

Adaptive Sliding Mode and Fuzzy Observer-Based Optimal Control for Electromagnetic Performance of Permanent Magnet Synchronous Motors

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ABSTRACT: To enhance the electromagnetic transient performance and torque dynamic response quality of permanent magnet synchronous motor vector control systems, this study proposes a novel adaptive sliding mode control strategy based on a state-dependent nonlinear approach law. This method first replaces the sign function in traditional sliding mode control with a sigmoid function, mechanically achieving continuous construction of quasi-sliding mode dynamics and effectively eliminating high-frequency chattering in control signals. Building upon this foundation, the electromagnetic-mechanical state variables are dynamically incorporated into the approach law design to construct a state-dependent nonlinear approach law. This enables the controller to adaptively adjust based on the motor's operational state, thereby achieving dynamic optimization control of electromagnetic torque and speed without relying on precise models. Furthermore, a global fast terminal sliding surface is introduced to achieve rapid convergence of system states within a finite time. For composite disturbances, such as load transients, flux fluctuations, and unmodeled dynamics, a fuzzy logic-based gain adaptive mechanism for extended state observers is designed. It dynamically adjusts observer bandwidth to enable real-time, precise observation and feedforward compensation for total disturbances. Experimental results demonstrate that the proposed method exhibits significant advantages in improving torque dynamic response, enhancing steady-state accuracy, and strengthening system disturbance rejection capabilities, providing an effective solution for high-performance permanent magnet synchronous motor drive control.

1. INTRODUCTION

Permanent magnet synchronous motors (PMSMs) inherently possess a high power density, high efficiency, and excellent dynamic response capabilities due to the superior air gap magnetic field established by high-energy permanent magnets. They have become core actuators in high-end drive applications, such as new energy vehicles and industrial servo systems [1–4]. However, the exceptional electromagnetic performance of PMSMs is often hindered in practical operation by inherent electromagnetic nonlinearities (such as magnetic saturation, cogging torque, and flux harmonics) and external load disturbances. These factors directly cause electromagnetic torque ripple, additional losses, and current harmonics, severely limiting the application potential of the system in precision scenarios. Therefore, developing advanced control strategies that actively suppress torque ripple and compensate for parameter variations — based on the intrinsic laws of motor electromagnetic operation — is crucial for achieving breakthroughs in the PMSM drive system performance. While traditional proportional-integral (PI) controllers feature a simple structure and perform well under steady-state conditions, their linear characteristics struggle to address the complex uncertainties arising from both internal electromagnetic parameter variations (e.g., flux fluctuations and inductance saturation) and external load disturbances. It results in sluggish dy-

amic responses and insufficient robustness, failing to satisfy the stringent requirements for electromagnetic torque stability demanded by high-performance control applications [5]. To overcome these limitations, researchers have proposed various nonlinear control strategies, including model predictive control [6], fuzzy logic control [7], neural network control [8], and sliding mode control (SMC) [9]. Among them, SMC demonstrates unique advantages in addressing electromagnetic uncertainties, owing to its inherent robustness against parameter perturbations and external disturbances, making it widely adopted in motor control applications. However, the inherent high-frequency chattering phenomenon in the traditional sliding mode control excites high-frequency electromagnetic harmonics in the motor. This not only leads to additional iron and copper losses and reduces system efficiency, but also directly translates into persistent torque pulsations, degrading operational smoothness, which severely limits its application in low-noise, high-precision PMSM systems [10]. Researchers have proposed various improvement strategies to effectively suppress chattering while preserving SMC robustness and enhancing the overall performance. Ref. [11] proposes an improved power-law approach that dynamically links the system state and convergence terms via an exponential component. It optimizes the dynamic performance throughout the entire process of moving from distant to close proximity to the sliding surface, thereby accelerating the stabilization of the electromagnetic energy conversion. Ref. [12] introduces an enhanced ex-

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ponential approach law by incorporating system state variables, accelerating the dynamic process to shorten the electromagnetic torque settling time and improving the system dynamic response. Ref. [13] proposes an innovative fuzzy sliding-mode velocity control strategy. It dynamically adjusts the gains based on the distance between the state variables and sliding surface to achieve an adaptive adjustment of the approach velocity. The sigmoid function replaces the sign function to smooth the control signal. This strategy significantly reduces the current harmonics caused by high-frequency switching of control quantities while ensuring robustness, thereby contributing to lower motor losses. Ref. [14] addresses parameter mismatch issues in non-differential beat predictive control for permanent magnet synchronous motors by proposing an autoregressive model-based parameter disturbance suppression method. This approach directly corrects the core factors affecting the magnetic field and torque generation accuracy by online estimation and compensation of key electromagnetic parameters, such as the stator resistance and inductance. It effectively enhances the system's robustness under parameter disturbances and improves the current tracking performance. Ref. [15] addresses the issues of parameter perturbations and load disturbances in the position control of permanent magnet linear synchronous motors by proposing an adaptive full-order dynamic sliding mode control strategy based on disturbance observers. This method integrates full-order and dynamic sliding mode control to suppress chattering while ensuring dynamic performance. It employs adaptive laws for online estimation of uncertainties combined with disturbance feedforward compensation. Experiments demonstrate that this method achieves high-precision position tracking and effectively enhances system robustness. Ref. [16] introduces a non-singular terminal sliding mode control method. This approach resolves the singularity issues of traditional terminal sliding mode control while ensuring the rapid finite-time convergence of electromagnetic state variables (e.g., current and flux linkage), thereby achieving a faster system response. Ref. [17] addresses the issue of insufficient adaptability in traditional fuzzy PI controllers for permanent magnet synchronous motors (PMSM) under multi-condition operation by proposing an improved fuzzy PI control strategy. Real-time performance is enhanced by restructuring the fuzzy rule table to streamline it to 28 rules. An adaptive integral separation strategy based on target speed is introduced to dynamically adjust the integral action and suppress overshoot. Controller parameters are optimized using an improved artificial bee colony algorithm. Simulation results demonstrate that this method outperforms conventional approaches in dynamic response, steady-state accuracy, and disturbance rejection, indicating promising engineering application prospects. Ref. [18] addresses the issues of slow response and poor disturbance rejection in PI controllers within permanent magnet synchronous motor speed control systems by replacing the speed-loop PI controller with a Linear Adaptive Disturbance Rejection Controller (LADRC). A hardware-in-the-loop (HIL) test system was constructed based on the NI platform and validated using a motor simulation model driven by an actual controller. Experiments demonstrate that the proposed method exhibits minimal overshoot and rapid response during startup, with small

speed fluctuations and swift recovery under load. This approach effectively enhances the system's disturbance rejection capability and control performance while providing a viable hardware-in-the-loop verification platform for rapid controller development. Ref. [19] addresses the issues of excessive overshoot and poor disturbance rejection in traditional PI control for the weak-field speed regulation system with built-in permanent magnet synchronous motors by proposing a segmented sliding mode control strategy. Below rated speed, a novel exponential approach law sliding mode controller is employed. By introducing a smoothing function and system state variables, it achieves accelerated convergence while suppressing chattering. During weak field speed expansion, an overspiral algorithm speed loop controller is designed based on the variable-axis voltage single-current regulator method, incorporating the motor's orthogonal-axis coupling characteristics. Simulations demonstrate that compared to conventional PI and sliding mode control, this strategy effectively reduces speed overshoot, accelerates dynamic response, and enhances disturbance rejection capability. Ref. [20] addresses the issue of external forces and parameter perturbations affecting segmented-supply permanent magnet linear synchronous motors by proposing a composite control strategy integrating a novel sliding-mode velocity controller with a terminal sliding-mode disturbance observer. The designed approach law accelerates convergence when deviating from the equilibrium point and reduces gain near the point to suppress chattering. The observer estimates and compensates for lumped disturbances such as load forces and friction forces in real time. Experiments demonstrate that this strategy outperforms conventional methods in speed tracking accuracy, disturbance rejection capability, and acceleration fluctuation suppression, significantly enhancing both dynamic and steady-state system performance. Ref. [21] addresses the reliance on precise mathematical models in permanent magnet synchronous motor control by proposing a model-free adaptive fast terminal sliding mode control method. By transforming the system into a compact dynamic linearized model, a control law integrating the advantages of model-free adaptation and fast terminal sliding mode is designed. This approach achieves control solely through input-output data while optimizing the online estimation of key parameters. Simulations and experiments demonstrate that compared to traditional PI and sliding mode control, this method achieves faster response and stronger disturbance rejection without model dependency. It exhibits reduced overshoot and quicker recovery during sudden speed changes and load disturbances, offering a model-free approach for high-performance motor control. Ref. [22] addresses the issue of traditional super-helix algorithms in permanent magnet synchronous motor control relying on prior knowledge of disturbance upper bounds by proposing a novel adaptive super-helix algorithm (NASTA). This algorithm incorporates an improved adaptive law that dynamically adjusts gains based on the system state, achieving gain enhancement during disturbance increases, steady-state convergence, and maintenance of optimal values. Combined with feedforward compensation from a disturbance observer, this approach effectively shortens the dynamic recovery process following load transients. Simulations and experiments demonstrate that NASTA outperforms tradi-

tional methods in terms of overshoot, settling time, and disturbance rejection, validating its superiority.

This study focuses on the design of an adaptive control strategy for the speed loop within a dual-closed-loop current-speed control system for permanent magnet synchronous motors. The objective is to suppress electromagnetic-mechanical coupling oscillations caused by parameter variations, load disturbances, and unmodeled dynamics. The specific design approach is as follows:

1. The sigmoid function replaces the sign function in traditional sliding mode control, enabling the continuous construction of quasi-sliding mode dynamics at the mechanism level and effectively eliminating high-frequency oscillations in the control signal.
2. The system's electromechanical state variables are dynamically incorporated into the constant-rate and exponential-rate gains of the convergence law. A state-dependent nonlinear convergence law is designed, enabling the controller to adaptively adjust based on the motor's real-time operating state. This achieves dynamic optimization control of electromagnetic torque and speed without relying on precise models.
3. Building upon traditional linear extended state observers (ESO), a fuzzy logic system is introduced to dynamically adjust the ESO gain matrix, endowing it with bandwidth adaptation capability. This achieves precise dynamic observation and feedforward compensation for total system disturbances, including unmodeled dynamics, parameter perturbations, and external interference.

The synergistic application of these three innovative layers to new energy wind power generation systems enables the construction of an intelligent wind turbine control system adaptable to complex, time-varying wind conditions. Through continuous approach law design, high-frequency electromagnetic-mechanical coupling oscillations caused by control discontinuities in the pitch system and torque control loop are effectively suppressed. This significantly improves actuator smoothness, reduces fatigue damage to critical mechanical components like the drive train, and extends turbine operational lifespan and reliability. State-dependent adaptability dynamically adjusts controller response characteristics based on real-time wind speed, rotor speed, and the unit's electromagnetic load. This approach maximizes wind energy capture while simultaneously balancing structural loads on the unit and grid connection stability requirements. Further integrated with a fuzzy logic-based adaptive extended state observer, the system precisely estimates electromechanical-electromagnetic composite disturbances caused by turbulence, wind shear, and grid voltage/frequency fluctuations in real time. It implements dynamic feedforward compensation to enhance system robustness under severe disturbances. The integrated control strategy enables wind turbines to maintain high-precision tracking and robust power output performance under highly fluctuating wind conditions, thereby achieving systematic improvements in power generation efficiency, grid-friendliness, and lifecycle operational economics.

Given the highly random, intermittent, and regional characteristics of wind energy resources, applying the proposed control strategy to actual wind power systems requires following a complete validation path from theoretical simulation to engineering practice. Specifically, thorough testing must be conducted in simulation environments encompassing diverse wind conditions (e.g., steady winds, gradually varying winds, turbulent winds, and extreme gusts). Performance must then be validated through hardware-in-the-loop experiments simulating real-world factors such as actuator dynamics, sensor noise, and communication delays. Ultimately, long-term field operation tests must be conducted at representative wind farms to systematically evaluate the strategy's adaptability and reliability across different seasons, climatic conditions, and complex grid interaction scenarios. This multi-stage, long-term empirical process is essential for ensuring the control algorithm maintains its expected robustness, stability, and performance advantages in practical applications. It also provides crucial field data support for subsequent parameter adaptive tuning and system fault-tolerant design.

2. ADAPTIVE VARIABLE SPEED APPROACH LAW DESIGN

The sliding mode approach law is one of the core concepts in the sliding mode variable structure control. Its function is to define the system state to rapidly and smoothly approach the sliding surface from its initial position, and to maintain a sliding state upon reaching the sliding surface, thereby achieving robust control of the system. The exponential approach law is widely applied in traditional sliding-mode variable-structure control. This approach law consists of a constant velocity term and an exponential term, expressed as follows:

$$\frac{ds}{dt} = -\varepsilon \text{sign}(s) - ks \quad (1)$$

In the equation: ε and k represent the gains of the exponential convergence law, satisfying $\varepsilon > 0$ and $k > 0$, and s denotes the sliding surface. The exponential term accelerates the convergence of the system state toward the sliding surface when the system state deviates significantly from it, working in tandem with the constant velocity term. The constant velocity term ensures that the system state converges to the sliding surface within a finite time when it approaches the sliding surface. When $s > 0$, if the state point reaches the sliding surface such that $s(t) = 0$, we integrate Equation (1) from 0 to t :

$$\int_0^t \frac{ds}{\varepsilon + ks} = \int_0^t dt \quad (2)$$

The time at which the state point reaches the sliding surface can be calculated as follows:

$$t = \frac{1}{k} \left\{ \ln \left[s(0) + \frac{\varepsilon}{k} \right] - \ln \frac{\varepsilon}{k} \right\} \quad (3)$$

From Equation (3), it is evident that the exponential gain k exhibits an inverse relationship with the convergence time t

required for the system state to reach the sliding surface. A larger gain k accelerates the approach of the system to the sliding surface. Therefore, increasing gain k effectively enhances the convergence speed. However, excessively high k values cause significant oscillations near the sliding surface owing to inertial effects, thereby inducing high-frequency current harmonics and exacerbating motor iron losses and torque ripples. Additionally, the sign function $\text{sign}(s)$ used in the traditional approach laws exhibit inherent discontinuity, readily inducing high-frequency oscillations near the sliding surface. This degrades the current waveform quality and limits the smoothness of electromagnetic torque. To suppress this phenomenon, this study replaced the sign function with a continuously adjustable sigmoid function. Its smoothing characteristics attenuate oscillations, thereby achieving smoother electromagnetic torque output and lower current harmonics. The sigmoid function expression is given by Equation (4).

$$G(s) = \frac{2}{1 + e^{-\sigma s}} - 1 \quad (4)$$

In the formula, $\sigma > 0$. The larger the σ is, the closer it approaches the sign function. To mitigate the jitter, σ should not be excessively large. To overcome the limitations of traditional exponential approach laws further, this study proposes an adaptive variable-speed approach law with the following advantages:

1. Oscillation Suppression and Enhanced Electromagnetic Performance: Replacing the discontinuous sign function ($\text{sign}(s)$) with a sigmoid function effectively reduces high-frequency switching of control signals. This suppresses current harmonics, minimizes iron and copper losses, and improves the smoothness of electromagnetic torque.
2. Adaptive Approach Mechanism: A gain adaptation mechanism is designed to enable rapid convergence when the state is far from the sliding surface, and to soften the deceleration when approaching it. This ensures a dynamic response speed while improving the smoothness of electromagnetic transient processes. The design approximation law is given by Equation (5):

$$\begin{cases} \dot{s} = -\varepsilon F(s) \text{Sigmoid}(s) - k|x|^d s \\ F(s) = \frac{\alpha + \lambda|s| + \beta e^{-\frac{1}{|s|^\theta}}}{1 + |s| + \beta e^{-\frac{1}{|s|^\theta}}} \end{cases} \quad (5)$$

In the formula: ε , k , α , λ , β , θ , and d are the parameters to be designed, and $\varepsilon > 0$, $k > 0$, $0 < \alpha < 1$, $\lambda > 1$, $\beta \neq 0$, $\theta > 0$, and $d > 0$. In the proposed variable-speed approach law (5), the convergence rate of the first term depends on the sliding variable s . Analysis shows that as $|s|$ approaches infinity, $F(s) = \lambda$ holds true. At this point, the equivalent gain $\varepsilon\lambda$ of the adaptive law significantly exceeds the constant gain ε of the traditional constant-speed approach. Consequently, the sliding variable s converges to zero more rapidly under the influence of a larger equivalent gain. As $|s|$ approaches 0, $F(s) = \alpha$ holds true, and the adaptive law's equivalent gain

$\varepsilon\alpha$ reverts to conventional levels, effectively suppressing current harmonics and electromagnetic torque pulsations caused by high-frequency switching. Therefore, in practical engineering applications, the parameters λ and α require reasonable adjustment. Although excessively small values may suppress chattering, they can lead to slow convergence and prolonged regulation times. Conversely, excessively large values may accelerate convergence but risk inducing high-frequency chattering near the sliding surface. In the proposed variable-speed approach law (5), the second term introduces the system state variable x , which endows the approach law with state-dependent adaptive damping characteristics. When the state error is large, the gain increases to accelerate convergence. As the system approaches the equilibrium point, the gain attenuates to prevent excessive gain from inducing electromagnetic resonance and torque ripple. Parameter d exhibits a positive correlation with the system convergence speed: a larger d value results in faster convergence. However, excessively high d values, while accelerating system convergence, significantly amplify the control action intensity and rate of change, thereby exacerbating high-frequency system oscillations. To address this, an adaptive function is introduced to dynamically adjust the parameter d based on the improved convergence law. The adaptive function is expressed by Equation (6).

$$d = \gamma + (1 - \gamma)e^{-\xi|s|} \quad (6)$$

where $\xi > 0$ and $\gamma > 1$, when the system state deviates from the sliding surface, $d \approx \gamma$, and when the system state approaches the sliding surface, $d \approx 1$. This ensures that the function continuously varies with the distance from the sliding surface, simultaneously enhancing the dynamic response speed and effectively suppressing the steady-state electromagnetic chatter. Consequently, the system achieves high-performance electromagnetic operation under all operating conditions. Figure 1 illustrates the comparison between the method designed in the manuscript and existing traditional methods as they approach the slip surface. As shown in the images, in terms of speed or stability, the method designed in the manuscript outperforms existing traditional methods.

In Figure 1, the comparison results demonstrate that the method designed in this study exhibits superior performance

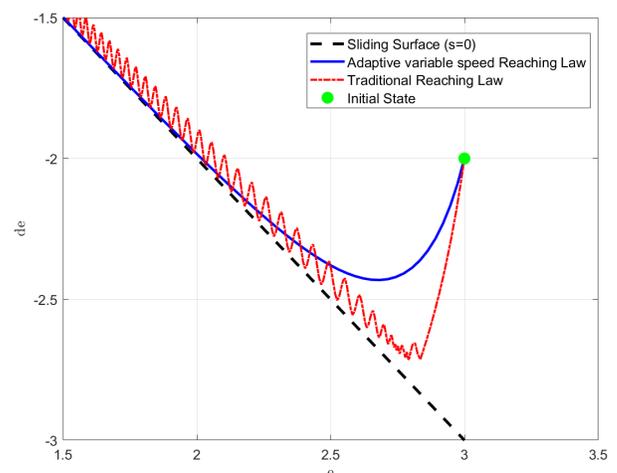


FIGURE 1. Phase trajectory of sliding mode motion.

in both approach speed and chatter suppression, contributing to smoother electromagnetic torque response and lower motor harmonic losses.

3. MATHEMATICAL MODEL OF PERMANENT MAGNET SYNCHRONOUS MOTOR

To facilitate controller design and theoretical analysis, this study investigates surface-mounted permanent magnet synchronous motors (PMSMs) and makes the following idealized assumptions during modeling: magnetic saturation in the motor core is neglected. Eddy current and hysteresis losses are disregarded, and the armature current is assumed to be a three-phase symmetrical sinusoidal waveform. Based on these assumptions, a mathematical model of the PMSM is established in the d - q rotating coordinate system. The stator voltage equation can be expressed as:

$$\begin{cases} u_d = R_s i_d + L_d \frac{di_d}{dt} - \omega_e L_q i_q \\ u_q = R_s i_q + L_q \frac{di_q}{dt} + \omega_e i_d L_q + \omega_e \psi_f \end{cases} \quad (7)$$

In the equation: u_d and u_q represent the d and q -axis components of the stator voltage, respectively; i_d and i_q represent the d and q -axis components of the stator current, respectively; R denotes the stator resistance; L_d and L_q denote the stator inductance with $L_d = L_q$; ω_e denotes the electrical angle; ψ_f denotes the permanent magnet flux linkage. For surface-mounted permanent magnet synchronous motors, when vector control is employed with $i^* d = 0$, the motion equations are:

$$J \frac{d\omega}{dt} = T_e - T_L - B\omega_m \quad (8)$$

The electromagnetic torque is:

$$T_e = \frac{3}{2} p_n \psi_f i_q \quad (9)$$

where T_e is the electromagnetic torque; T_L is the load torque; J is the rotational inertia; B is the friction coefficient; p_n is the number of pole pairs in the motor; and ω_m is the mechanical angular velocity of the motor. It should be noted that the permanent magnet flux ψ_f and stator inductances L_d and L_q in the aforementioned model are not constant. ψ_f undergoes significant decay as the motor operating temperature increases, while L_d and L_q exhibit pronounced nonlinear variations due to magnetic saturation effects from the armature reaction. The actual changes in these critical electromagnetic parameters constitute the primary sources of system model uncertainty and internal disturbances, and represent key factors that must be compensated for in the design of high-performance control strategies.

4. DESIGN OF A GLOBAL FAST TERMINAL SLIP MODE CONTROLLER

4.1. Global Fast Terminal Sliding Surface

Traditional sliding mode control typically employs linear sliding mode hyperplanes, which exhibit nonzero residual errors

under stable conditions. To address this issue, some researchers have proposed improvements using nonlinear sliding surfaces, but such approaches often suffer from slow convergence. To achieve finite-time fast convergence from any initial state to the equilibrium point, this study employed a global fast terminal sliding mode dynamic control method that combines linear sliding surfaces with fast terminal sliding surfaces. The sliding surface function was selected as follows:

$$s = \dot{x}_1 + \alpha_0 x_1 + \beta_0 x_1^{\frac{q_0}{p_0}} \quad (10)$$

In the formula: α_0 and $\beta_0 > 0$, p_0 and q_0 ($p_0 > q_0$) are positive odd integers.

4.2. Design of Terminal Sliding Mode Controller Based on Adaptive Variable Speed Approach Law

Define the state variable as:

$$\begin{cases} x_1 = \omega_{ref} - \omega \\ x_2 = \dot{x}_1 = -\dot{\omega} \end{cases} \quad (11)$$

where ω_{ref} is the motor reference speed, and ω is the actual motor speed. Taking the derivative of Equation (11) again yields:

$$\dot{x}_2 = -\ddot{\omega} = \left(-\frac{3}{2} p_n \psi_f \dot{i}_q + B\dot{\omega} + \dot{T}_L \right) / J \quad (12)$$

Considering that unknown disturbances exist during the actual operation of the motor, Equation (12) can be rewritten as:

$$\begin{aligned} \dot{x}_2 = & [-3p_n \psi_f / (2J) + \Delta_1] \dot{i}_q \\ & + (B/J + \Delta_2) \dot{\omega} + (\dot{T}_L + \Delta \dot{T}_L) / J \end{aligned} \quad (13)$$

where Δ_1 and Δ_2 represent the corresponding uncertainty factors that fluctuate within a certain range, and $\Delta \dot{T}_L$ denotes the first derivative of the unknown disturbance torque. To address the uncertainties within the system, their disturbances can be processed collectively, yielding the following expression:

$$\dot{g}(t) = B\dot{\omega}/J + \dot{T}_L/J + \Delta_1 \dot{i}_q + \Delta_2 \dot{\omega} + \Delta \dot{T}_L \quad (14)$$

where $\dot{g}(t)$ represents the lumped uncertainty, which is bounded and satisfies $\dot{g}(t) < \Sigma$, where Σ is a constant. Based on Equations (11), (13), and (14), the system state variables are:

$$\begin{cases} \dot{x} = x_2 \\ \ddot{x} = -D \dot{i}_q + \dot{g}(t) \end{cases} \quad (15)$$

Therefore, based on the design principles of continuous terminal sliding surfaces and adaptive variable-speed approach laws, the controller is designed by combining Equations (5), (10), and (15) as follows:

$$\begin{aligned} u = \dot{i}_q = & \frac{1}{D} \left[\alpha_0 \dot{x}_1 + \beta_0 x_1^{\frac{q_0-p_0}{p_0}} \dot{x}_1 + \varepsilon F(s) Sigmoid(s) \right. \\ & \left. + k |x|^d s + \dot{g}(t) \right] \end{aligned} \quad (16)$$

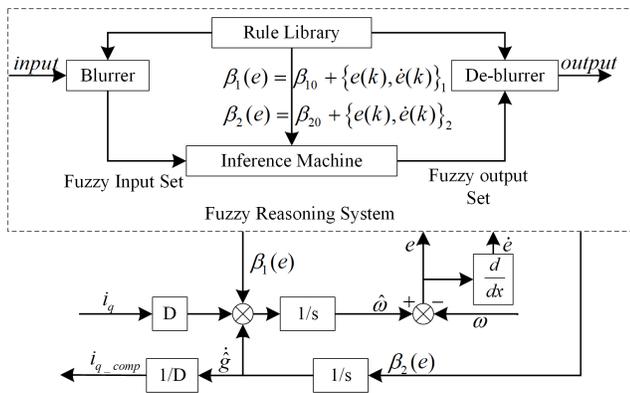


FIGURE 2. Structure of fuzzy adaptive extended state observer system.

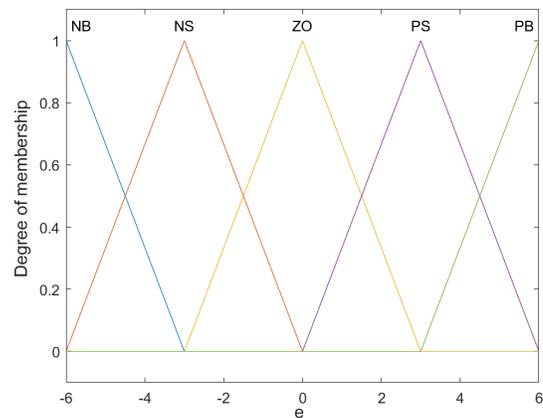


FIGURE 3. Membership functions of inputs e and \dot{e} .

4.3. Stability Analysis

The Lyapunov stability criterion was employed to verify the global stability of the system. The Lyapunov function is constructed as follows:

$$V = \frac{1}{2}s^2 \tag{17}$$

According to the Lyapunov stability theorem, the sufficient conditions for a system to be asymptotically stable are: V is positive definite, and \dot{V} is negative definite (or \dot{V} is semi-definite). Taking the derivative of the Lyapunov function and solving Equations (5) and (17) yields:

$$\dot{V} = s \cdot \dot{s} = -\varepsilon s F(s) Sigmoid(s) - k|x|^d s^2 \tag{18}$$

First, given $\varepsilon > 0, k > 0, 0 < \alpha < 1, \lambda > 1, \beta \neq 0, \theta > 0$, and $d > 0$, we have $F(s) > 0$. Moreover, based on the properties of sigmoid(s), when $s \neq 0$, we have $s \cdot Sigmoid(s) > 0$. Second term: because $k > 0$ and $|x|^d \geq 0$ (because $|x|^d > 0$ and $d \geq \gamma > 0$), we have $-k|x|^d s^2 \leq 0$, with equality holding if and only if $s = 0$. Therefore, by combining the analyses of the two terms, $\dot{V} \leq 0$ holds for all values, indicating that the system is globally stable.

5. ADAPTIVE EXTENDED STATE OBSERVER BASED ON FUZZY LOGIC

In this study, an ESO observer was designed to estimate and compensate for lumped disturbances by feeding the compensation back into the control system. Equation (15) was transformed into the kinematic equations of the PMSM, and the state equations were constructed based on the following kinematic equations:

$$\begin{cases} \dot{z}_1 = Di_q + z_2 \\ \dot{z}_2 = h(t) \end{cases} \tag{19}$$

where z_1 denotes the estimated actual angular velocity of the motor, and z_2 represents the extended state, denoting the estimated lumped disturbance. Based on Equation (19), an extended state observer can be constructed as:

$$\begin{cases} \dot{e} = \omega - z_1 \\ \dot{z}_1 = Di_q + z_2 + \beta_1(e) \\ \dot{z}_2 = \beta_2(e) \end{cases} \tag{20}$$

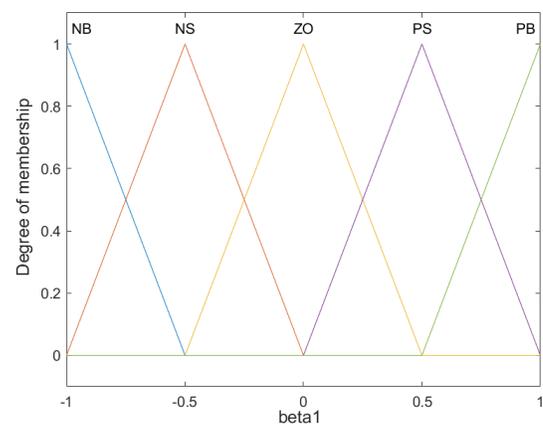


FIGURE 4. Membership function of output $\beta_1(e)$.

where $\beta_1(e)$ and $\beta_2(e)$ represent the observer matrix gains. Conventional observers typically employ linear gains that cannot be adaptively adjusted based on observation errors, which result in suboptimal control performance. To address disturbance suppression issues in extended state observers for non-linear systems, this study proposes an adaptive adjustment of observer matrix gains using fuzzy logic. The gain matrix $\beta_i(e)$ is dynamically selected using a fuzzy inference system. This inference system uses the speed error e and its rate of change \dot{e} as inputs and the observer matrix gains $\beta_1(e)$ and $\beta_2(e)$ as outputs. Based on adaptive calculations using fuzzy control rules, the observer matrix gains can respond in real time to dynamic changes in the speed error e and its rate of change \dot{e} , thereby significantly enhancing the disturbance compensation performance of the system. The structural diagram is shown in Figure 2. In this study, trigonometric functions with a domain of $[-6, 6]$ were used as membership function curves for the input variables e and \dot{e} , and trigonometric functions with a domain of $[-1, 1]$ were used as membership function curves for the output variables $\beta_1(e)$ and $\beta_2(e)$, as shown in Figures 3 and 4. The fuzzy subsets for the variables are $\{NB, NS, ZO, PS, PB\}$, where each element represents negative large, negative small, zero, positive small, or positive large, respectively. The changes in the relationship are shown in Figure 5.

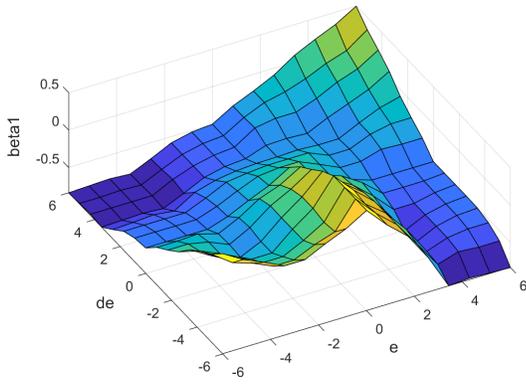


FIGURE 5. Variation surface of $\beta_1(e)$ versus inputs e and \dot{e} .

During adaptive tuning, the following conditions must be satisfied: When e and \dot{e} are large, the system rapidly deviates from the equilibrium point, necessitating a significant increase in gain. When e and \dot{e} are zero, the system is stable and requires no gain adjustments. When e and \dot{e} are small but nonzero, the gain must be adjusted smoothly based on the error magnitude to achieve gradual stabilization. Fuzzy rules can be designed based on the above principles, as listed in Tables 1 and 2.

TABLE 1. β_{10} fuzzy logic inference rule.

e/\dot{e}	NB	NS	ZO	PS	PB
NB	PS	ZO	NS	NB	NB
NS	ZO	NS	NS	NB	NB
ZO	PS	PS	ZO	NS	NS
PS	NB	NB	NS	NS	ZO
PB	NB	NS	NS	ZO	PS

TABLE 2. β_{20} fuzzy logic inference rule.

e/\dot{e}	NB	NS	ZO	PS	PB
NB	PB	PS	PS	NB	NB
NS	PS	PS	NS	NB	NB
ZO	PS	ZO	ZO	ZO	PS
PS	NB	NB	NS	NS	ZO
PB	NB	NB	NB	NS	NS

Based on the membership functions of the input and output variables and the fuzzy control rule table, the fuzzy adaptive tuning formula for $\beta_i(e)$ can be derived as follows:

$$\begin{cases} \beta_1(e) = \beta_{10} + \{e(t), \dot{e}(t)\}_1 \\ \beta_2(e) = \beta_{20} + \{e(t), \dot{e}(t)\}_2 \end{cases} \quad (21)$$

where β_{10} and β_{20} are the initial values of the matrix gain, and $\{e(t), \dot{e}(t)\}_1$ and $\{e(t), \dot{e}(t)\}_2$ are the fuzzy inference results.

6. SIMULATION RESULTS AND COMPARATIVE ANALYSIS

Simulation and experimental studies were conducted to validate the effectiveness of the control method. The motor simulation parameters are listed in Table 3.

TABLE 3. Motor parameters.

Parameters	Parameter value
Stator Inductance L_s/mH	8.5
Stator resistance R/Ω	2.875
Magnetic chain ψ_f/Wb	0.175
Extreme logarithm p	4
Moment of inertia J	0.003
Damping coefficient B	0.008
DC voltage U_{dc}/V	311

To validate the effectiveness of the proposed control method, comparative simulations were conducted among four controllers: conventional Sliding Mode Control (SMC) using a traditional exponential reaching law, the recently developed Novel Exponential Approach Law SMC (NSMC) as an advanced strategy, the Adaptive Speed Approach Law SMC (ASMC) based on the adaptive law proposed in this work, and the Global Terminal Fast Adaptive SMC (GTFASMC), which integrates the proposed adaptive law with a global terminal fast sliding surface. The parameters were set as follows: for SMC parameters: $k = 150, c = 250, \varepsilon = 300$ for NSMC parameters: $k = 150, c = 250, \varepsilon = 300, b = 25, c = 0.001$ for ASMC parameters: $\theta = 1, \gamma = 1.2, \alpha = 1000, \lambda = 0.98, \beta = 1$ for GTFASMC parameters: $\alpha_0 = 600, \beta_0 = 0.01, p_0 = 7, q_0 = 5$, with the remaining parameters identical to ASMC. Fuzzy Expanded State Observer (FESO) parameters: $\beta_{10} = 160, \beta_{20} = 400$.

6.1. Analysis of No-Load Starting Performance

Under no-load start conditions, with a target speed of 1000 r/min and a simulation duration of 0.2 s, the performance comparison of the four control methods is shown in Figure 6 and Table 4.

TABLE 4. Performance comparison of four control methods during no-load starting.

Performance Metrics	NSMC	SMC	ASMC	GTFASMC
Speed overshoot				
/(r/min)	10	0	5	0
Speed rise				
time/s	0.015	0.015	0.035	0.022
Speed stabilization				
time/s	0.026	0.044	0.035	0.020

The results of the dynamic velocity response shown in Figure 6 demonstrate that during the dynamic process of the elec-

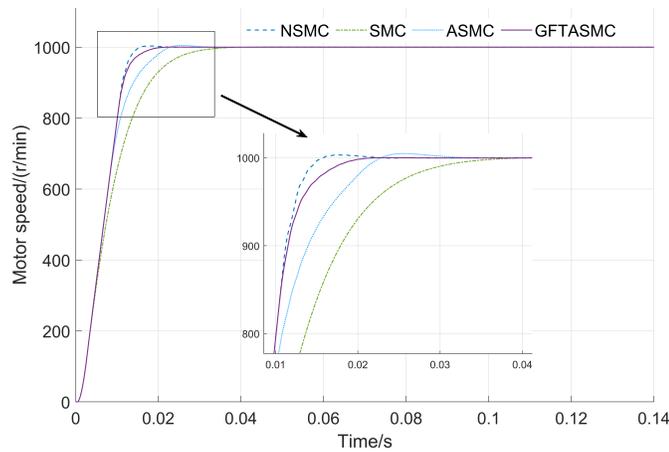


FIGURE 6. No-load response comparison of four control methods.

tromechanical system, the proposed adaptive sliding mode control (ASMC) exhibits a faster electromagnetic transient response and higher steady-state tracking accuracy. Its performance significantly outperforms traditional sliding mode control (SMC) and also holds distinct advantages over existing advanced sliding mode control strategies. The improved strategy employing Global Fast Terminal Sliding Surface (GTFASMC) further effectively shortens the duration of electromechanical transient processes, markedly enhancing the system's dynamic convergence characteristics. According to the quantitative analysis data in Table 4, under the GTFASMC strategy, the rotational speed stabilization time was only 76.92%, 45.45%, and 57.14% of those achieved by the novel NSMC, traditional SMC, and ASMC methods, respectively. This demonstrates the strategy's advantages in improving motor electromagnetic transient processes and enhancing the torque response consistency.

Figure 7 shows a comparison of the dynamic response characteristics of the four control strategies under no-load startup and speed step disturbance conditions. The experimental results demonstrate that during electromagnetic transients induced by motor startup and abrupt speed changes, the proposed GTFASMC method exhibits significant advantages over both

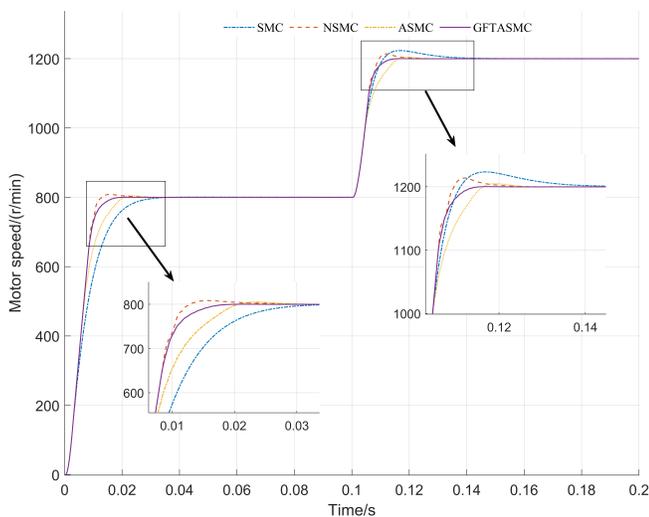


FIGURE 7. Comparison of speed response under sudden load change for four control methods under no-load conditions.

traditional SMC and novel NSMC strategies. These advantages are manifested in both the speed of the electromagnetic torque dynamic response and smoothness of the speed regulation processes. Consequently, this method effectively enhances the system's disturbance recovery capability and the overall electromagnetic performance quality under dynamic operating conditions.

To validate the disturbance suppression capability of the fuzzy extended state observer designed in this study, a comparison was conducted between the proposed observer and an existing extended state observer under identical step load conditions, and the results are shown in Figure 8. The experiment was conducted at a rotational speed of 1000 r/min, with a $10 \text{ N} \cdot \text{m}$ load applied at 0.1 seconds and a $-10 \text{ N} \cdot \text{m}$ load applied at 0.2 seconds. Figure 8 demonstrates that the introduction of the fuzzy extended state observer designed in this study further enhances both the speed stability and the disturbance suppression capability of the GFTASMC.

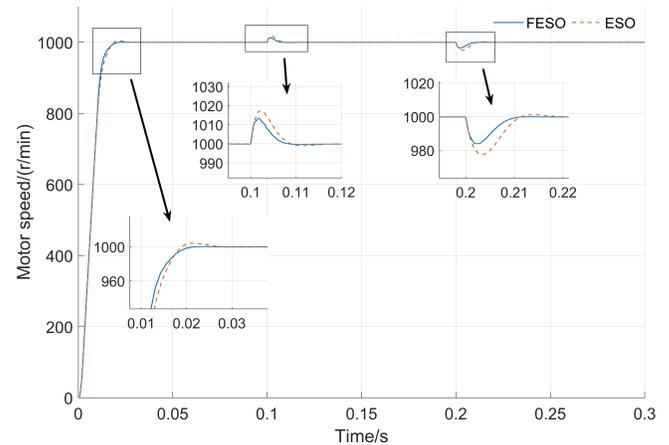


FIGURE 8. Performance comparison of the proposed control strategy.

When the system encounters sudden load changes, under traditional sliding mode control strategies, the stator current response exhibits significant oscillation phenomena. This not only exacerbates the current harmonic components but also increases the electromagnetic torque pulsations, significantly prolonging the system's convergence to steady-state electromagnetic equilibrium. The controller proposed in this study effectively suppresses current oscillations during such transient electromagnetic processes, significantly improving current waveform quality. The three-phase stator current response curves shown in Figure 9 fully demonstrate the design's outstanding electromagnetic dynamic performance.

6.2. Comparative Analysis of Sudden Load Performance

A 0.5-second simulation was conducted at 1000 r/min. A sudden $5 \text{ N} \cdot \text{m}$ load disturbance was applied at 0.2 seconds and removed at 0.3 seconds. The comparison results in Figure 10 demonstrate that when responding to this sudden load, the motor controlled by GTFASMC exhibits significantly smaller speed fluctuations than NSMC and recovers to steady-state operation more rapidly, revealing a distinct advantage in suppression performance.

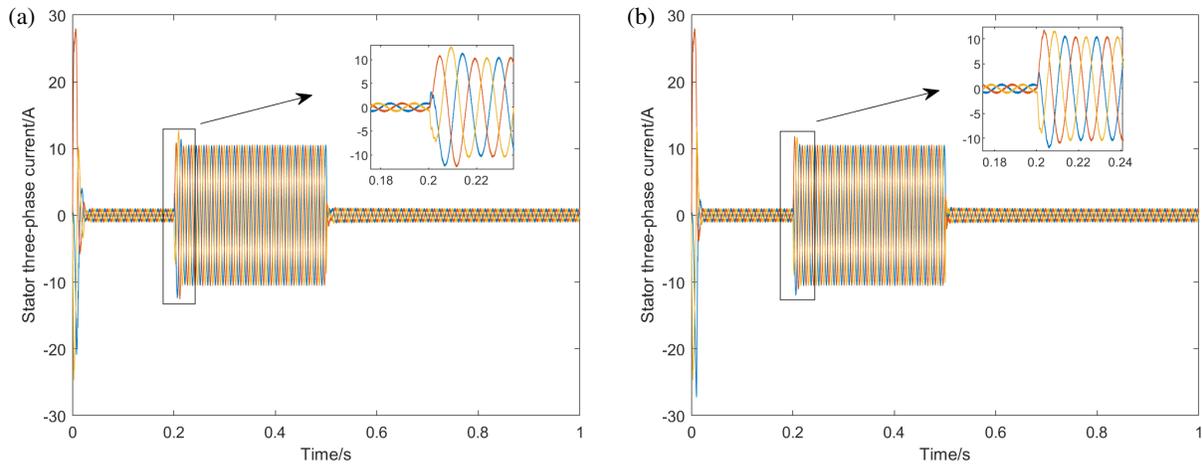


FIGURE 9. Three-phase current variation diagram. (a) ASMC. (b) GTFASMC.

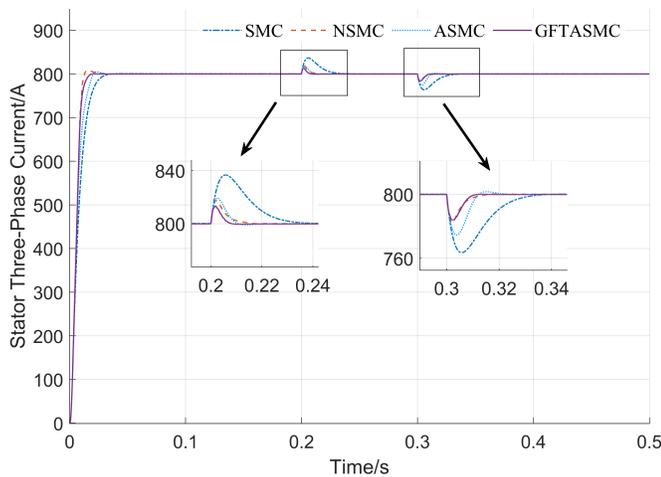


FIGURE 10. Speed response under step load for four control methods.

Under these operating conditions, the dynamic response curve of the electromagnetic torque is shown in Figure 10, clearly revealing both the transient process and steady-state fluctuation characteristics.

7. CONCLUSION

To enhance the electromagnetic transient performance and dynamic response quality of permanent magnet synchronous motor vector control systems, this study proposes a novel adaptive speed-approaching law. This approach effectively suppresses the current harmonics and electromagnetic torque ripple caused by high-frequency switching while significantly enhancing the system's response speed during dynamic processes. Building on this foundation, a globally fast terminal sliding surface was innovatively introduced to achieve rapid convergence of the electromagnetic state variables of the system within a finite time. This not only further improves the convergence efficiency of the electromechanical energy conversion process but also effectively mitigates the high-frequency chattering phenomena in the control torque. To address complex electromagnetic disturbances in the system, such as load transients and flux fluctuations, a fuzzy logic-based gain adaptive mechanism

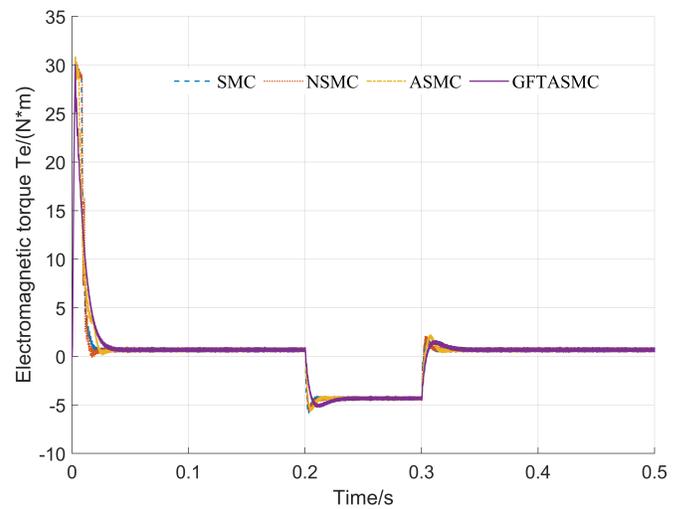


FIGURE 11. Torque variation under step loads for four control methods.

for extended state observers was developed. By real-time identification and feedforward compensation of these disturbance components, the electromagnetic disturbance immunity of the system was significantly enhanced. The experimental results demonstrate that the proposed control strategy exhibits significant advantages in improving the electromagnetic torque dynamic response, enhancing steady-state operational accuracy, and strengthening the suppression capabilities against electromagnetic disturbances.

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