the effectiveness of the proposed method, confirming its superiority in refining the FOC vector control strategy for PMSM drive systems.

II. PMSM MODEL AND VECTOR FOC

Vector FOC is a widely recognized technique used for controlling PMSM drives. This method provides effective control across the entire range of torque and speed, enabling rapid acceleration and deceleration of the motor, which facilitates precise control in high-performance motors. FOC primarily utilizes two common control modes: speed control and torque control. Speed control involves a motor controller that regulates the motor based on a reference speed value, generating a reference torque to manage torque, thus forming an internal subsystem. Conversely, torque control, commonly used in traction applications, focuses on a control system that monitors and adjusts according to the reference torque value. To implement the FOC algorithm, real-time feedback of current and rotor position is required. These quantities are typically measured using sensors. FOC involves controlling the stator current, represented by a vector, through time-dependent three-phase transformations and projections into a time-invariant two-coordinate system (d and q frames). These transformations and projections result in a control structure analogous to that of a DC motor. The voltage equations used to describe the mathematical model of the PMSM in the d-q reference frame can be represented as:

$$\begin{cases} u_d = R_s i_d - \omega_e L_q i_q + \frac{di_d}{dt} L_d \\ u_q = R_s i_q + \omega_e L_d i_d + \omega_e \psi_f + \frac{di_q}{dt} L_q \end{cases} \tag{1}$$

where u_d and u_q denote the stator voltages expressed in the d-q frame. The electromagnetic torque of the PMSM in the rotating d-q coordinate frame can be expressed by:

$$T_e = \frac{3p_n}{2}\left(i_d i_q L_d - i_d i_q L_q + i_q \psi_f\right) \tag{2}$$

The mechanical motion of the PMSM can be mathematically described by the following equation of motion:

$$J\frac{d\omega_m}{dt} = T_e - T_L \tag{3}$$

where ω_m denotes the mechanical angular velocity of the rotor, J represents the moment of inertia, and T_L is the load torque. To achieve optimal control performance, this paper utilizes the control technique of setting i_d=0. By enforcing i_d to be zero, the torque equation can be mathematically expressed as:

$$T_e = 3p_n\psi_f i_q/2 \quad (4)$$

where the flux components along the q-axis and d-axis are defined as $\psi_q = L_q i_q$ and $\psi_d = \psi_f$, respectively.

III. ROBUST CONTROL APPROACH

In this section, the design process of the PMSM control system with a speed loop based on SNTS is presented. Initially, the mathematical model of the PMSM is reformulated in (5). To achieve high control performance in the PMSM system, the reference current along the d-axis is set to zero. The differential equations describing the current and dynamics of the motor can be expressed as follows:

$$\begin{cases} \frac{di_q}{dt} = \frac{1}{L_q}\left(-R_s i_q - p_n\omega_m\psi_f + u_q\right) \\ \frac{d\omega_m}{dt} = -\frac{1}{J}T_L + \frac{3}{2J}p_n\psi_f i_q \end{cases} \quad (5)$$

The state space of the PMSM system can be described using the speed error and its derivative as state variables. The state variables are represented by: $\Theta_1 = \omega_r - \omega_m$ and $\Theta_2 = \dot{\Theta}_1$ where ω_r denotes the desired motor speed and ω_m represents the actual measured motor speed. The mathematical representation of the PMSM can be expressed through differential equations by incorporating the data provided in Eq. (5) and the state variables Θ_1 and Θ_2. Consequently, the state space of the system can be reorganized as $\dot{\Theta}_1 = \frac{1}{J}T_L - \frac{3p_n\psi_f i_q}{2J}$ and $\dot{\Theta}_2 = -3p_n\omega_f \dot{i}_q/2J$. The state equation can be formulated using the currents as the state variables and is expressed as:

$$\begin{bmatrix}\dot{\Theta}_1 \\ \dot{\Theta}_2\end{bmatrix} = \begin{bmatrix}0 & 1 \\ 0 & 0\end{bmatrix}\begin{bmatrix}\Theta_1 \\ \Theta_2\end{bmatrix} + \begin{bmatrix}0 \\ -\mathcal{R}\end{bmatrix}\mathcal{Q} \quad (6)$$

The derivative of the q-axis current component, denoted as $\mathcal{Q} = \dot{i}_q$, is typically considered as the input vector. Additionally, the motor characteristics can be represented using the parameter $\mathcal{R}$, which is defined by: $\mathcal{R} = 3p_n\omega_f/2J$. Thus, the system's state can be coherently expressed in the following form:

$$\dot{\Theta} = \mathcal{A}_1\Theta + \mathcal{A}_2 u \quad (7)$$

where $\Theta = \begin{bmatrix}\Theta_1 \\ \Theta_2\end{bmatrix}$ represents the state vector. The parameter matrices are defined as $\mathcal{A}_1 = \begin{bmatrix}0 & 1 \\ 0 & 0\end{bmatrix}$ and $\mathcal{A}_2 = \begin{bmatrix}0 \\ -\mathcal{R}\end{bmatrix}$, respectively.

Traditional methods based on linear control techniques often exhibit slow response times and low stability. To enhance the response speed and stability of the speed control loop in PMSM systems, this study introduces a non-singular terminal sliding-mode surface. This control strategy aims to achieve rapid tracking with minimized steady-state errors. The formula for the non-singular terminal sliding-mode surface is:

$$\Xi = \Theta_1 + \frac{\Theta_2^{\varkappa/\varrho}}{\zeta} \quad (8)$$

where $\varkappa$ and ϱ are positive odd numbers, ζ is a positive parameter, and the condition $1 < \varkappa/\varrho < 2$ is satisfied. Taking the time derivative of the sliding-mode surface Ξ yields:

$$\dot{\Xi} = \Theta_2 + \frac{\varkappa}{\zeta\varrho}\dot{\Theta}_2\Theta_2^{\frac{\varkappa}{\varrho}-1} \quad (9)$$

To achieve accurate tracking and minimize chattering, a second-order control law is designed for the outer loop. The control law is formulated as:

$$\dot{\Xi} = -\xi_1|\Xi|^{\Omega}f(\Xi) - \int_0^{\tau}\xi_2 f(\Xi)\,d \quad (10)$$

where $f(\Xi)$ is a continuous function and the constants ξ_1, ξ_2, and Ω are positive, with ξ_1, ξ_2 > 0 and $0 < \Omega < 1$. The function V can be designated as a function of $\dot{\Xi}$. To enhance dynamic performance and achieve superior tracking for the system described by (6), a controller is designed utilizing the surface (8) and a second-order control law. The enforcement of this control strategy assures that the system state on the sliding mode surface will reach zero within a finite duration. The overall schematic of the SNTS method is visually represented in Figure 1. The reference current for the q-axis is generated by the proposed control law and is mathematically expressed by:

$$\mathcal{Q} = \frac{\zeta\varrho}{\mathcal{R}\varkappa}\Theta_2^{2-\varkappa/\varrho} - \frac{V}{\mathcal{R}}\left(\frac{\varkappa}{\zeta\varrho}\Theta_2^{\varkappa/\varrho-1}\right)^{-1} \quad (11)$$

A positive Lyapunov function $\mathfrak{L}_1$ is used to verify the stability of the proposed method. The positive Lyapunov function is given by:

$$\mathfrak{L}_1 = \Xi^2/2 \quad (12)$$

Taking the time derivative of the Lyapunov function and combining it with (11), yields:

$$\dot{\mathfrak{L}}_1 = \Xi\Theta_2 + \frac{\varkappa\Xi}{\zeta\varrho}\Theta_2^{\varkappa/\varrho-1}\dot{\Theta}_2 \le 0 \quad (13)$$

The results clearly indicate that $\Xi f(\Xi)$ is positive. It can be observed that the derivative $\dot{\mathfrak{L}}_1$ of the Lyapunov function remains less than or equal to zero. Consequently, it can be concluded that the optimized controller is asymptotically stable and fully adheres to the principles of Lyapunov stability theory. This stability property guarantees that the system state will reach the sliding-mode surface within a finite time.

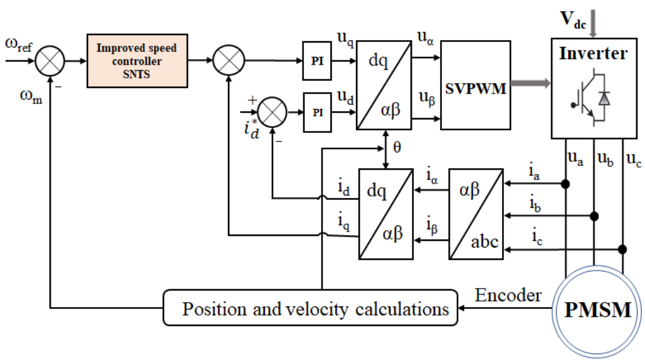

Fig. 1. SNTS method applied to the PMSM drive system.

IV. RESULTS AND DISCUSSION

Simulations and experiments were conducted on identical PMSM systems to validate the effectiveness of the proposed method. To clearly distinguish the performance and benefits of the proposed approach, it was compared with a classical PI control method. Equivalent test conditions were established for both simulations and experiments. Additionally, vector control using FOC was implemented for both the proposed method and the PI control method. The d-axis current was set to zero to optimize system performance. Furthermore, identical PI parameters were used for the inner current loop in both methods. The key parameters for the PMSM motor are detailed as follows: stator resistance of 0.79 Ω, stator inductance of 2.8e-4 H, number of pole pairs of 4, and moment of inertia of 1.7e-5 kg·m². The control algorithms were developed and tested in the MATLAB/Simulink environment. The block diagram illustrating the SNTS for the speed loop of the PMSM drive is shown in Figrue 1.

A Simulation Evaluation

In the case of constant speed, simulations were conducted over a 3-second period starting from t = 0. The simulation results are presented in Figure 2. After 1.5 s, a load torque is applied to the system, with the reference speed set to 1500 rpm. The results clearly highlight the superiority of the SNTS method over the traditional PI method in terms of speed response and error reduction. The SNTS method demonstrates significantly faster speed response and smaller errors compared to the PI method under the same FOC strategy configuration.

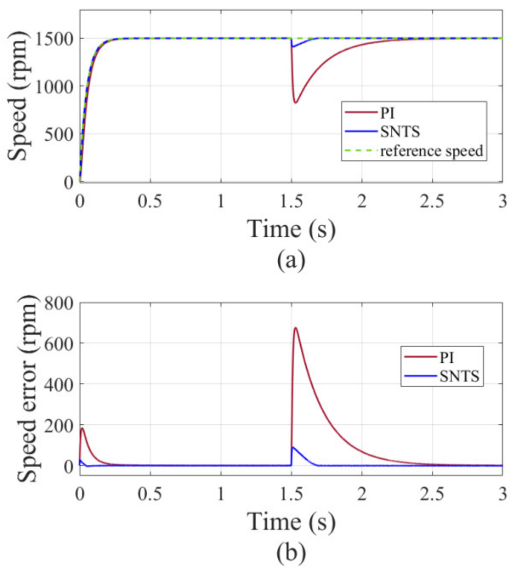

Fig. 2. Analysis of (a) speed response and (b) error of PI and SNTS controllers.

Furthermore, an extensive evaluation is performed on motor speeds ranging from 500 rpm to 1500 rpm to further assess the effectiveness of the proposed method. The proposed method shows precise tracking of the reference speed and exhibits faster response times compared to the conventional PI method. Figure 3 presents a comparison of speed errors between the two methods, indicating that the SNTS method results in smaller speed errors. A comprehensive performance comparison between the two methods is illustrated in Figure 4.

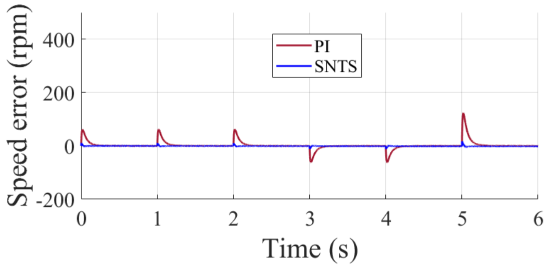

Fig. 3. Comparison of speed error between PI and SNTS.

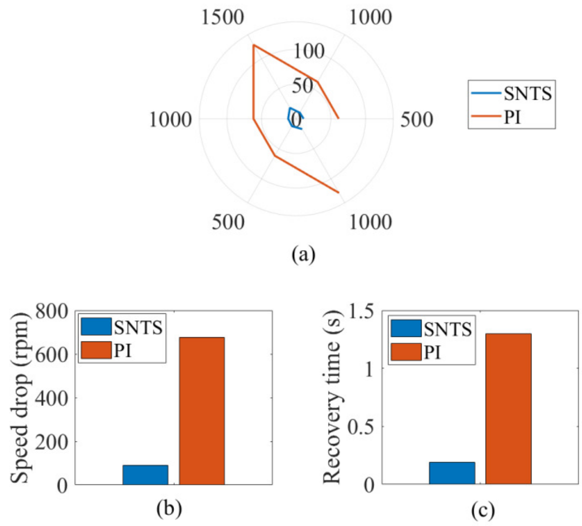

Fig. 4. Performance comparison between SNTS and PI. (a) Speed error under variable speed, (b) speed drop, (c) recovery time.

In particular, Figure 4(a) highlights the superior performance of the proposed SNTS method in terms of speed error reduction. As illustrated, the speed error envelope of the SNTS method (depicted by the blue line) is significantly smaller than that of the traditional PI controller (depicted by the red line). This demonstrates that the proposed SNTS controller is more effective at maintaining accurate speed regulation, even when the system experiences variations in speed. The smaller error envelope for the SNTS method indicates enhanced robustness and precision compared to the larger envelope observed with the PI controller. The simulation results provide additional confirmation of the superior performance and robustness of the SNTS method in PMSM drives across various operating conditions. It is evident that the proposed SNTS method outperforms the PI method in terms of speed error, speed reduction, and recovery time.

B Experimental Evaluation

Validation experiments were conducted on a hardware platform to confirm the accuracy of the simulations and to verify the effectiveness of the proposed method. The experimental setup was meticulously designed to eliminate any external influences on the results and to ensure an objective comparison between the considered techniques (PI control and the proposed method) within the same FOC configuration. The control theories were implemented using the Texas Instruments DSP TMS320F28379D. The overall configuration of the experimental block diagram is illustrated in Figure 5.

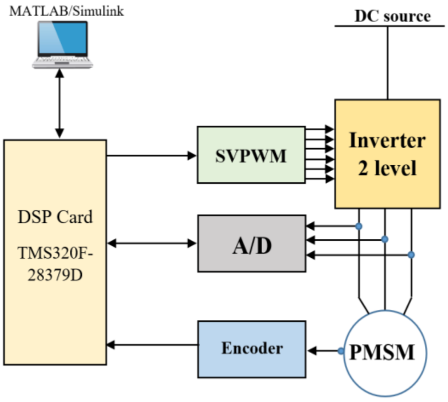

Fig. 5. Block diagram of the experimental system.

The evaluation was carried out under two scenarios: a fixed speed case at 1500 rpm with load applied for 1.5 s, and a variable speed case for the motor. The experimental results are detailed in Figures 6 and 7.

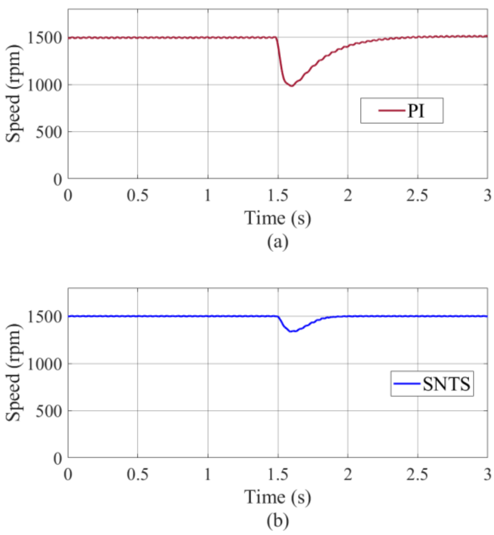

Fig. 6. Experimental results under applied load. (a) PI, (b) SNTS.

In the first scenario, where the speed is maintained at a constant 1500 rpm, a sudden load torque is applied for 1.5 s. The results, shown in Figure 6, clearly demonstrate that the proposed SNTS method exhibits significantly lower speed drop compared to the conventional PI method, with faster recovery time. In the second scenario, speed response is analyzed over a range of [700-1500] rpm within a 3-second period. The results presented in Figure 7 further highlight the superior speed response of the SNTS method compared to the PI method. The SNTS method shows better adherence to the reference speed values, while the PI method exhibits noticeable speed oscillations. Furthermore, speed ripple is easily detectable with the PI method, but is not observed with the SNTS method. Both simulation and experimental results demonstrate that the proposed method enhances tracking performance and achieves superior quality compared to the traditional PI method within the same FOC control strategy configuration. These results underscore the effectiveness and reliability of the proposed method in achieving optimal control and stable performance in PMSM applications.

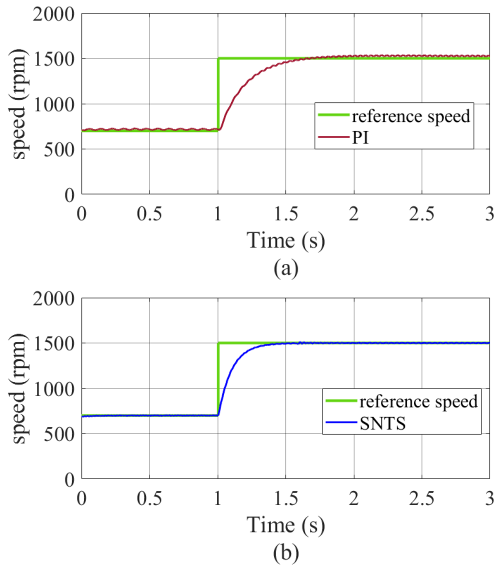

Fig. 7. Experimental results under variable speed. (a) PI; (b) SNTS.

V. CONCLUSION

The vector control strategy for PMSM systems using field-oriented control often faces limitations and suboptimal performance due to the reliance on linear control techniques during the control configuration design process. This paper presents a novel robust control method based on the SNTS approach for PMSM drives. The primary objective of the proposed SNTS method is to enhance robustness and improve speed control performance within the FOC strategy. To achieve rapid and accurate tracking while minimizing tracking errors, a nonlinear sliding mode surface using a non-singular terminal sliding mode is employed instead of a linear surface. This approach ensures the system state quickly converges to the sliding surface and eliminates the need for discontinuous switching functions typically required in second-order control laws. During operation, the system state can smoothly traverse along the sliding mode surface with a continuous function. This behavior helps reduce noise around the sliding surface. The stability of the SNTS control scheme for PMSM drives is demonstrated through Lyapunov stability theory. Both simulation and experimental results confirm the effectiveness and superiority of the proposed SNTS method compared to the traditional PI control within the FOC control strategy. The proposed method offers several advantages, including reduced speed oscillations, enhanced dynamic response, and precise tracking with minimal deviation compared to traditional linear control techniques. The SNTS method significantly improves the performance and durability of the PMSM drive system, thereby advancing the efficacy of the FOC strategy.

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